Smoke Control, An Overview with a Discussion of the Benefits of Firestopping

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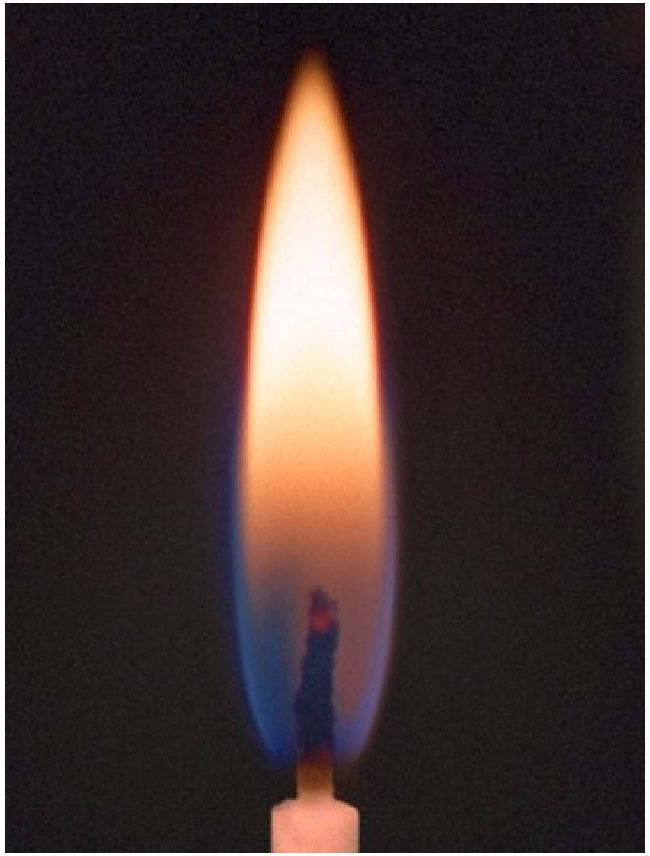
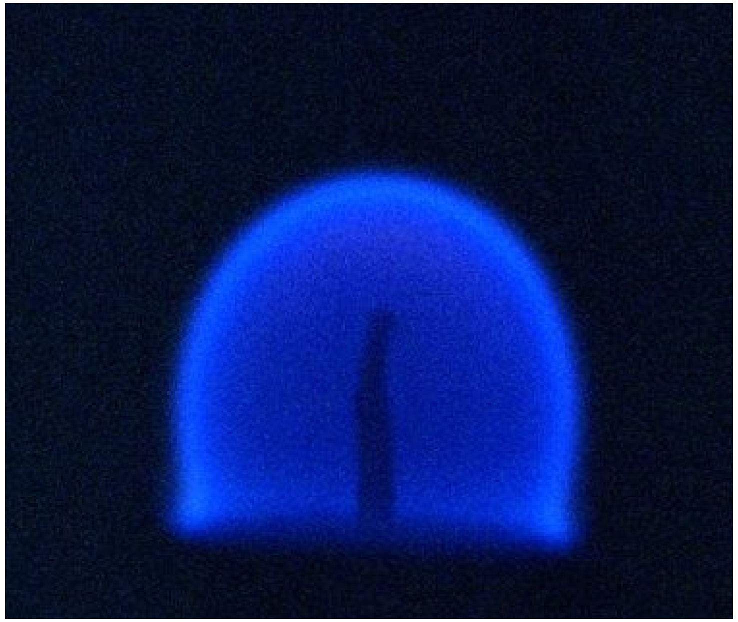
Smoke Control, An Overview with a Discussion of the Benefits of Firestopping

- An overview of the physical forces driving smoke movement within a building.
- A basic understanding of CONTAM as one frequently used computer smoke leakage model.
- An overview of how firestopping and mechanical systems work together to limit smoke migration.

Micro-gravity experiments
NASA KC-135 Aircraft (Glenn Research Center, Ohio)



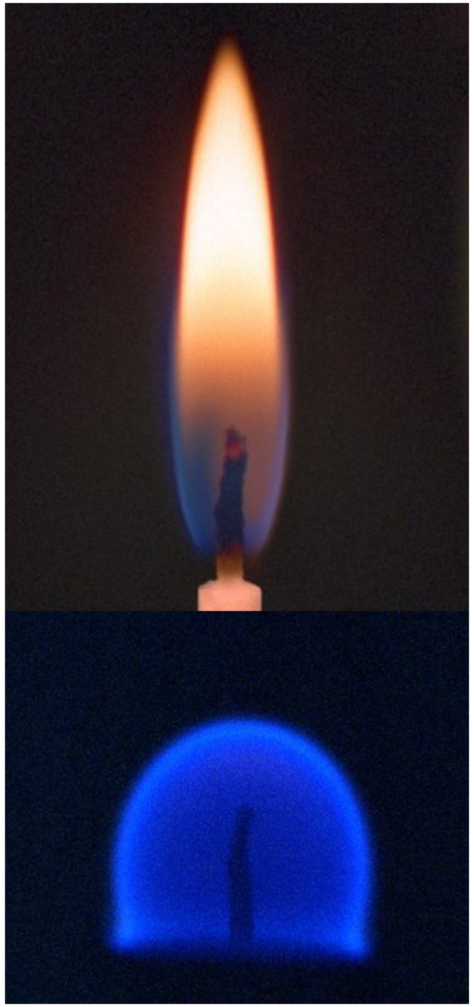


Objectives of the NASA Test Program

- Provide NASA with a normal gravity test methodology (FIST) that will complement its existing material fire testing protocol (Test 6001.1) and provide a relative ranking of material flammability.

- Test a number of solid materials and find *flammability properties* which can be used to rank their fire safety performance in an environment expected in space facilities.

- Provide theoretical background and a few validation tests of the methodology with microgravity experiments.



The Fire Safety System

How do Flammability Assessments make their way into the built environment?

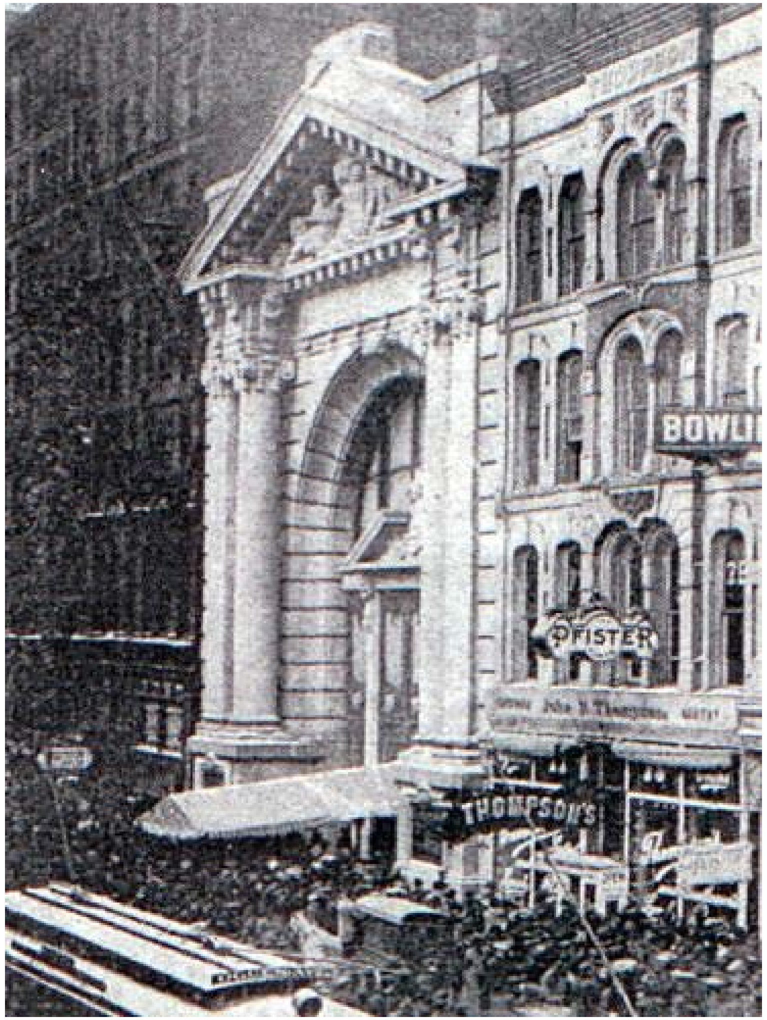
- Fire safety expressed in edicts, many of which follow major fires
- Legal requirements emanate from government departments concerned with the risk of fire not from the people assessing the hazard. Legal requirements change regularly, fire physics don't
- Local authorities, insurance companies, standards bodies, and code writing organizations support these government departments
- Scientists conducting tests of fire resistance or flammability support these organizations.

How do fire regulations make their way into the built environment?

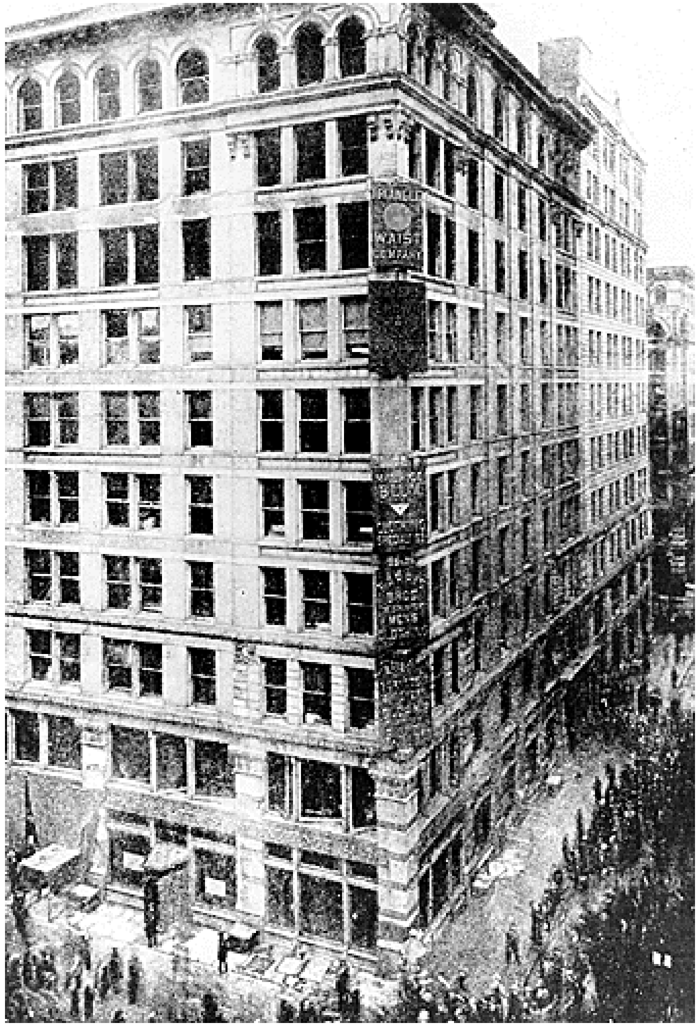
Entire Cities

- –Portland, Me (1866)
- –Atlanta, Ga (1917)
- –Baltimore, Md (1904)
- –Boston, Ma (1872)
- –Chicago, Il (1871)
- –Jacksonville, Fl (1901)
- –New Orleans, La (1788, 1794)
- –New York, NY (1776, 1794)
- –Salem, Ma (1910)
- –Seattle, Wa (1889)
- –St. Louis, Mo (1849)
- –San Francisco, Ca (1906)

Historical efforts to control fire losses: Large Buildings



Iroquois Theatre fire, December 30th, 1903.

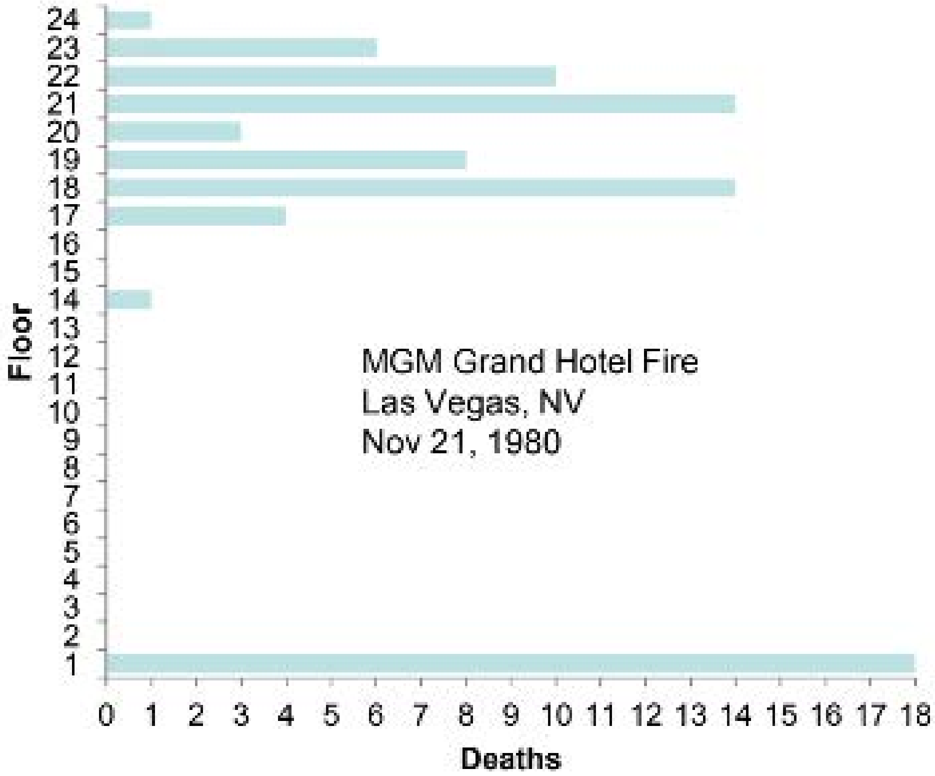


Triangle Shirtwaist fire, March 25th, 1911.

Historical efforts to control fire losses: Large Buildings

- La Salle Hotel – Chicago, June 5th 1946
  - 61 deaths, Open stairways, flammable materials, open vents.
- Hotel Canfield – Dubuque Iowa, June 19th, 1946
  - 19 deaths, Open stairways, flammable materials, no sprinklers or fire alarms
- Winecoff Hotel – Atlanta, GA, December 7th, 1946
  - 119 deaths, open stairs, transoms above doors, flammable materials
- MGM Grand Fire – Las Vegas, NV, November 21st, 1980
  - 85 deaths, Smoke migration through elevator shafts, stairwells, and seismic joints, sprinkler rule exceptions.
- Dupont Plaza– San Juan, Puerto Rico, December 31st, 1986
  - 98 deaths, Malfunctioning safety equipment, non automated sprinklers, lack of emergency plans, arson.

Historical efforts to control fire losses: Large Buildings



These and other fires from the 1960s on led to a push for increased methods of controlling smoke in the codes

Reference Klote and Milke, Principles of Smoke Management, ASHRAE and SFPE, 2002

Regulating Smoke - IBC 2018

Chapter 4 Requirements Based on Use and Occupancy: Past fire experience has shown that interior finish and decorative materials are key elements in the development and spread of fire. The performance of the material is evaluated based on test standards.

Chapter 7 Fire and Smoke Protection Features: The provisions of Chapter 7 present the fundamental concepts of fire performance that all buildings are expected to achieve in some form. The fire-resistance-rated construction requirements provide passive resistance to the spread and effects of fire. Types of separations addressed include fire walls, fire barriers, fire partitions, horizontal assemblies, smoke barriers and smoke partitions.

