

CHAPTER 4

TALL BUILDINGS

<i>Stack Effect</i>	4.1	<i>Central Mechanical Equipment Room Versus</i>	
<i>Typical HVAC Design Process</i>	4.8	<i>Floor-by-Floor Fan Rooms</i>	4.11
<i>Systems</i>	4.9	<i>Central Heating and Cooling Plants</i>	4.14
<i>System Selection</i>		<i>Water Distribution Systems</i>	4.17
<i>Considerations</i>	4.9	<i>Vertical Transportation</i>	4.19
<i>Displacement Ventilation</i>	4.11	<i>Life Safety in Tall Buildings</i>	4.20

TALL buildings have existed for more than 100 years and have been built in cities worldwide. Great heights only became possible after the invention of the elevator safety braking system in 1853; subsequent population and economic growth in cities made these taller buildings very popular. This chapter focuses on the specific HVAC system requirements unique to tall buildings.

ASHRAE Technical Committee (TC) 9.12, Tall Buildings, defines a tall building as one whose height is greater than 300 ft. The Council on Tall Buildings and Urban Habitat (CTBUH 2014) defines a tall building as one in which the height strongly influences planning, design, or use; they classify recently constructed tall buildings as **supertall** (buildings taller than 984 ft) and **megatall** (buildings taller than 1968 ft).

Traditionally, model codes in the United States were adopted on a regional basis, but recently the three leading code associations united to form the International Code Council (ICC 2012), which publishes the unified *International Building Code*® (IBC). Another important national code, developed by the National Fire Protection Association (NFPA), is *NFPA Standard 5000*®.

The overall cost of a tall building is affected by the floor-to-floor height. A small difference in this height, when multiplied by the number of floors and the area of the perimeter length of the building, results in an increase in the area that must be added to the exterior skin of the building. The final floor-to-floor height of the office occupancy floors of any building is jointly determined by the owner, architect, and structural, HVAC, and electrical engineers.

There are increasing numbers of tall buildings in the world (either planned or built) that will have a much greater height than 300 ft. There is also a trend that most of the new tall buildings today are of the mixed-use type: for example, many will have a combination of commercial offices, hotel, apartments, observation deck, club floor, etc., stacked on top of each other. Tall buildings with these heights and mixed uses will significantly affect HVAC system design.

Much of the material in this chapter derives from Ross (2004).

1. STACK EFFECT

Stack effect occurs in tall buildings when the outdoor temperature is lower than the temperature of the spaces inside. A tall building acts like a chimney in cold weather, with natural convection of air entering at the lower floors, flowing through the building, and exiting from the upper floors. It results from the difference in density between the cold, denser air outside the building and the warm, less dense air inside the building. The pressure differential created by stack effect is directly proportional to building height as well as to the difference between the warm inside and cold outdoor temperatures.

When the temperature outside the building is warmer than the temperature inside the building, the stack effect phenomenon is reversed. This means that, in very warm climates, air enters the building at the upper floors, flows through the building, and exits at the

lower floors. The cause of **reverse stack effect** is the same in that it is caused by the differences in density between the air in the building and the air outside the building, but in this case the heavier, denser air is inside the building.

Reverse stack effect is not as significant a problem in tall buildings in warm climates because the difference in temperature between inside and outside the building is significantly less than the temperatures difference in very cold climates. Accordingly, this section focuses on the problems caused by stack effect in cold climates. Note that these measures can be very different than those in hot and humid climates.

Theory

For a theoretical discussion of stack effect, see Chapter 16 in the 2013 *ASHRAE Handbook—Fundamentals*. That chapter describes calculation of the theoretical total stack effect for temperature differences between the inside and outside of the building. It also points out that every building has a **neutral pressure level (NPL)**: the point at which interior and exterior pressures are equal at a given temperature differential. The location of the NPL is governed by the actual building, the permeability of its exterior wall, the internal partitions, and the construction and permeability of stairs and shafts, including the elevator shafts and shafts for ducts and pipes. Other factors include the air-conditioning systems: exhaust systems that extend through the entire height of the building tend to raise the NPL, thereby increasing the total pressure differential experienced at the base of the building. This also increases infiltration of outdoor air, which tends to lower the NPL, thus decreasing the total pressure differential experienced at the base of the building. Finally, wind pressure, which typically increases with elevations and is stronger at the upper floors of a building, also can shift the neutral plane, and should be considered as an additional pressure to stack effect when locating the neutral plane.