Chapter 8 Interior Finishes: This chapter contains the performance requirements for controlling fire growth within buildings by restricting interior finish and decorative materials. As smoke is also a hazard associated with fire, this chapter contains limits on the smoke development characteristics of interior finishes.

Chapter 9 Fire Protection Systems: Prescribes the minimum requirements for active systems of fire protection equipment to perform the following functions: detect a fire; alert the occupants or fire department of a fire emergency; and control smoke and control or extinguish the fire.

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Chapter 7 – Fire and Smoke Protection Features

- 701.1 Scope. The provisions of this chapter shall govern the materials, systems and assemblies used for structural fire resistance and fire-resistance-rated construction separation of adjacent spaces to safeguard against the spread of fire and smoke within a building and the spread of fire to or from buildings.
- Smoke Dampers, barriers, partitions, compartments, penetration protection, detectors especially as part of automatic systems.
- Specification of hardware supporting pressurization systems
- Fire Walls, Fire Barriers, Fire Partitions, Smoke Barriers, Smoke Partitions (approved materials), Horizontal Assemblies, Shafts Enclosures
  - All require compliance with Sections on Penetrations (Section 714) and Joints (Section 715)

Compartmentation

- Compartmentation provides physical barrier to unmitigated smoke spread between spaces
- Benefit of compartmentation depends on quality and integrity of compartment boundaries
- Commonly used in combination with pressurization to manage smoke movement
- Openings, penetrations and joints in smoke barriers and partitions must be constructed with materials and systems that limit air leakage through the barrier or partition when subjected to a pressure differential
- Standard test methods used to certify products for smoke barrier and partition applications

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Chapter 7 – Fire and Smoke Protection Features, provides requirements for air leakage of firestop systems

- 714 Penetrations of Fire Resistance rated assemblies, Horizontal Assemblies
  - Listed penetrations firestops installed in accordance with the manufacturer's instructions.
  - Materials prevent the passage of flame and hot gases when subjected to ASTM E119 under a pressure of 0.01 inch (2.49 Pa)
  - Through penetration shall be protected by an approved penetration firestop system installed as tested in accordance with ASTM E814 with a pressure differential of 0.01 inch (2.49 Pa)

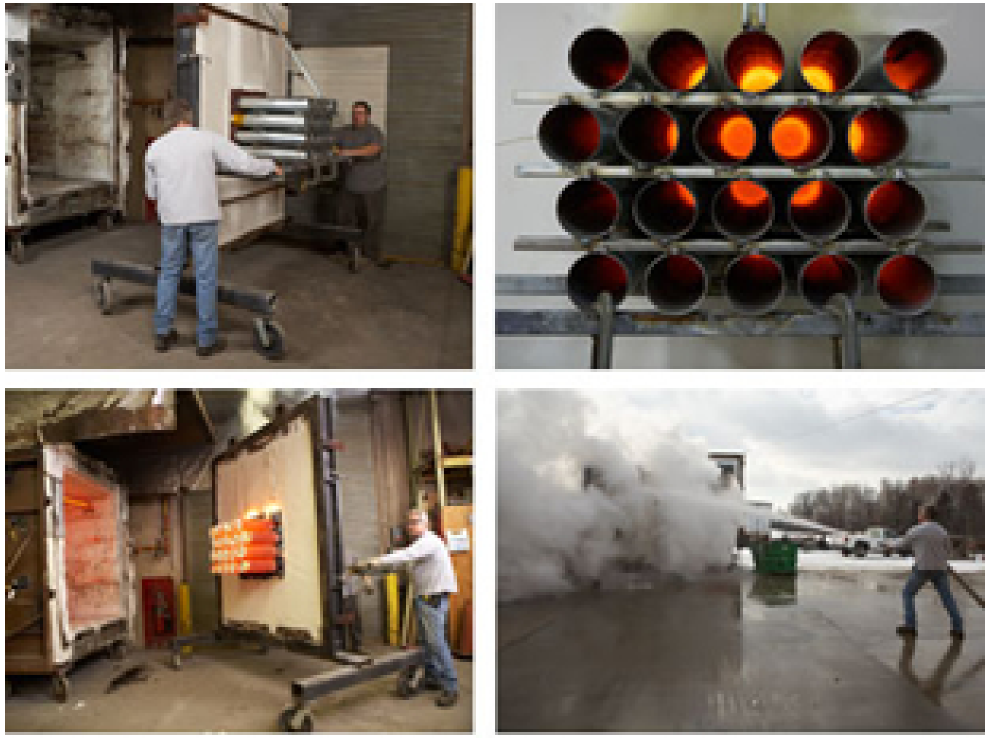
714.5.4 Penetrations in Smoke Barriers

- Require an approved through penetration firestop system tested in accordance with UL 1479 for air leakage. The L rating of the system measured at 0.30 inch (74.7 Pa).

715 Fire Resistant Joint Systems

- Joints between fire resistance rated walls, floor ceiling assemblies, protected by an approved fire resistant joint system
- Exterior curtain wall floor intersections tested in accordance with ASTM E2307 or for non-fire rated assemblies, an approved material to retard the interior spread of fire and hot gases between stories.
- Fire resistance in joints systems of smoke barriers, shall not exceed 5 cfm per linear foot of a joint at 0.30 inch (74.7 Pa).

ASTM E814 (UL 1479) – Fire Test for Through-Penetration Firestops



Before, during and after an ASTM E 814 Fire Test at 3M Fire Test Center

- T-Rating Max. temperature rise of 325 F above ambient on the non-fire side.
- F-Rating: Prohibits flame passage through the system for the duration of the fire test.
- L-Rating: Amount of air leakage (at 0.3 inches water)
- Hose Stream Test

Pressure effects can be treated in two separate categories as follows:

- Fire effects
  - Pressure differences due to buoyancy, i.e. density differences between hot and cold gases
  - Pressure differences due to thermal expansion in an enclosure

- Environmental effects
  - Pressure differences between inside and outside of building
  - Pressure differences caused by wind acting on the building
  - Pressure differences due to mechanical ventilation

Karlsson, B., Quintiere, J.G., “Enclosure Fire Dynamics”, CRC Press, 2000 pgs. 82-83

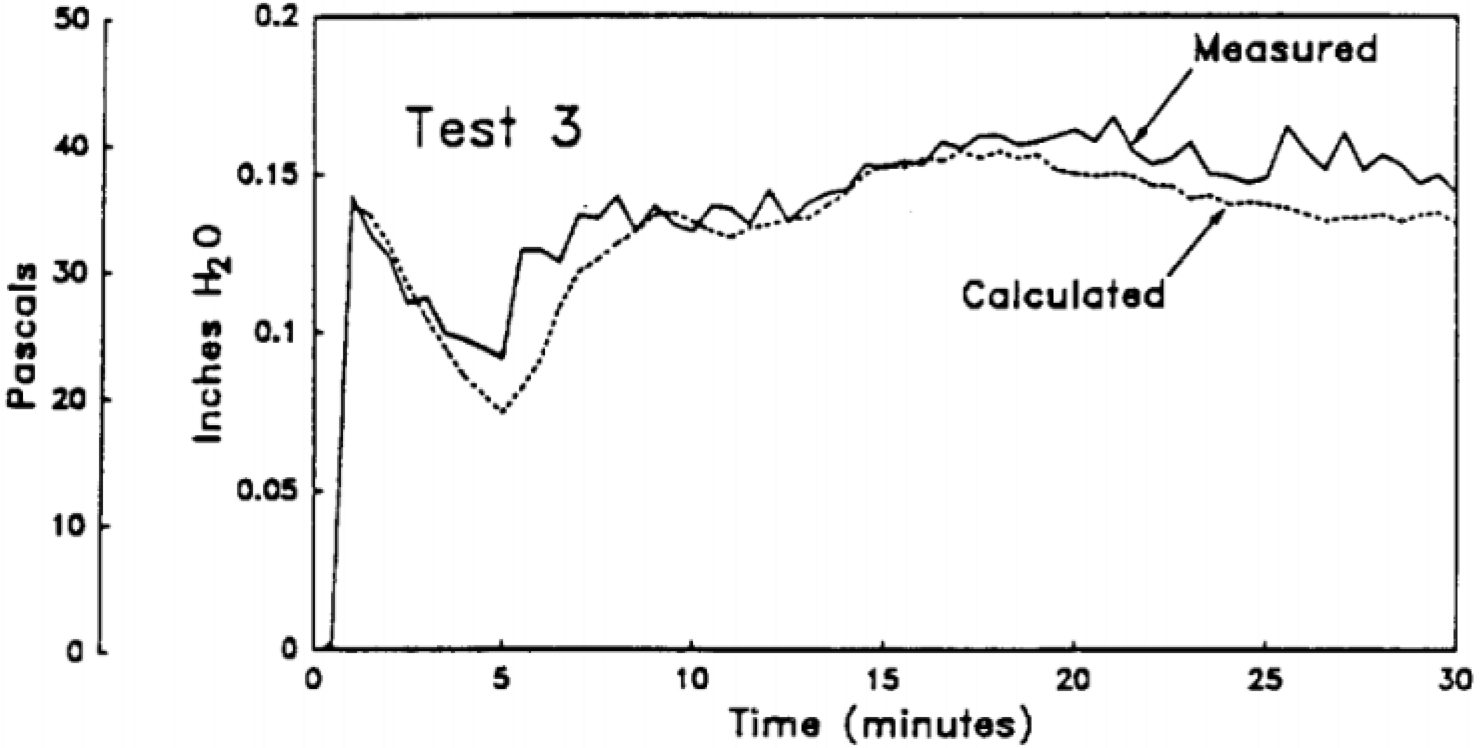
Pressure effects due to thermal expansion

FIRE EXPERIMENTS OF ZONED SMOKE CONTROL AT THE PLAZA HOTEL IN WASHINGTON DC

John H. Klote

U.S. DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
National Engineering Laboratory
Center for Fire Research
Gaithersburg, MD 20899

February 1990



Pressure effects due to thermal expansion

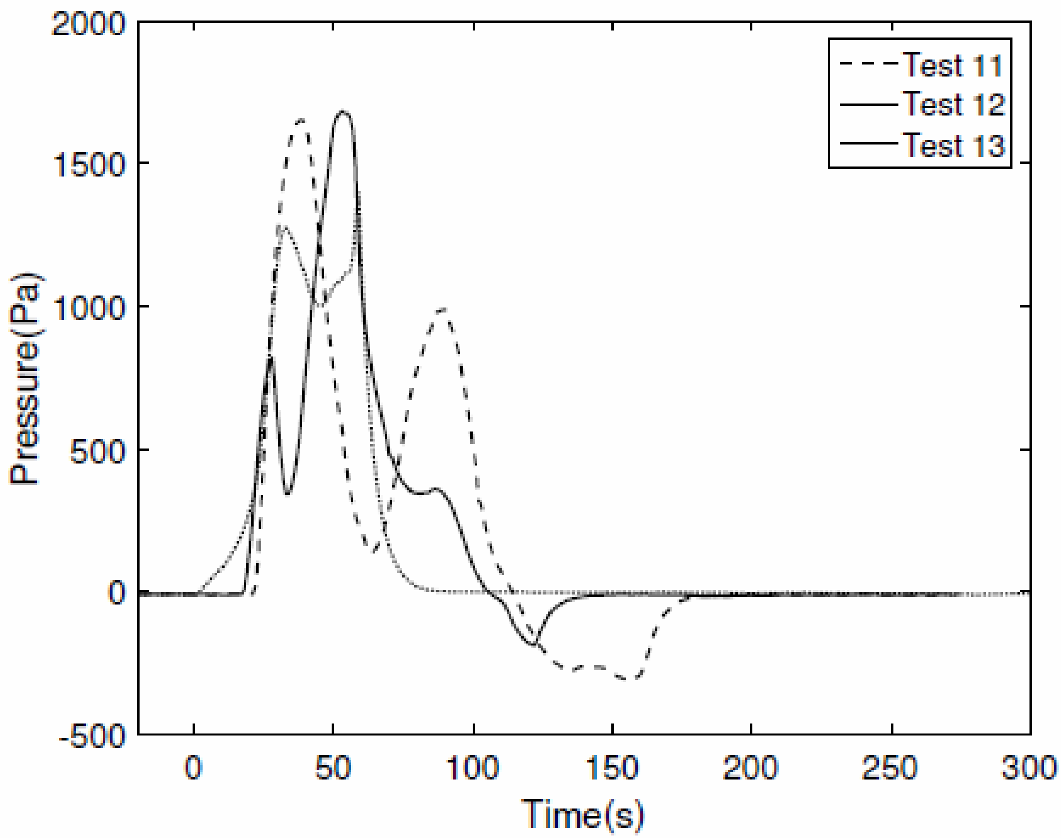
Fire Technology, 53, 1353–1377, 2017

Manufactured in The United States
DOI: 10.1007/s10694-016-0641-z

CrossMark

Experiments and Numerical Simulations of Pressure Effects in Apartment Fires

R. Kallada Janardhan and S. Hostikka, Aalto University, Espoo, Finland*



Compartmentation
Calculating the pressure from buoyant fire gases

$$\Delta\text{Pressure} = K\left(\rho_{cold} - \rho_{hot}\right)h$$

$$\Delta\text{Pressure} = K\left(\frac{1}{T_{cold}} - \frac{1}{T_{hot}}\right)h$$

$$\Delta P = 7.64\left[\frac{1}{T_o} - \frac{1}{T_F}\right]h$$

where:

ΔP = pressure difference due to buoyancy of hot gases (in. w.g.)

T_o = absolute temperature of surroundings (R)

T_F = absolute temperature of hot gases (R)

h = distance above neutral plane (ft)

Compartmentation

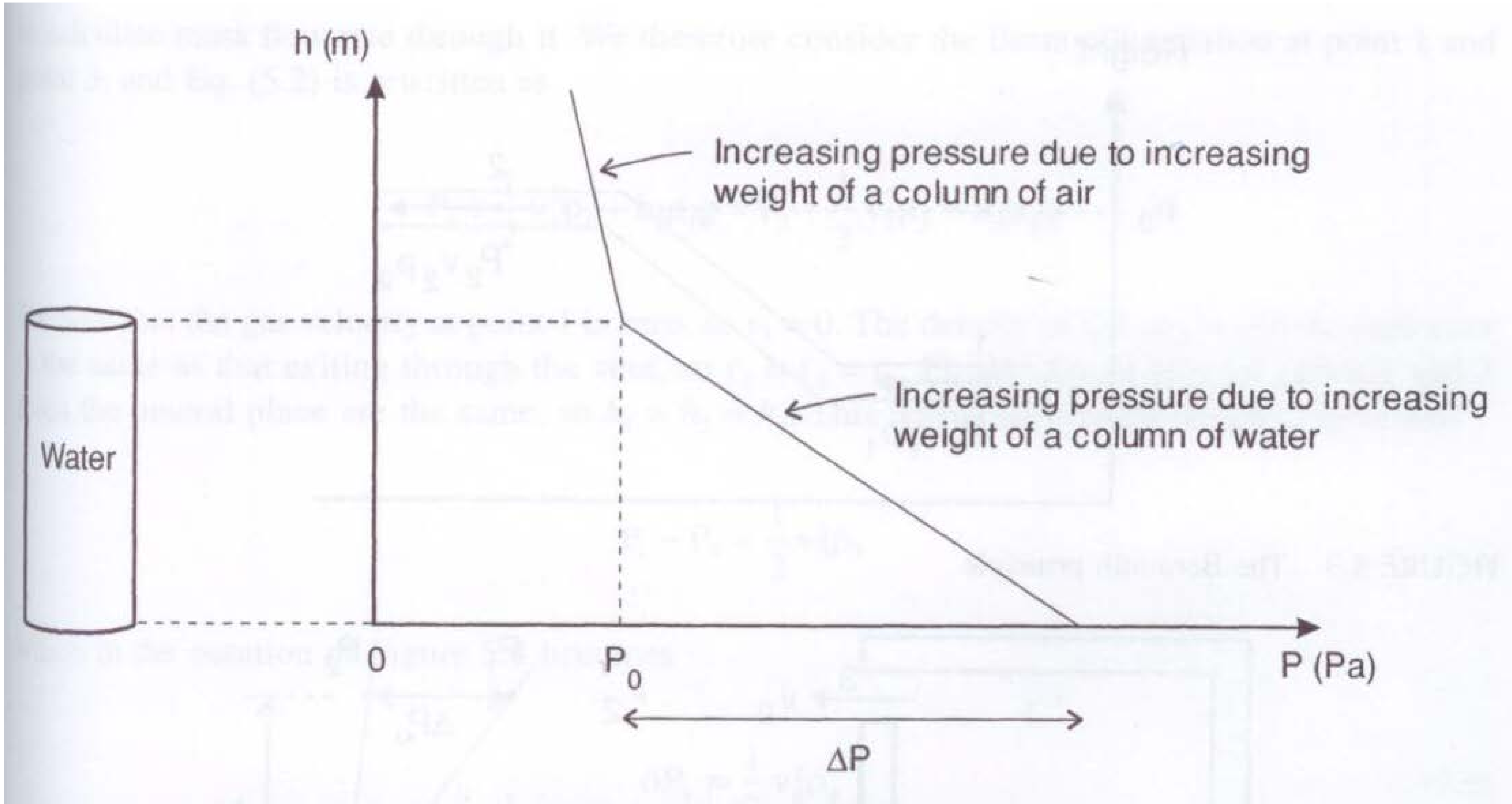
For example, calculate the minimum design pressure difference for a ceiling height of 12 ft as follows:

$$T_o = 70 + 460 = 530\text{R}$$
$$T_F = 1700 + 460 = 2160\text{R}$$
$$h = (12)\left(\frac{2}{3}\right) = 8 \text{ ft}$$

From the above equation, ΔP = 0.087 in. w.g. Adding the safety factor and rounding off, the minimum design pressure difference is 0.12 in. w.g. (about 29 Pa).

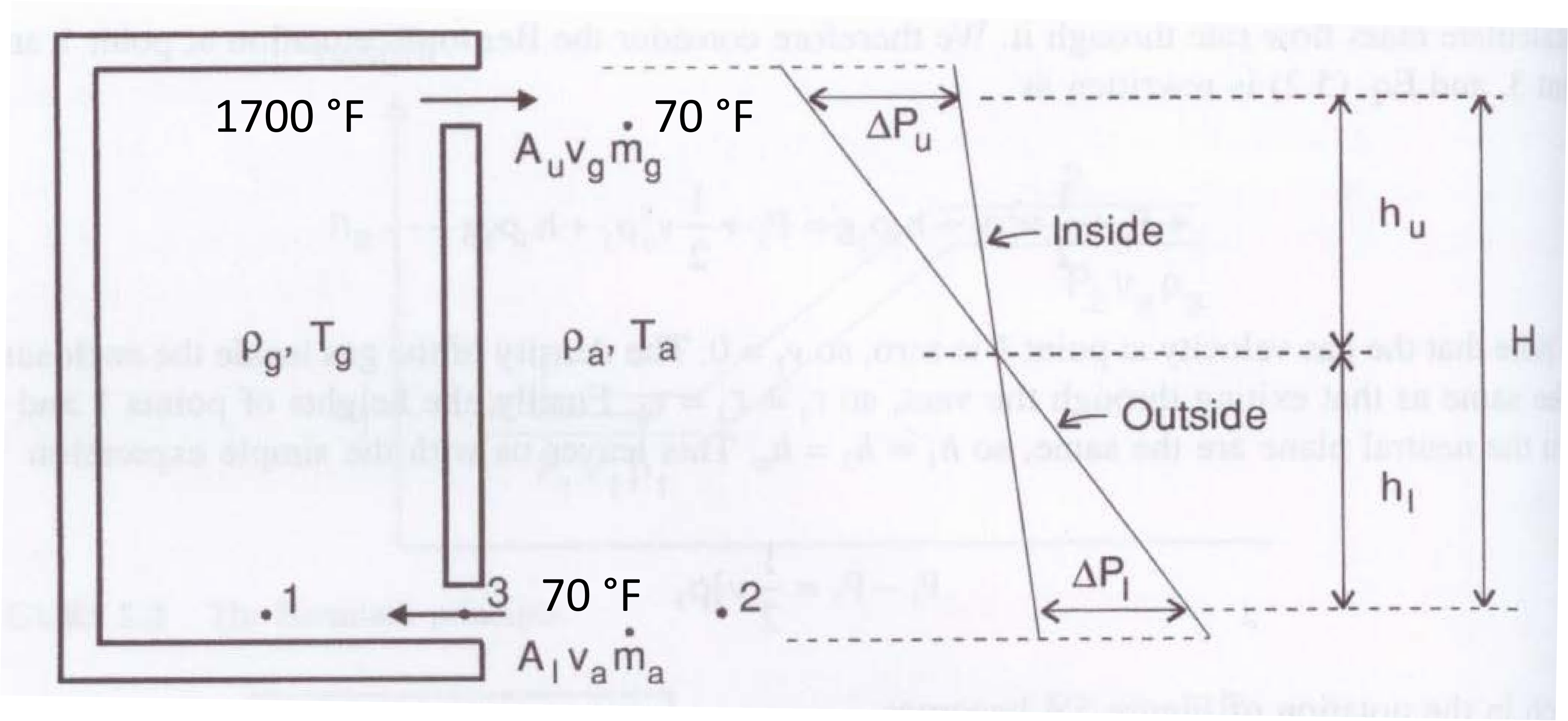
High temperature creates high pressure
High pressure drives flow from P_{high} to P_{low}

Natural ventilation

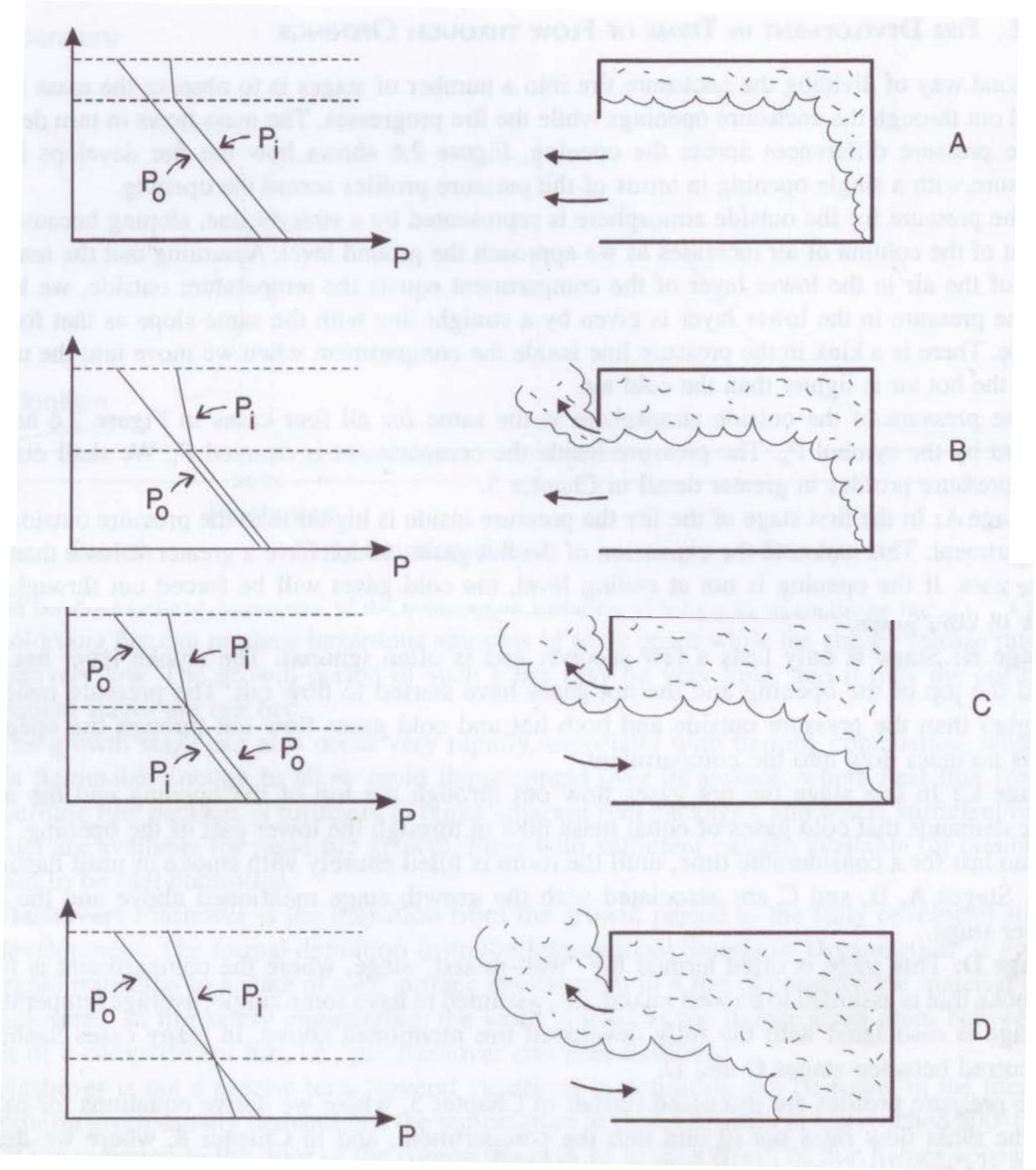


Karlsson, B., Quintiere, J.G., “Enclosure Fire Dynamics”, CRC Press, 2000 pg. 85

Natural ventilation



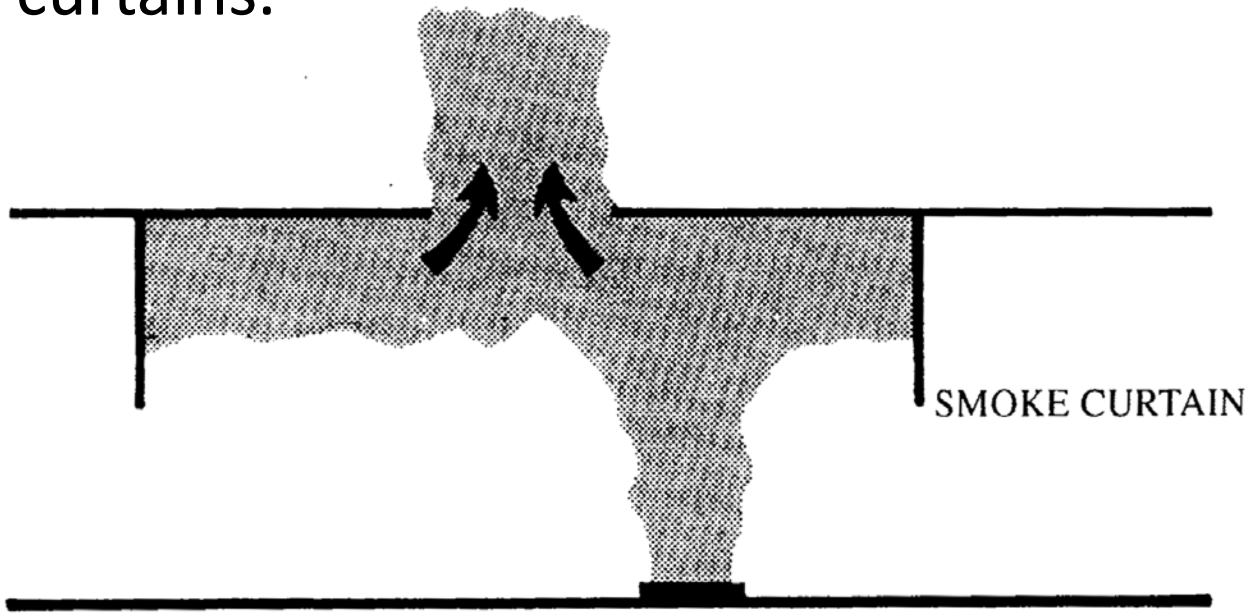
Karlsson, B., Quintiere, J.G., “Enclosure Fire Dynamics”, CRC Press, 2000 pg. 88



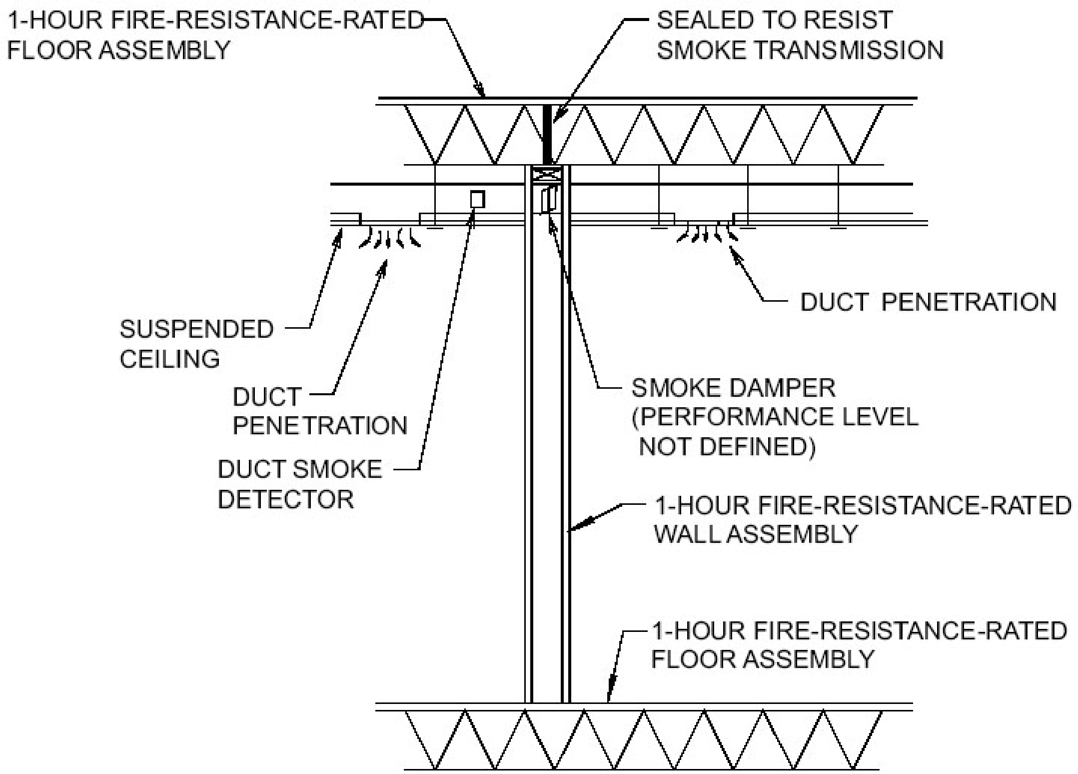
Karlsson, B., Quintiere, J.G., “Enclosure Fire Dynamics”, CRC Press, 2000 pg. 20

Smoke Reservoirs – In warehouse and high ceiling applications

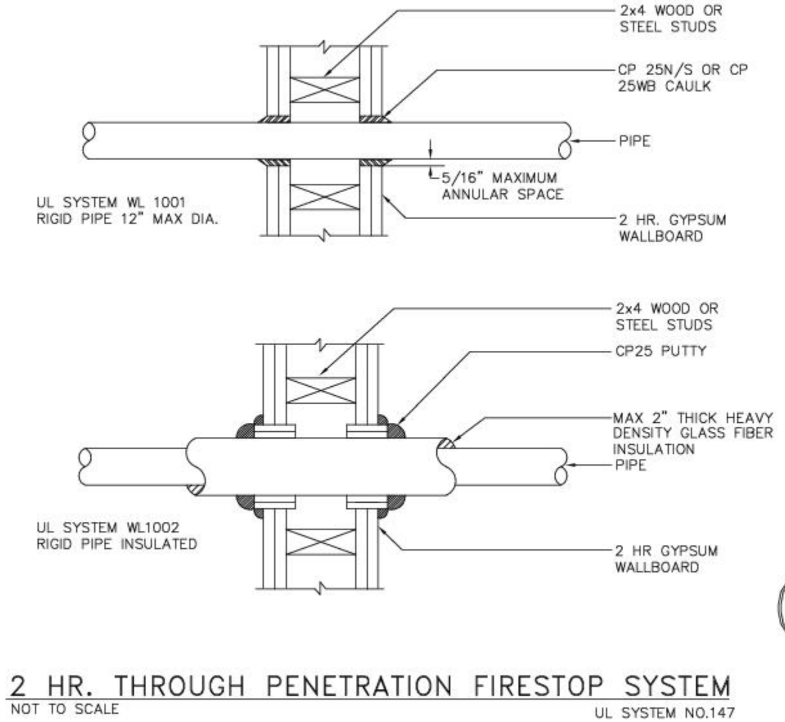
- To ensure the proper operation of the roof vents, smoke reservoirs must be provided.
- These are either deep wells which are either part of the structure of the mall or can be created with smoke curtains.