Figure 1 depicts airflow into and out of a building when the outdoor temperature is cold (stack effect) and hot (reverse stack effect). Not shown is the movement of air up or down in the building as a

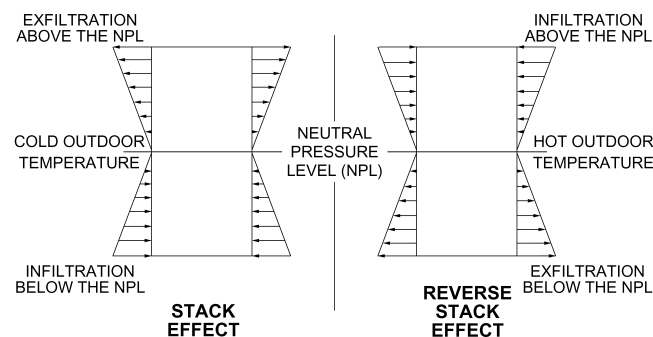
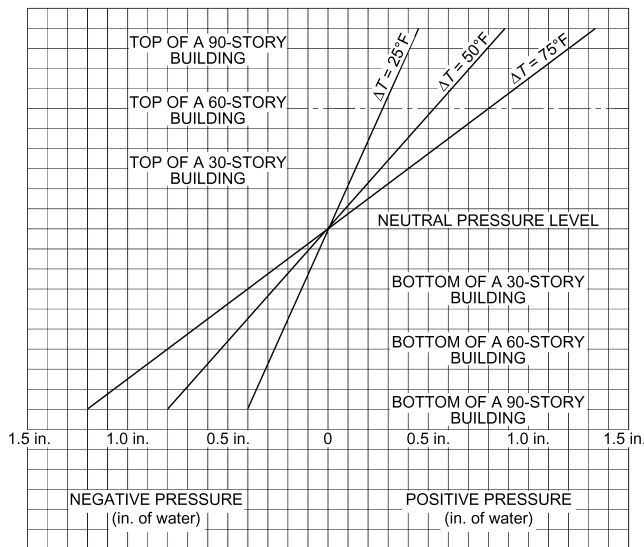


Fig. 1 Airflow from Stack Effect and Reverse Stack Effect
(Ross 2004)

The preparation of this chapter is assigned to TC 9.12, Tall Buildings.



NOTES:

1. ΔT equals differences between condition inside and outside building.
2. Floor-to-floor height for alternative buildings is assumed to be 13 ft 0 in.

Fig. 2 Theoretical Stack Effect Pressure Gradient for Various Building Heights at Alternative Temperature Differences
(Ross 2004)

function of stack effect. Assuming there are no openings in the building, the NPL is the point in the building elevation where air neither enters nor leaves the building. Vertical movement of air in the building occurs at the paths of least resistance, including but not limited to shafts and stairs in the building as well as any other openings at the slab edge or in vertical piping sleeves that are less than totally sealed. Figure 1 also indicates that air movement into and out of the building increases as the distance from the NPL increases. Elevator shafts, especially ones that connect the top and bottom of a tall building (e.g., a fire lift), are likely paths of least resistance for airflow. The total theoretical pressure differential can be calculated for a building of a given height and at various differences in temperature between indoor and outdoor air.

The theoretical stack effect pressure gradient for alternative temperature differences and building heights is shown in Figure 2. The diagram illustrates the potential maximum differentials that can occur (which are significant), but these plotted values are based on a building with no internal subdivisions in the form of slabs and partitions. The plot, therefore, includes no provisions for resistance to airflow in the building. Further, the outer wall's permeability influences the values on the diagram and, as noted previously, the wind effect and operation of the building air-handling systems and fans also affect this theoretical value. Thus, the diagram should be considered an illustration of the possible magnitude of stack effect, not as an actual set of values for any building. The actual stack effect and location of the NPL in any building are difficult (if not in a practical sense impossible) to determine. Nevertheless, stack effect can be troublesome, and its possible effects must be recognized in the design documentation for a project.

Practical Considerations

Stack effect in tall buildings often presents major problems:

- **Elevator doors** may fail to close properly because of the pressure differential across the doors, which causes the door to bind in its guideway enough that the closing mechanism does not generate sufficient force to overcome it.