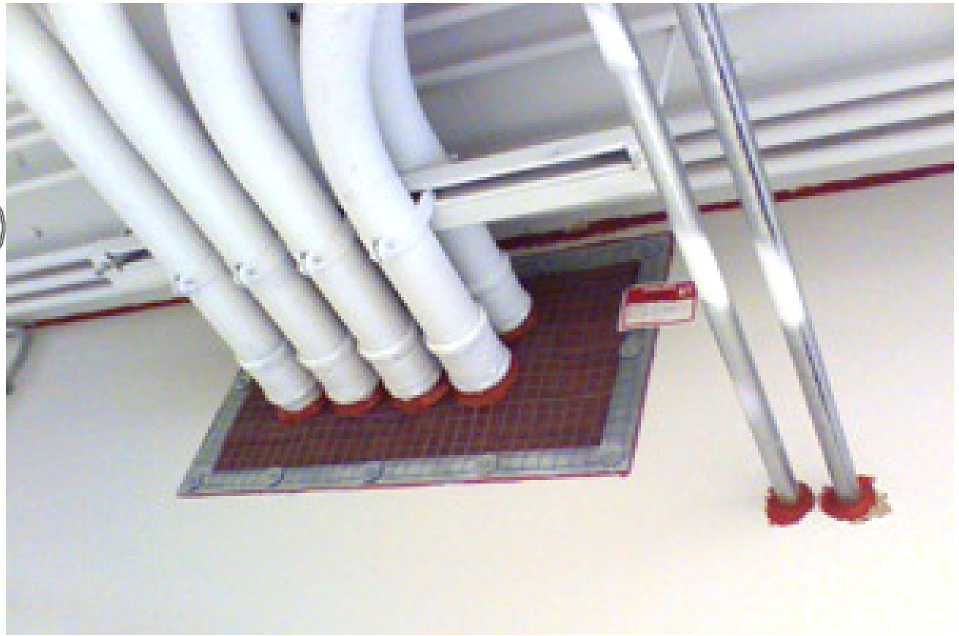


Compartmentation



Compartmentation





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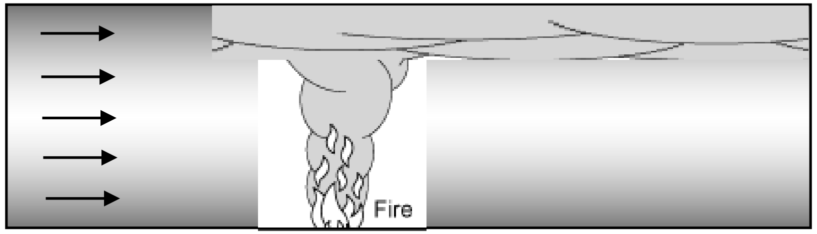
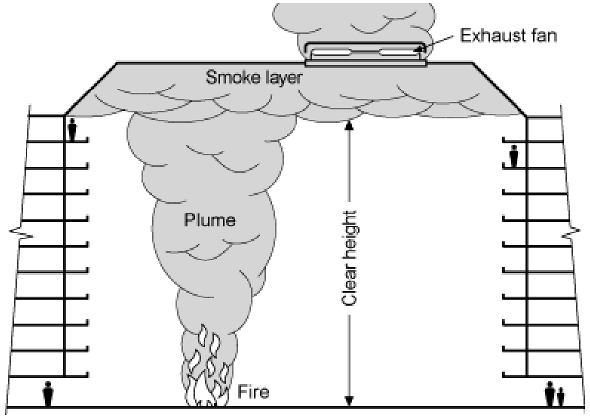
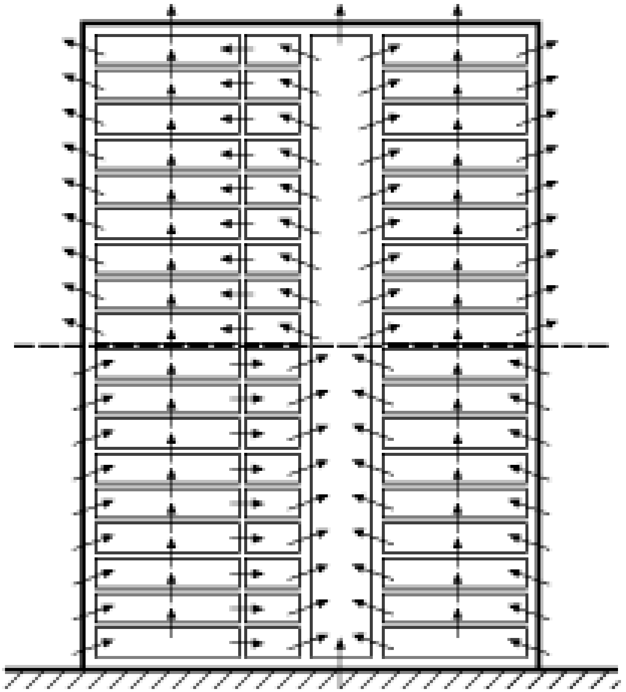
IBC (Sections 909.7 and 909.8) directs designers of <u>active</u> smoke control systems using the air movement and exhaust methods to NFPA 92. It retains design specification for the pressurization method (Section 909.8)

- Types of active smoke control:
- Pressurization
- Exhaust
- Airflow







Pressure Difference Method - IBC 2018

- The Pressurization method employs the following:
  - Maintain pressure differences across smoke barriers.
  - Minimum pressure difference across smoke barriers is 0.05 inches of water (12.5 Pa) in a sprinklered building.
  - Maximum pressures are dictated by door opening forces, also calculated.
  - The minimum pressure differential ranges in stairways are from 0.05 in H_2O (sprinklered building) to 0.1 in H_2O (non-sprinklered building or IBC stair pressurization), and are meant to counteract the anticipated buoyancy force resulting from a compartment fire adjacent to the stair, incorporating appropriate safety factors.
  - Measurements of pressure differences are required as part of commissioning.
  - For non-sprinklered, calculations are required.

NFPA 92 (2018)- Standard for Smoke Control Systems

NFPA 92 Section 1.2 Purpose, to provide requirements for smoke management systems to accomplish one or both of the following:

- (1) Maintain a tenable environment in the means of egress from large-volume building spaces during the time required for evacuation
- (2) Control and reduce the migration of smoke between the fire area and adjacent spaces
- Pressurization is form of smoke management sometimes used in combination with compartmentation to prevent the spread of smoke from a fire compartment into adjacent spaces, including stairways.

Managing Smoke – NFPA 92
Standard for Smoke Control Systems

Building Type	Ceiling Height (ft)	Design Pressure Difference* (in. w.g.)
AS	Any	0.05
NS	9	0.10
NS	15	0.14
NS	21	0.18

For SI units, 1 ft = 0.305 m; 0.1 in. w.g. = 25 Pa.
AS: Sprinklered. NS: Nonsprinklered.
Notes:
(1) The table presents minimum design pressure differences developed for a gas temperature of 1700°F (927°C) next to the smoke

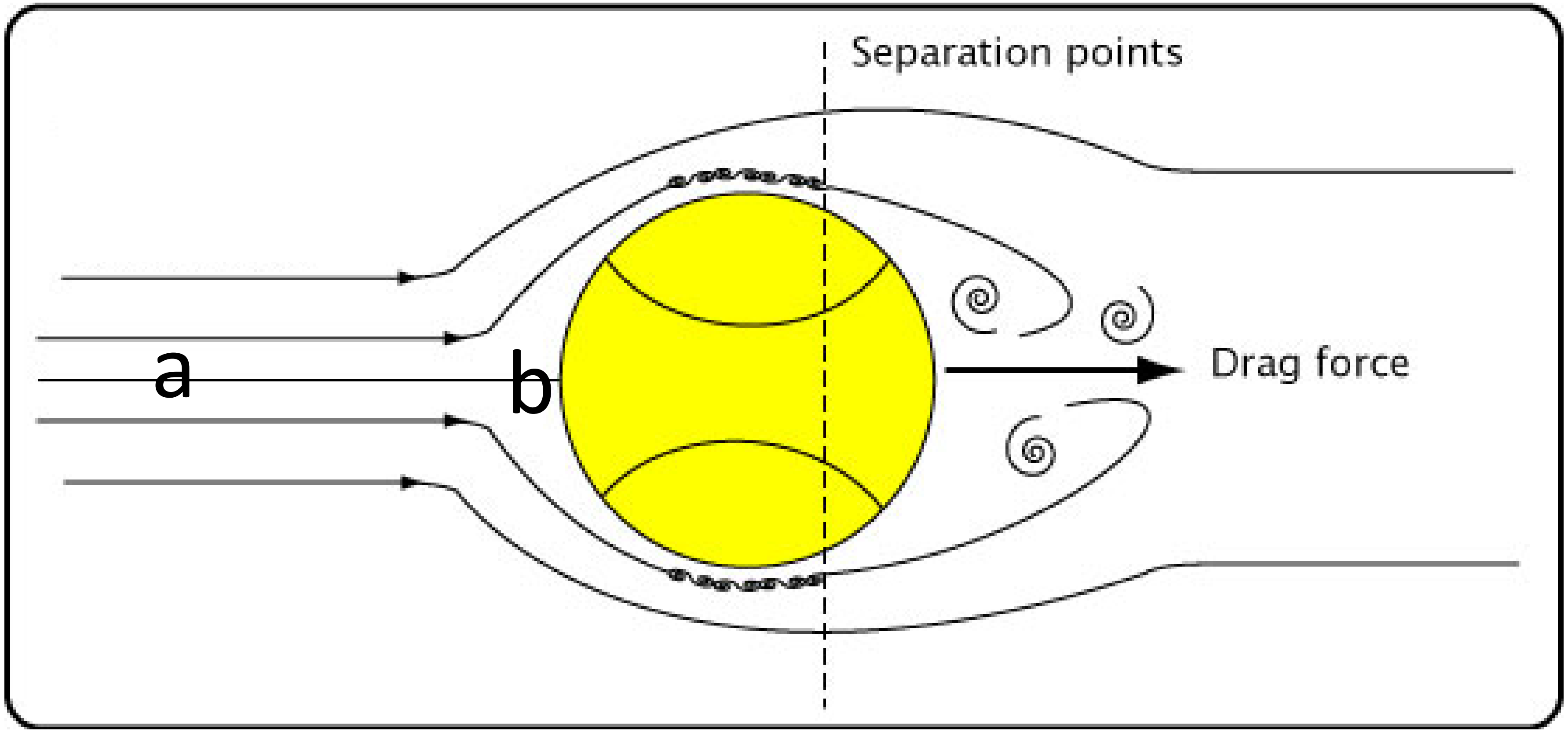
$$\Delta P = 7.64\left[\frac{1}{T_o} - \frac{1}{T_F}\right]h$$

Overview

- The movement of smoke in buildings is governed by a number of driving forces
  - fire-induced buoyancy and expansion
  - stack effect
  - wind effect
  - mechanical ventilation
- To manage smoke movement in buildings, the IBC and NFPA 92 require that these driving forces need to be accounted for in a smoke control analysis.

Bernoulli's Equation

$$\left(Pressure + \frac{1}{2}\rho(Vel^2) + \rho g(height)\right)_a = \left(Pressure + \frac{1}{2}\rho(Vel^2) + \rho g(height)\right)_b$$



Bernoulli's Equation

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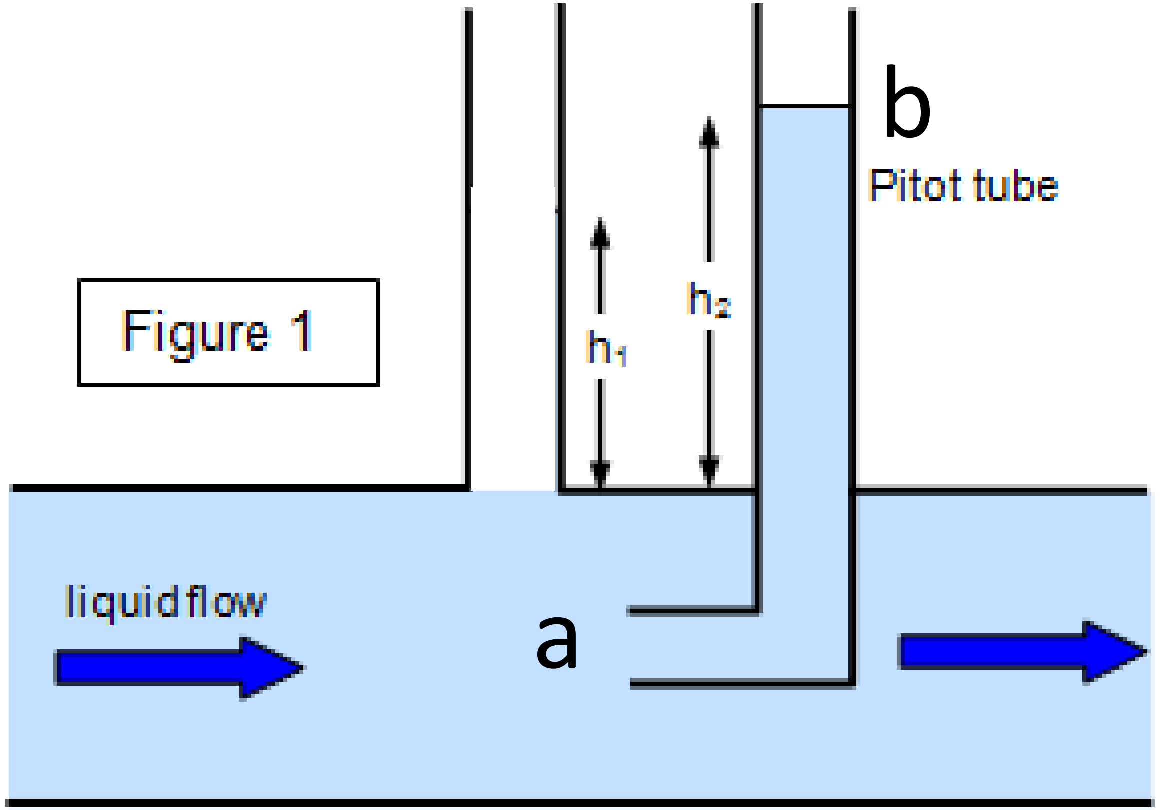
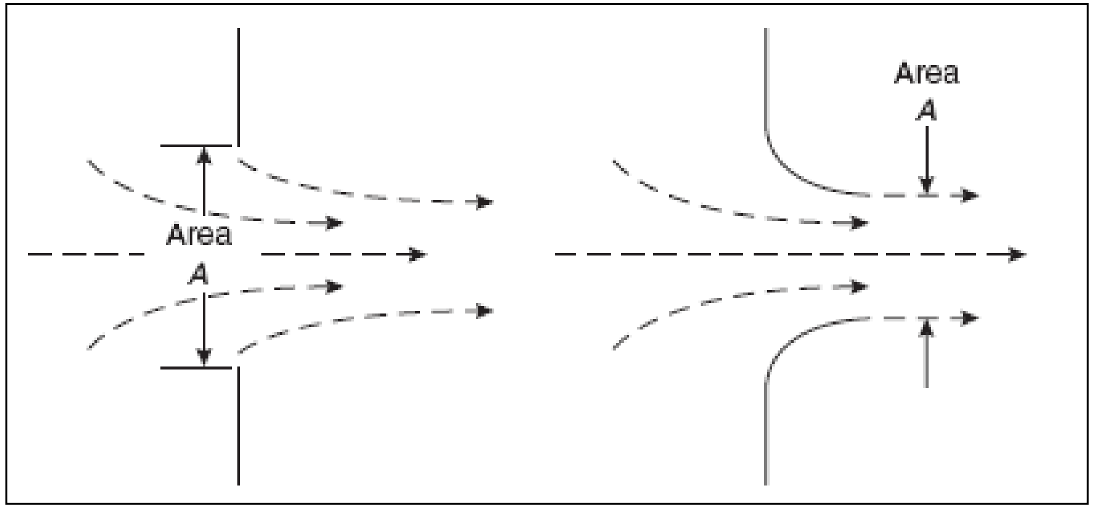


Bernoulli's Equation

The orifice equation is a form of the Bernoulli Equation commonly used to describe air flow which occurs as a result of a pressure difference across an opening,

$$\left(Pressure + \frac{1}{2}\rho(Vel^2) + \rho g(height)\right)_a = \left(Pressure + \frac{1}{2}\rho(Vel^2) + \rho g(height)\right)_b$$

$$\text{Velocity} = \sqrt{\frac{2(\text{Pressure})}{\rho}}$$



$$\text{Volume Flow} = \text{Flow Coefficient} \times \text{Area} \times \sqrt{\frac{2 \times \text{Pressure}}{\rho}}$$

Calculating the pressure from buoyant fire gases

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$$\Delta \text{Pressure} = K\left(\frac{1}{T_{cold}} - \frac{1}{T_{hot}}\right)h$$

$$\Delta P = 7.64\left[\frac{1}{T_o} - \frac{1}{T_F}\right]h$$

where:

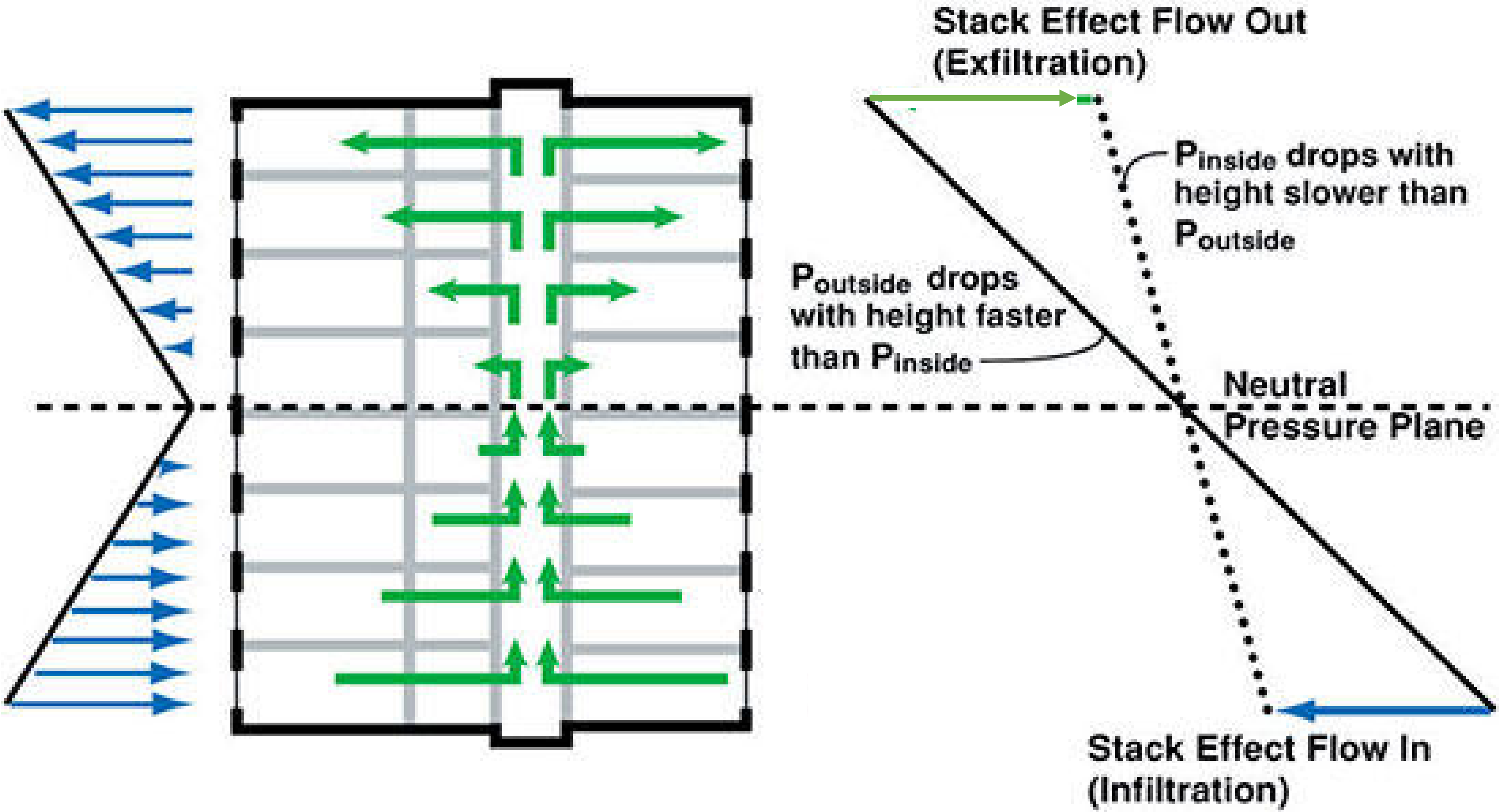
ΔP = pressure difference due to buoyancy of hot gases (in. w.g.)

T_o = absolute temperature of surroundings (R)

T_F = absolute temperature of hot gases (R)

h = distance above neutral plane (ft)

Stack Effect – Heated Building



Stairwell Pressurization- Stairwell analysis

Substitute:

$$d\dot{V} = \frac{\mathrm{NCA_{SBOe}}}{\mathrm{H}} \sqrt{\left({2\left(\Delta p_{SOb} \right)} \middle/ {\rho} \right)}\, dy$$

Integrate from 0 to H to find the total flow:

$$\dot{V}_{SBO} = \frac{2}{3} \mathrm{NCA_{SBOe}} \left(\frac{\Delta p_{SOt}^{3/2} - \Delta p_{SOb}^{3/2}}{\Delta p_{SOt} - \Delta p_{SOb}} \right)$$

Where:

$\dot{V}_{SBO}$ = Volumetric flow from the building to the stair to the outside, cfm (m^3/sec)

Pressurization - stairways

- Design issues with pressurized stairways:
  - Varying pressure differences over the stairway height due primarily to stack effect
  - Large pressure fluctuations caused by opening and closing of doors
  - Location of supply air inlets and fans
  - Force required to open stairway doors
- The movement of smoke in buildings is governed by a number of driving forces
  - fire-induced buoyancy and expansion
  - stack effect
  - wind effect
  - mechanical ventilation

Regulating Smoke - IBC 2018

Chapter 9 – Section 909 Smoke Control Systems

- 909.4 Analysis. A rational analysis supporting the types of smoke control systems to be employed, their methods of operation, the systems supporting them and the methods of construction to be utilized shall accompany the submitted construction documents and shall include, but not be limited to, the items indicated in Section 909.4.1 through 909.4.6 which include:
  - 909.4.1 Stack effect.
  - 909.4.2 Temperature effect of fire.
  - 909.4.3 Wind effect.
  - 909.4.4 HVAC systems.
  - 909.4.5 Climate
  - 909.4.6 Duration of operation.