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- **Manual doors** may be difficult to open and close because of strong pressure created by stack effect.
- **Smoke and odor propagation** through the air path of stack effect can also occur.
- **Heating problems** can occur in lower areas of the building that may be difficult to heat because of a substantial influx of cold air through entrances and across the building's outer wall (caused by higher-than-anticipated wall permeability). Heating problems can be so severe as to freeze water in sprinkler system piping, cooling coils, and other water systems on lower floors. Generally accepted standards suggest a maximum leakage per unit of exterior wall area of 0.06 cfm/ft² at a pressure difference of 0.30 in. of water exclusive of leakage through operable windows. In reality, tall buildings in cold climates can exceed this pressure difference through a combination of stack, wind, and HVAC system pressure. Even when leakage similar to the NAAMM criterion is included in project specification, it is not always met in actual construction, thereby causing potential operational problems.

Calculation

Uncontrolled infiltration and ventilation is caused by climate, wind pressure, and stack effect; environmental factors associated with stack effect include wind pressure, stack pressure difference, airflow rate, outdoor and indoor temperature, building height, and building construction.

Wind creates a distribution of static pressure on the building envelope that depends on wind direction and velocity against the building envelope. The basic formula to determine this pressure can be expressed as

$$\Delta P_W = P_o + CC_p \rho V_w^2 / 2 \quad (1)$$

where

- ΔP_W = wind pressure above outdoor air (OA) pressure, in. of water
- C = unit conversion factor, 0.0129
- C_p = surface (location on building envelope) pressure coefficient, dimensionless
- ρ = air density, lb_m/ft³ (about 0.075)
- V_w = wind speed, mph
- o = outdoor

When using this equation, wind pressure is 0.1 in. of water at 15 mph on the windward side.

Air density varies with temperature. In cold weather, low-density air infiltrates the high-rise building and rises in the building's vertical shafts as it warms, creating stack effect pressure. The basic stack effect theory is expressed as

$$\Delta P_s = C_2 \rho_i g (h - h_{neutral}) (T_i - T_o) / T_o \quad (2)$$

where

- ΔP_s = stack pressure difference (indoor – outdoor), in. of water
- $C_2 \rho_i g$ = air density and gravity constant, 0.01444
- h = building height, ft
- $h_{neutral}$ = height of neutral pressure level, ft
- i = indoor
- T = temperature, °F

When using Equation (2), the stack pressure is 1.1 in. of water for a 60-story building with –10°F OA temperature.

Once the wind pressure ΔP_W and stack pressure difference ΔP_s are calculated, total pressure ΔP_{total} can be found, based on indoor and outdoor pressure difference, and used to calculate the airflow rate:

$$\Delta P_{total} = (P_o - P_i) + \Delta P_W + \Delta P_s \quad (3)$$

The resultant pressure difference will cause air flow based on the following expression for flow through an orifice:

$$Q = C_f A \sqrt{2 \Delta P_{total} / \rho} \quad (4)$$

where

Q = airflow, cfm

C_f = flow coefficient

A = cross-sectional area of opening, ft²

ΔP_{total} = total pressure difference across flow area, in. of water

ρ = air density, lb_m/ft³

Temperature, air density, and pressure can also be calculated, as follows:

$$T = T_G - 0.00356h \quad (5)$$

$$\rho = 2.7 \times P_{abs} / (T + 459.7) \quad (6)$$

where

T = temperature, °F

T_G = ground temperature, °F

P_{abs} = absolute pressure, psi

P = pressure, psi

Calculation Examples. For the calculation examples, four cities were selected, each with its own unique climate characteristics: Beijing (cold, dry), Bangkok (hot, humid), Dubai (hot, arid), and Copenhagen (cold, humid). Because stack effect has different influences on buildings of different heights, in each city, buildings of various heights were calculated.

For each city, climate data (acquired from a climate consultant) show the average winter and summer temperature and humidity, which can be used to calculate stack effect in different ASHRAE climate zones (Figure 3). The lighter shade indicates the averages, and the darker shade shows the summer and winter temperature extremes.

The building type is residential. Outdoor temperature and humidity levels are equal to the heating or cooling seasons' average temperature. Indoor temperature is 70°F, height above sea level is 0 ft, wind speed is 5 mph, typical building floor height is 14 ft, air pressure is 29.92 in. Hg, and results are per square foot of envelope area.