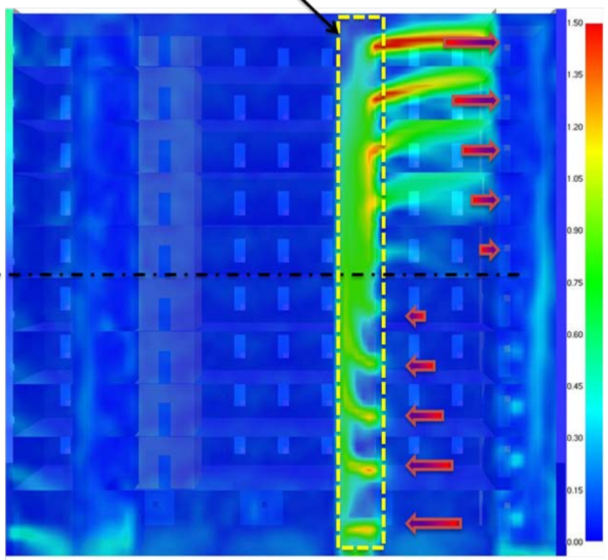
Challenges: Stack Effect

- Building height and climate influence stack effect

Stack Effect and Reverse Stack Effect

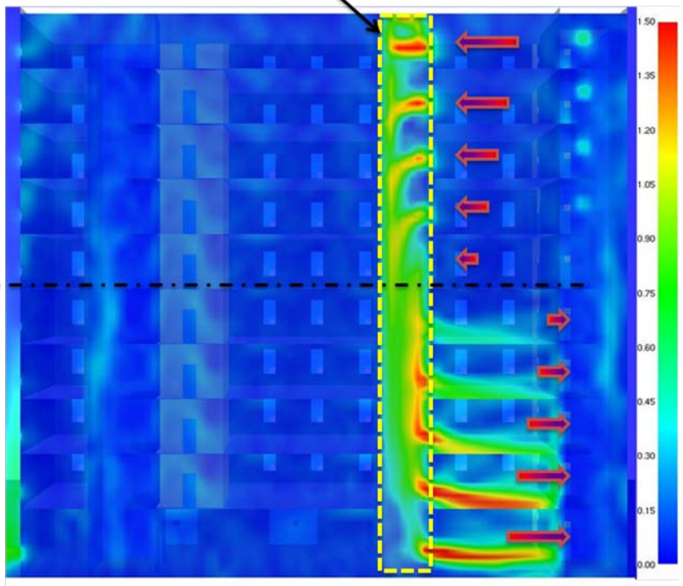
Stack Effect

- Tamb = 37F
- Tindoor = 67F

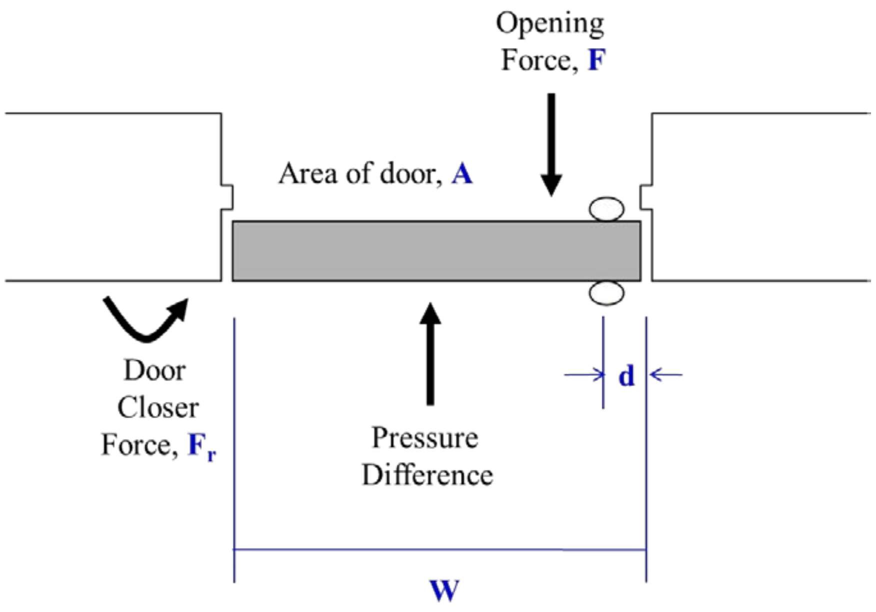


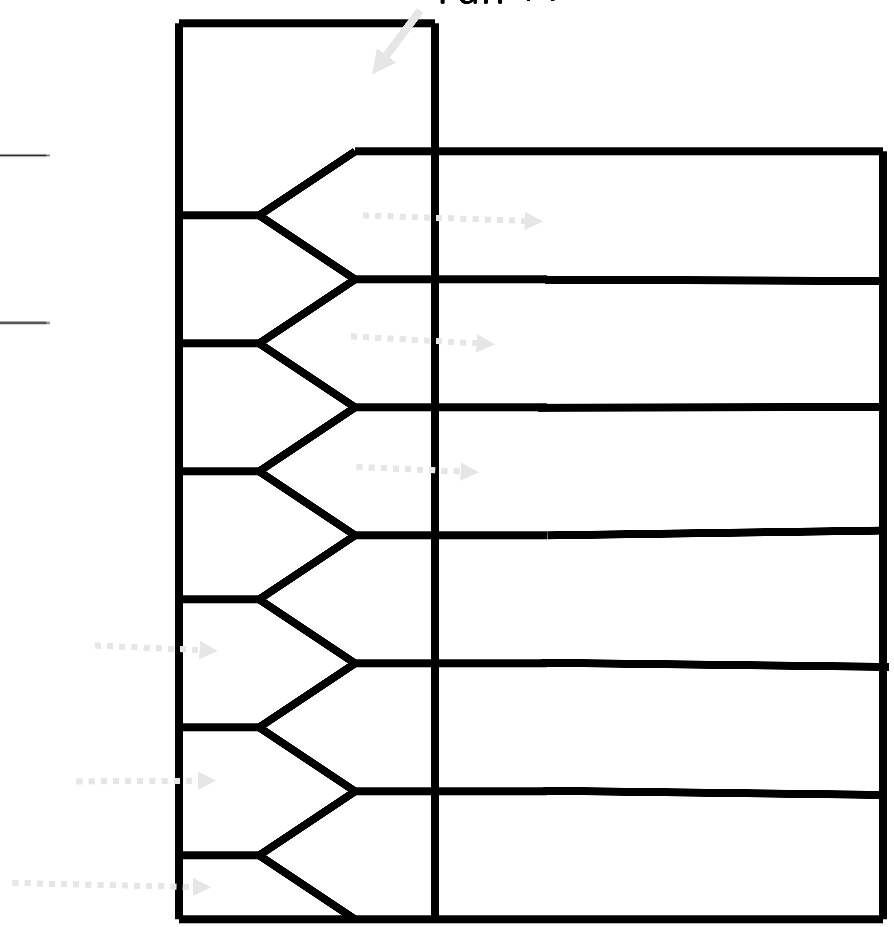
Reverse Stack Effect

- Tamb = 83F
- Tindoor = 67F



Stack Effect Can Create Door Opening Force Problems

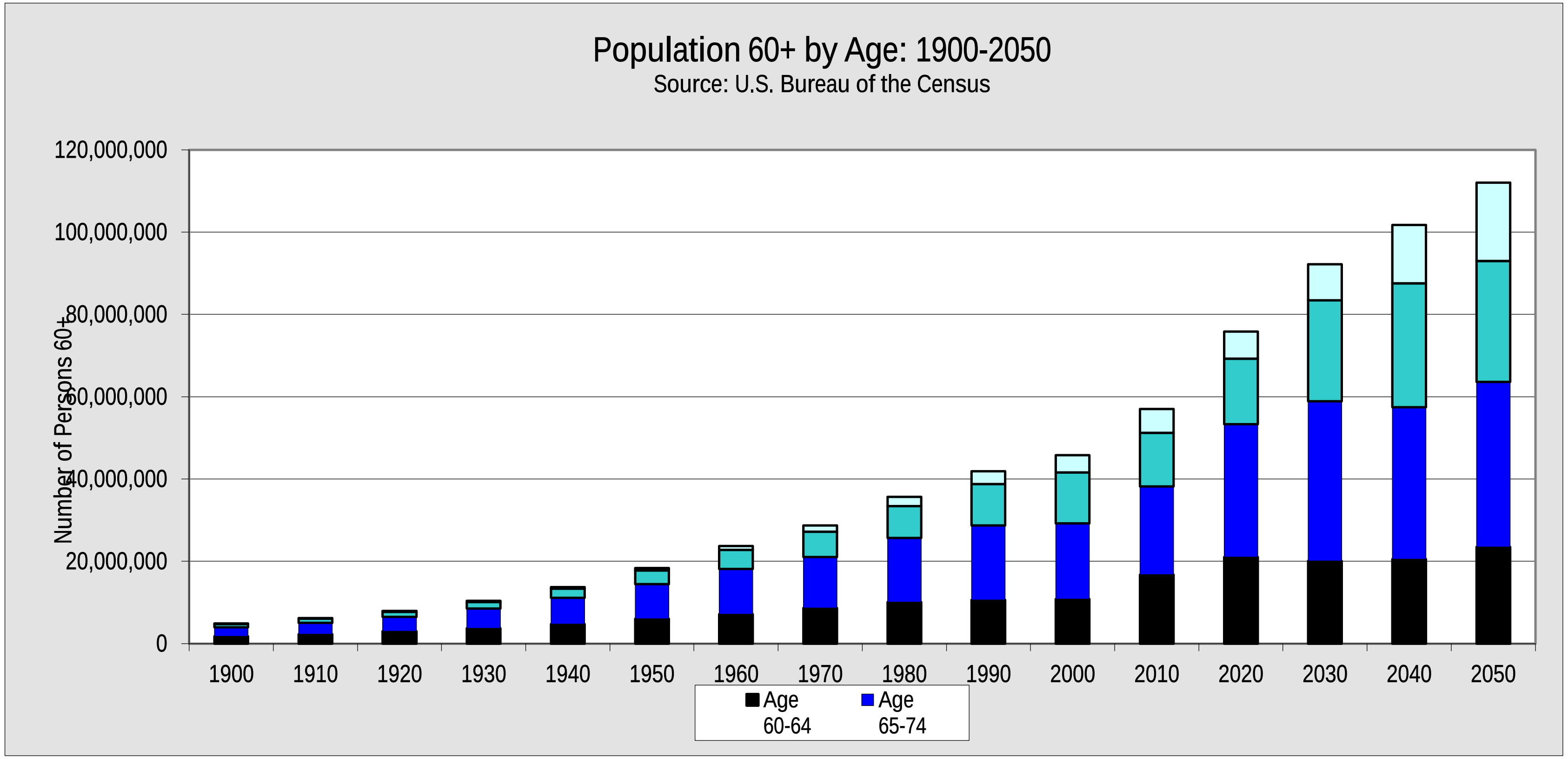




In the winter, stack effect tends to cause excessive pressures inside a pressurized stairshaft near its top while barely achieving the minimum differential at the bottom.

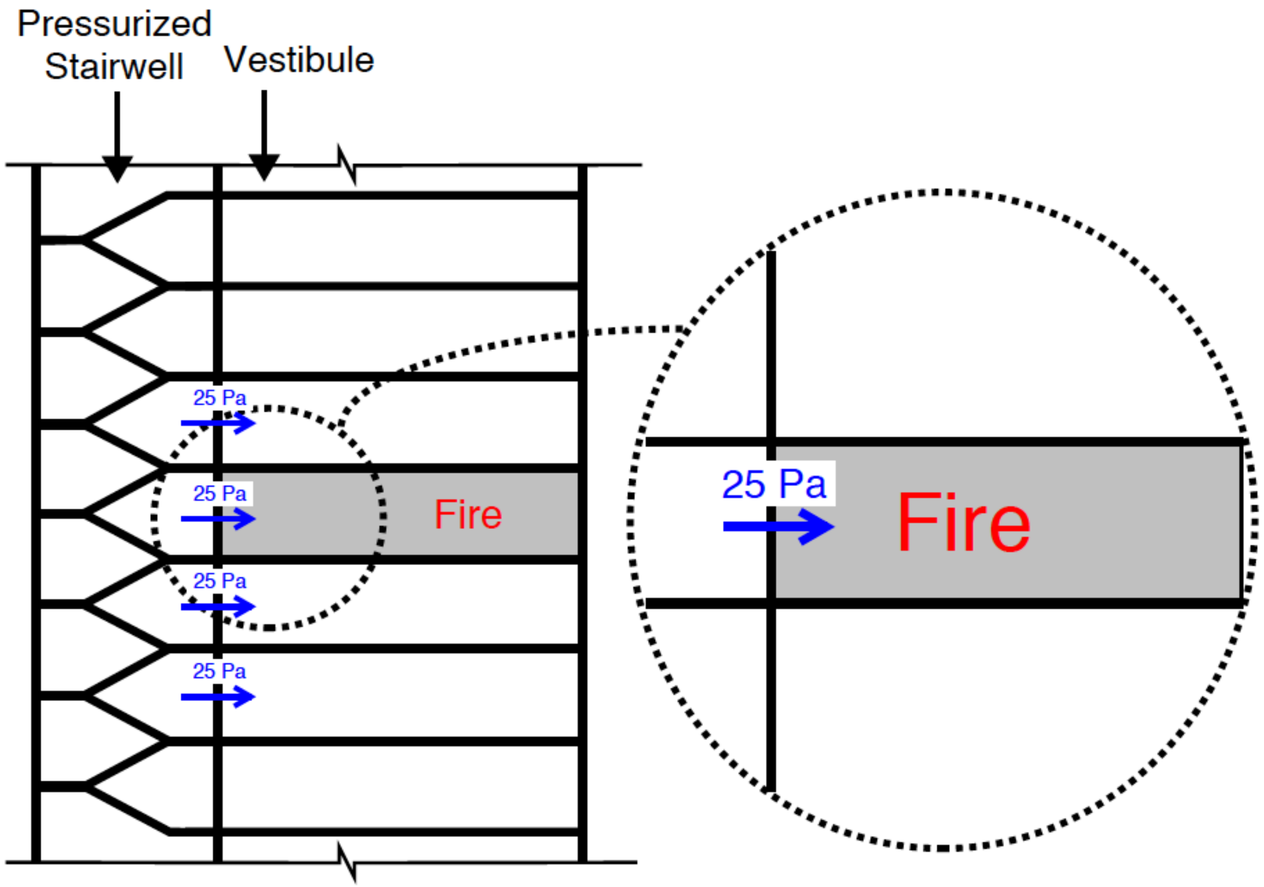
Functional Strength Values for Age Group 60 to 75 Years[1]

Function	Gender	Mean, lb (N)	Maximum, lb (N)	Minimum, lb (N)	Fifth Percentile, lb (N)
Push	M	53 (237)	121 (540)	21 (92)	23 (101)
	F	36 (162)	70 (309)	19 (83)	20 (91)
Pull	M	69 (306)	177 (786)	23 (102)	23 (102)
	F	45 (201)	91 (407)	22 (100)	21 (95)



Taming Stack Effect on Stairshaft Pressurization Systems

The Seattle Approach: Allows for pressure differential to be met only to the floors in evacuation mode.



Benefits

Sensible to meet pressure differentials only to the fire zone/floors in alarm.

Allows pressure differentials outside of zone in alarm be measured to the exterior.

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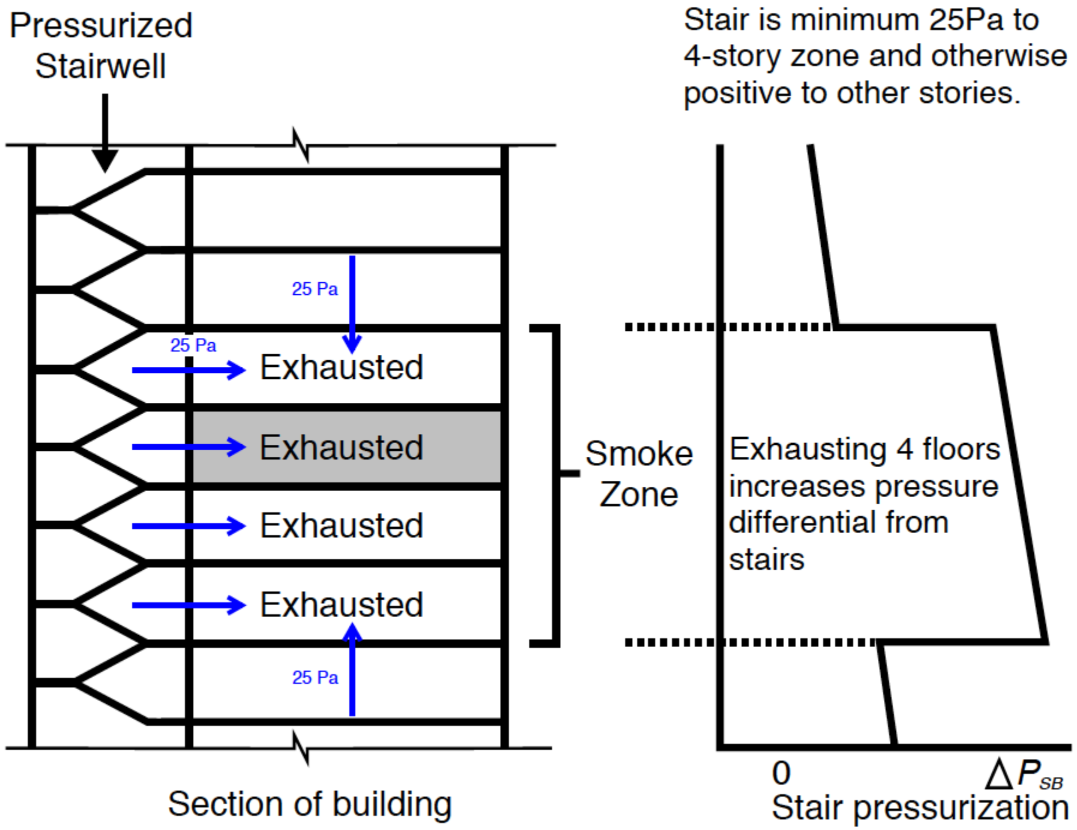
Detriment

On some floors, still may result in overpressures/door difficult to open.

Taming Stack Effect on Simple Stairshaft Pressurization Systems

The Modified Seattle Approach :
Adding active exhaust to floor



Benefits
Can reduce the stair pressurization fan rate considerably so that maximum pressures are not exceeded on any other stories during stack effect.

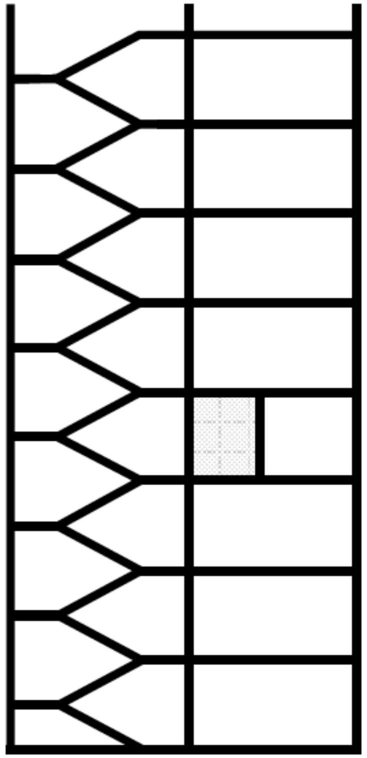
Variable drive fans can have bespoke settings for given floors.

Detriment
Although the normal building air ventilation system can be used, it will require connection to emergency/standby power.

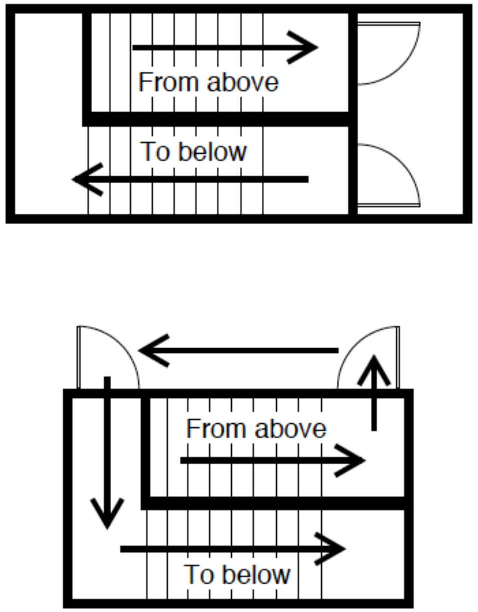
Taming Stack Effect on Stairshaft Pressurization Systems

The Split Stair : Separating Stair into Vertical Zones

Section of building



Potential floorplans of transition area



<u>Benefits</u>

Reduces the height and volume of the stairshaft which needs pressurization.

Can be incorporated with refuge floors.

<u>Detriment</u>

Requires:

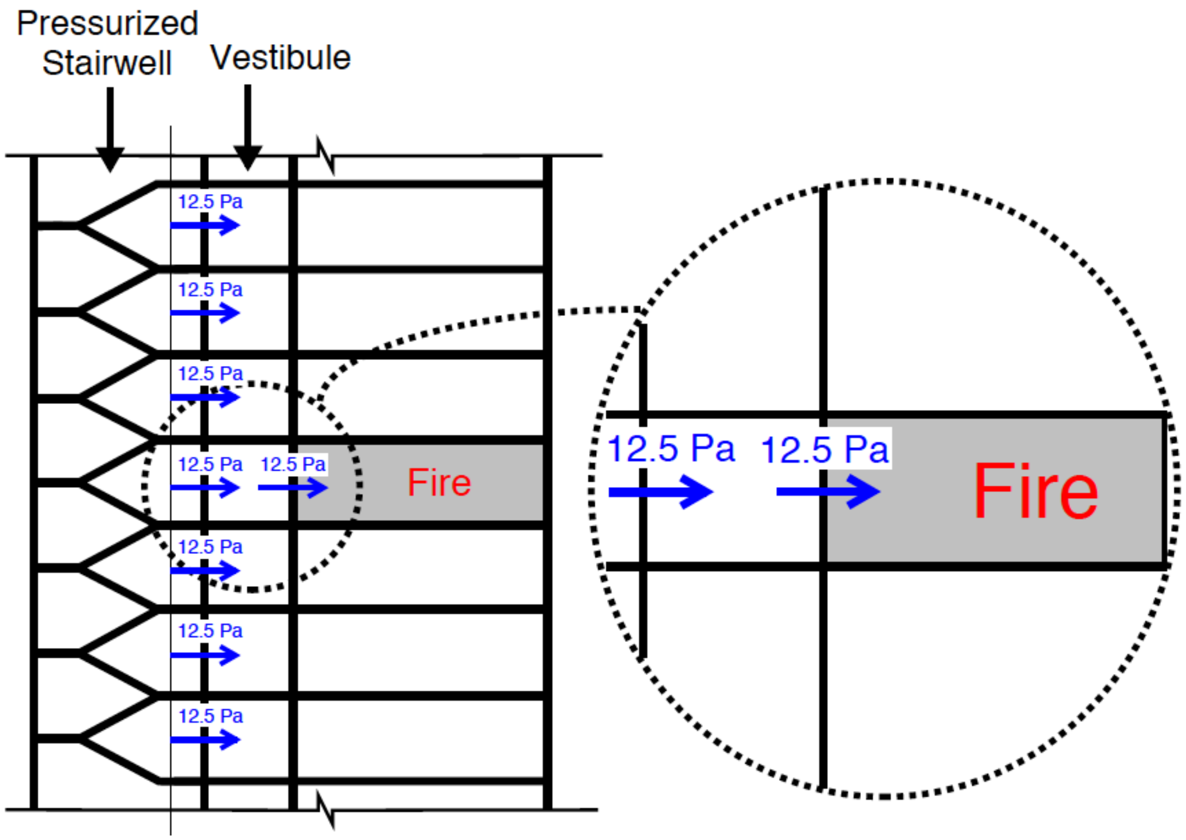
1. transition/transfer connector between stairshafts or
2. doors at landings within stairshaft.

Space at landings needs to be adequate for the door/frame and usability.

Requires multiple fans serving multiple zones with potentially multiple shafts.

Taming Stack Effect on Stairshaft Pressurization Systems

The Las Vegas Variation, Add vestibules on every story, Pressure differential stair to vestibule =12.5 Pa, while Pressure differential vestibule to fire floor = 25 Pa



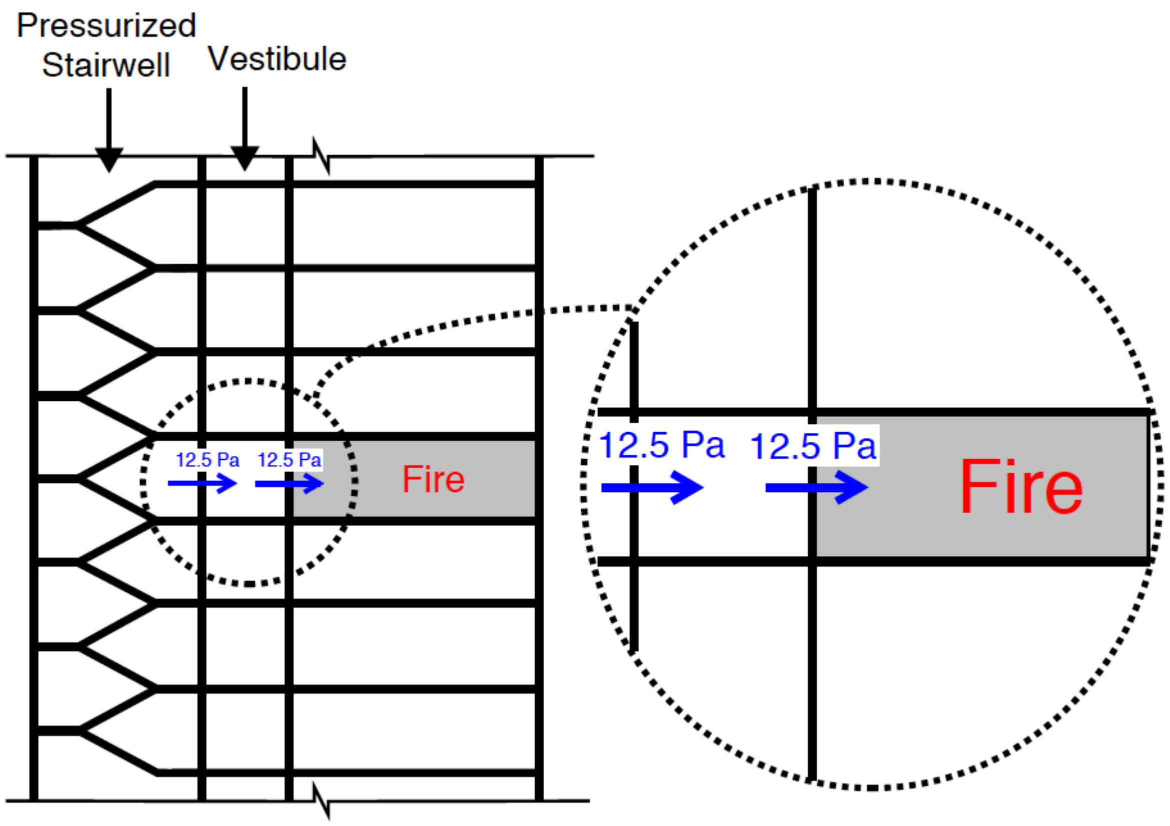
Benefits
Allows for reduced pressure differentials which means that under the same temperature differences one can meet the minimum and maximum in much taller buildings.

Detriment
Vestibules, at roughly $2m^2$ reduce leasable space on every level.

Pressure differential from stair to vestibule all floors.

Taming Stack Effect on Stairshaft Pressurization Systems

The California Approach, Add vestibules to every story
Pressure differentials only to fire floor.



<u>Benefits</u>

Allows for **reduced** pressure differentials which means that under the same temperature differences one can meet the minimum and maximum in much taller buildings.

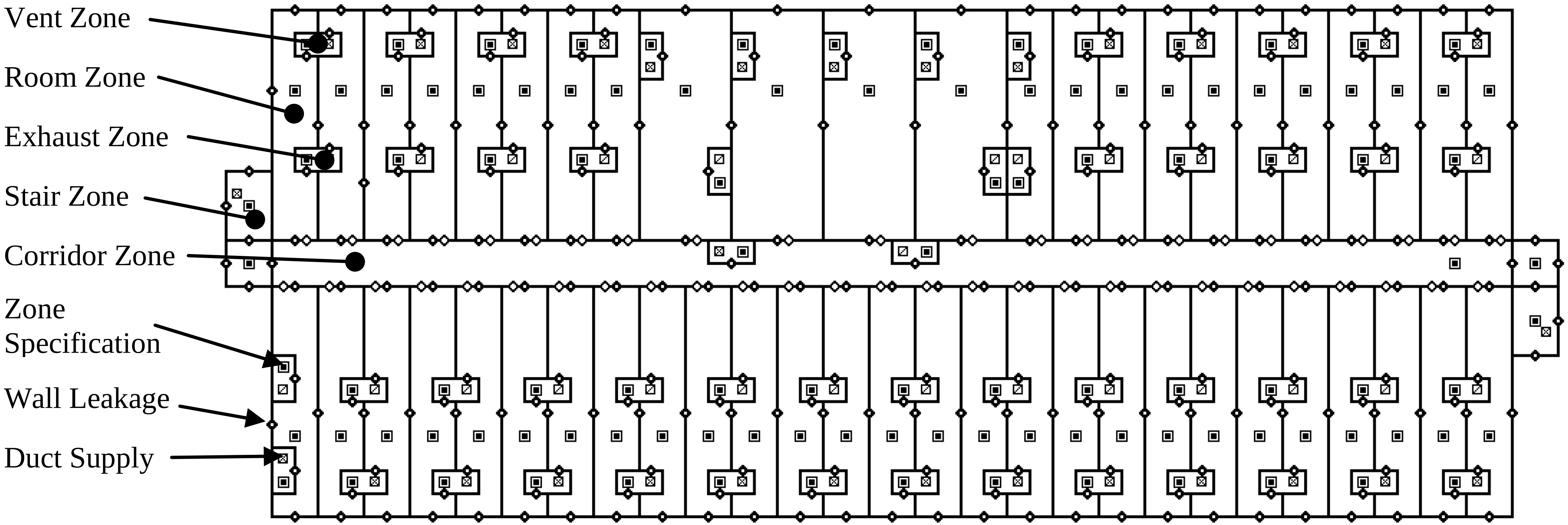
Pressure differential to fire floor only.

<u>Detriment</u>

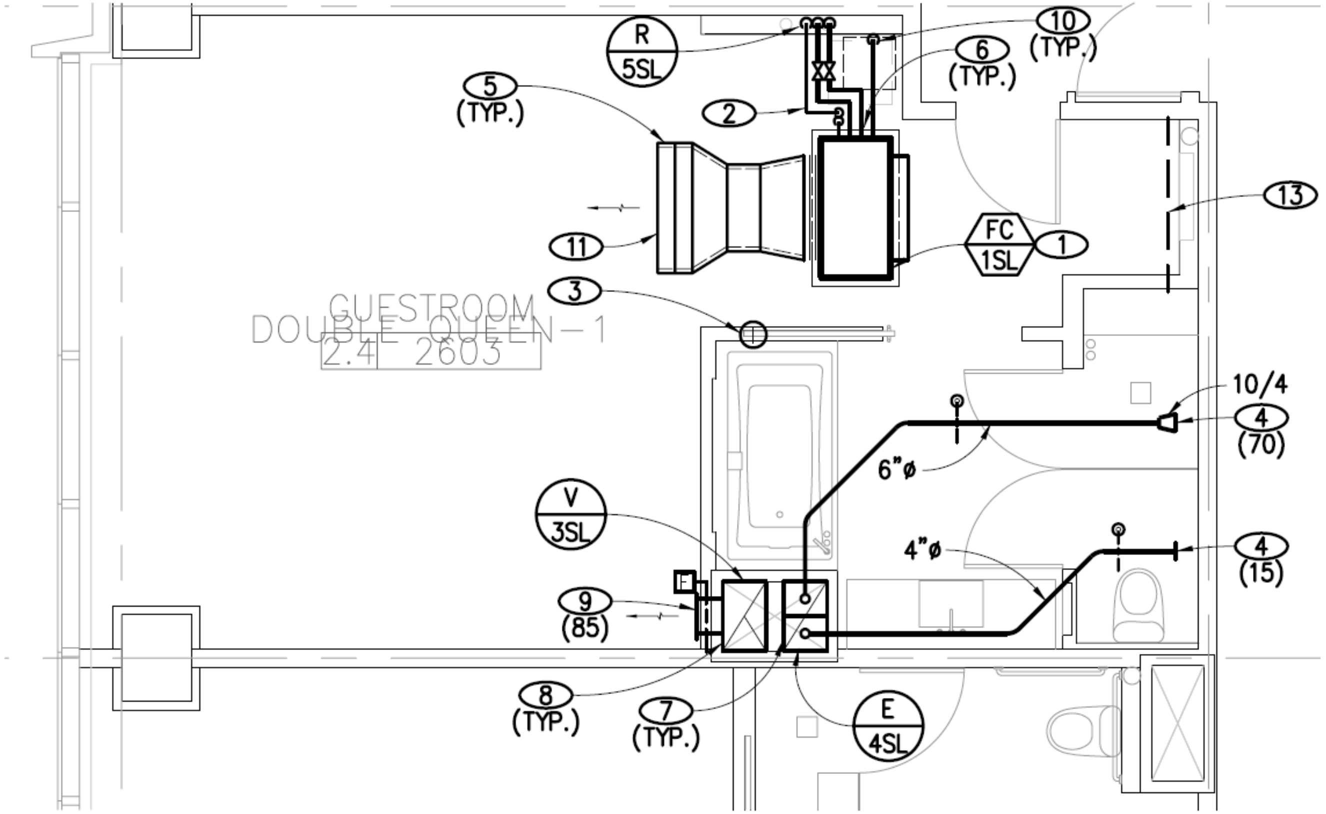
Vestibules, at roughly $2m^2$ reduce leasable space on every level.

CONTAM background

- CONTAM is a multi-zone indoor air quality and ventilation analysis program designed to help determine:
  - airflows and pressures – infiltration, exfiltration, and room-to-room airflows and pressure differences in building systems driven by mechanical means, wind pressures acting on the exterior of the building, and buoyancy effects induced by temperature differences between the building and the outside.



CONTAM Intro



Exhaust (labeled E) and ventilation (labeled V) flow rates are generally equal. Stairs and vestibules are assumed to be pressurized at approximately 0.05” H_2O. Numbers in parenthesis represent flow rates in standard cubic feet per minute (scfm). Rooms are equipped with fan coil cooling and heating units (labeled FC).

CONTAM background

K24

300/350 Grilles • Return • Performance Data

Titus

Performance Data

350R, 350F and 350R-SS

Performance based on nominal sizes shown in bold.

NC-20

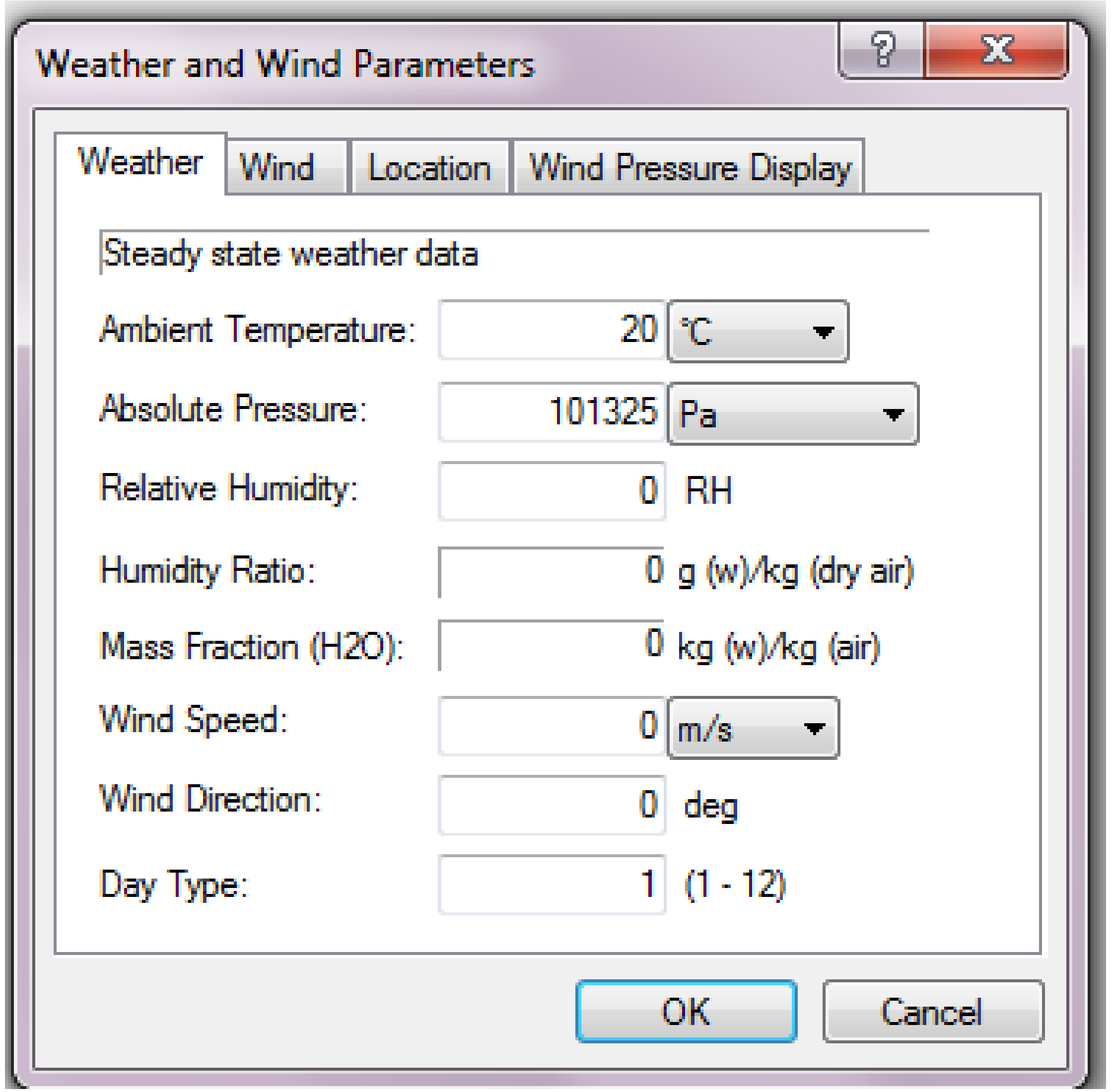
NC-30

Nominal Duct Size (in.)	Nominal Duct Area (ft^2)	Core Area (ft^2)	Core Velocity Velocity Pressure Neg. Static Pressure	100 0.001 0.002	200 0.002 0.008	300 0.006 0.018	400 0.010 0.032	500 0.016 0.051	600 0.022 0.073	700 0.031 0.099	800 0.040 0.130	900 0.050 0.164
6x6	**0.25**	**0.19**	Airflow, cfm NC	19 -	38 -	57 -	76 -	95 -	114 13	133 19	152 25	171 29
8x6	**0.33**	**0.26**	Airflow, cfm NC	26 -	52 -	78 -	104 -	130 -	156 15	182 20	208 26	234 30
10x6	**0.42**	**0.34**	Airflow, cfm NC	34 -	68 -	102 -	136 -	170 -	204 16	238 21	272 28	306 32
8x8	**0.44**	**0.37**	Airflow, cfm NC	37 -	74 -	111 -	148 -	185 -	222 16	259 22	296 28	333 32
12x6	**0.5**	**0.41**	Airflow, cfm NC	41 -	82 -	123 -	164 -	205 -	246 17	287 22	328 30	369 34
14x6	**0.58**	**0.48**	Airflow, cfm NC	48 [illegible]	96 [illegible]	144 [illegible]	192 [illegible]	240 [illegible]	288 [illegible]	336 [illegible]	384 [illegible]	432 [illegible]

- Static pressure is the pressure created on the discharge end of your air handler blower. It is much like the pressure in your water system. The higher the pressure the more flow you get.
- Negative static pressure is the pressure in the air return ducts. It is also created by the air handler blower only on the intake side. The blower is sucking on the return ducts to get the air in the house back to the evaporator coils so it can be cooled and dehumidified.

CONTAM background

- Weather-



Wind Flow Over Buildings

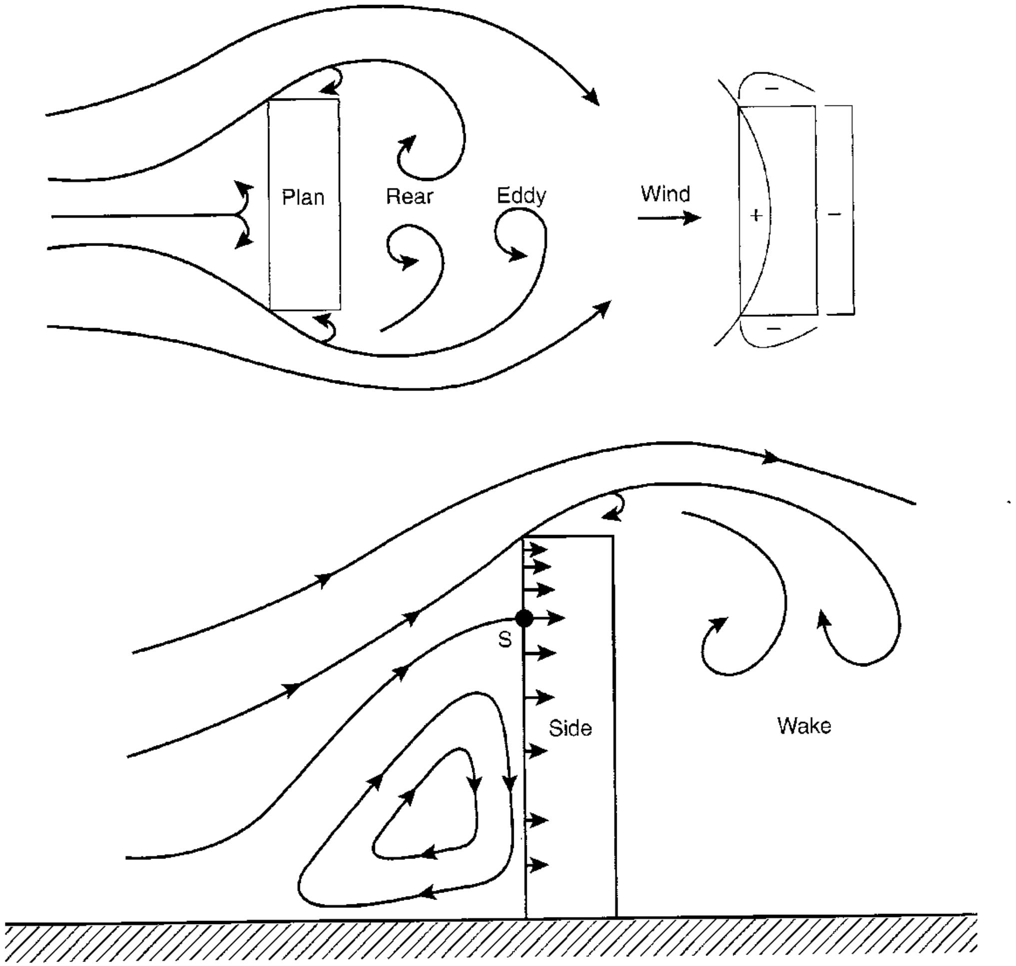


Figure 1-1.28. *Flow over a tall building.*

Terrestrial Boundary Layer

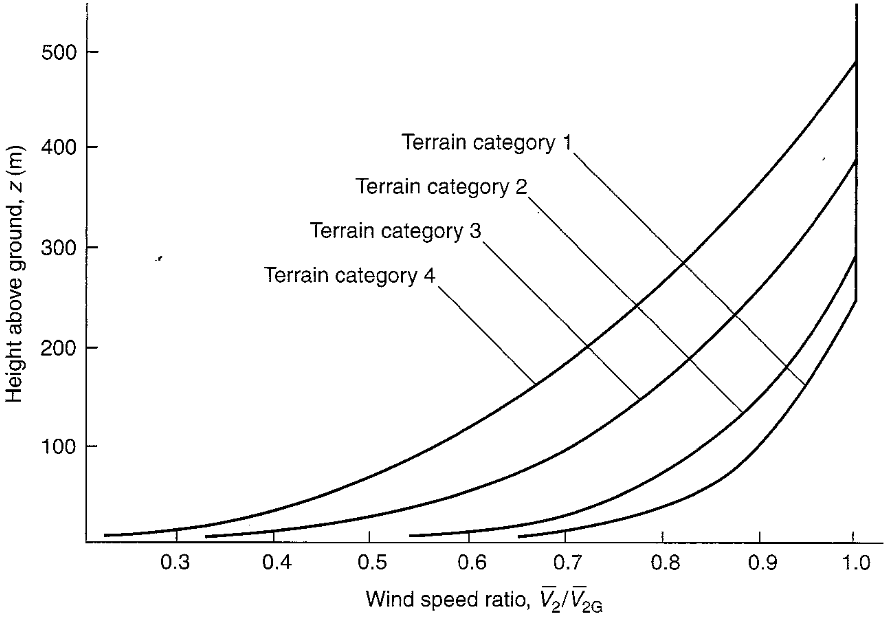
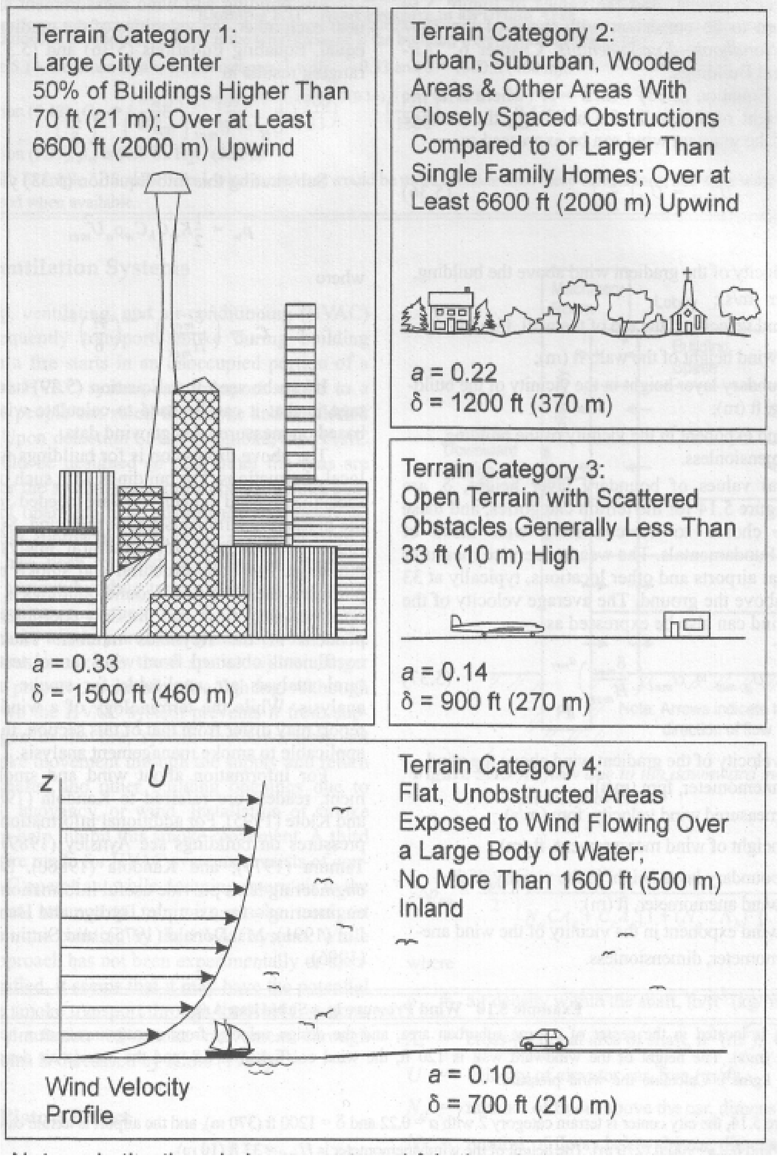
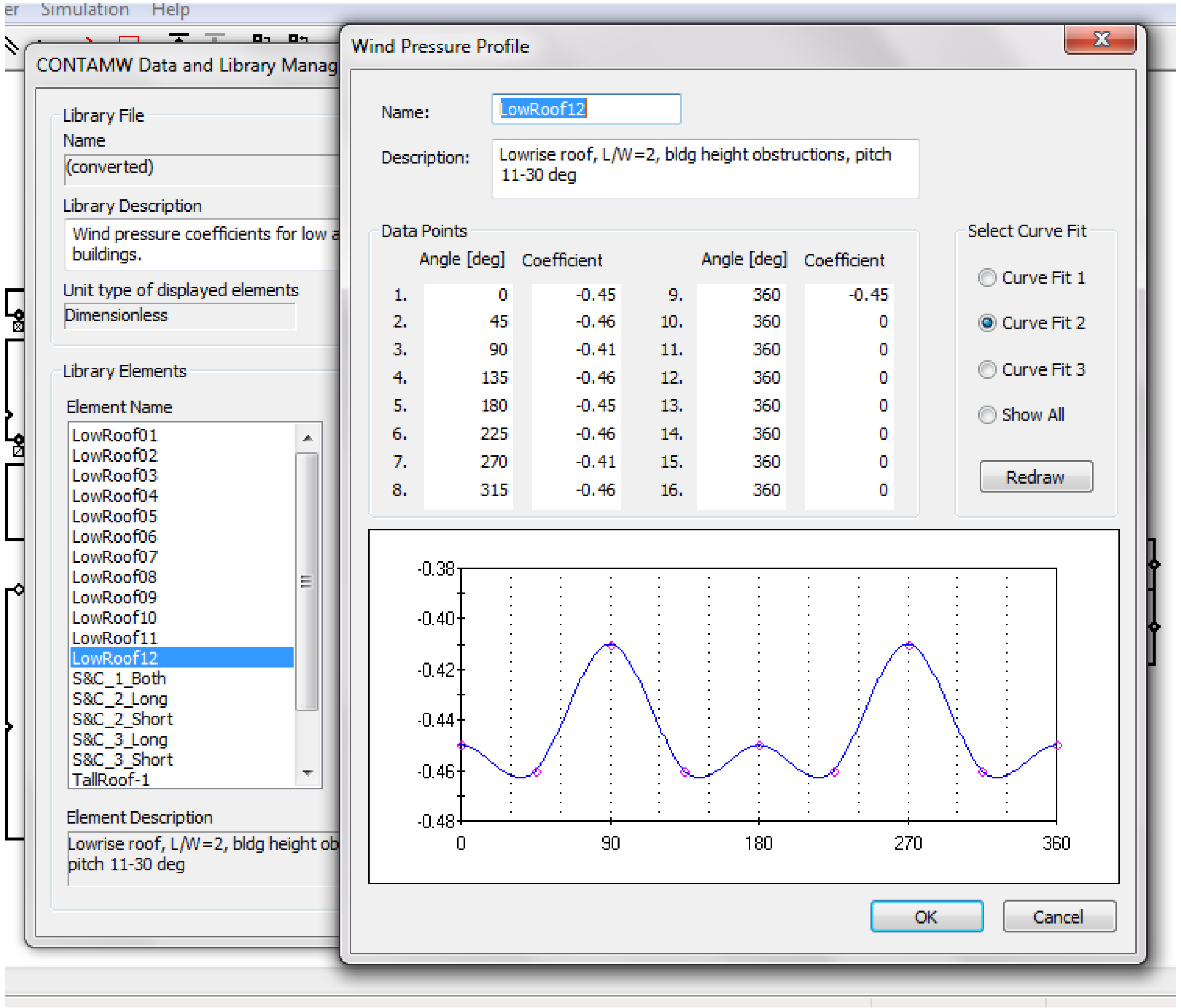


Figure 1-1.27. ***Velocity profile in the terrestrial boundary layer.*** [8]



CONTAM-Wind Pressures



Smoke Control, An Overview with a Discussion of the Benefits of Firestopping

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