Beijing. Table 1 gives the example parameters, and Table 2 shows the calculation results. As shown in Figure 4, the biggest difference between internal pressure occurs in winter, when internal

Table 1 Parameters for Beijing Example Building

	Summer	Winter
Outdoor temperature, °F	94.9	15.6
Indoor temperature, °F	75	68
Relative humidity, %	54	15
Height above sea level, ft	180	180
Wind speed, mph	14.9	14.9
Air pressure, in. Hg	29.77	29.77

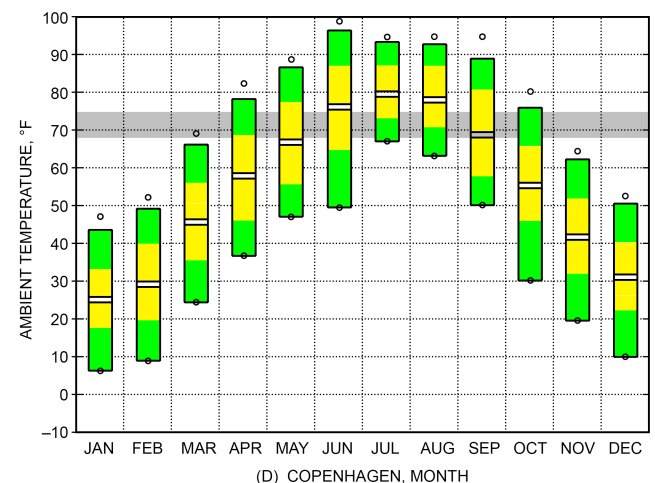
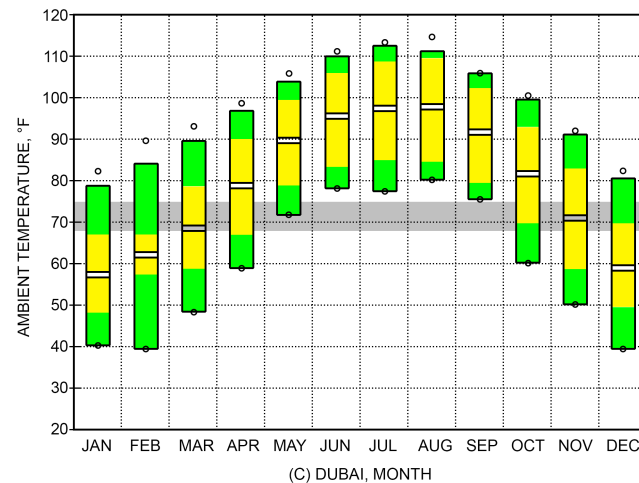
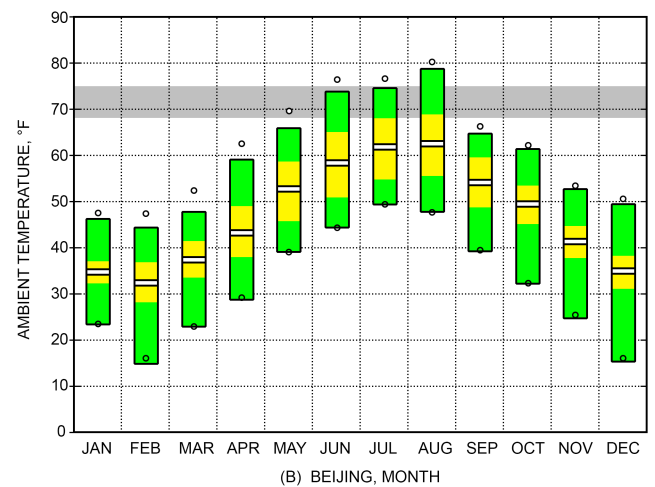
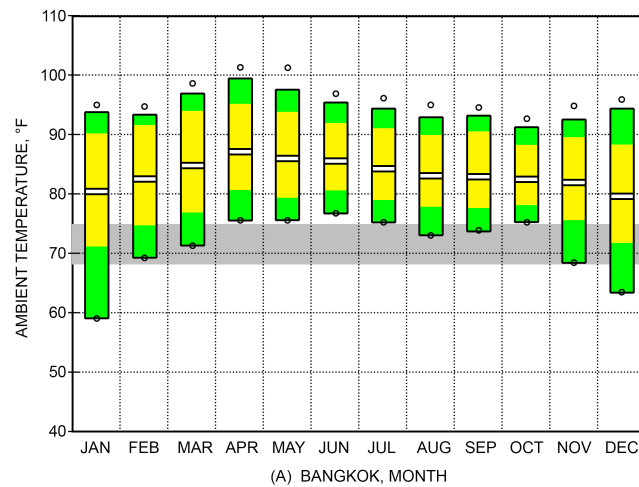
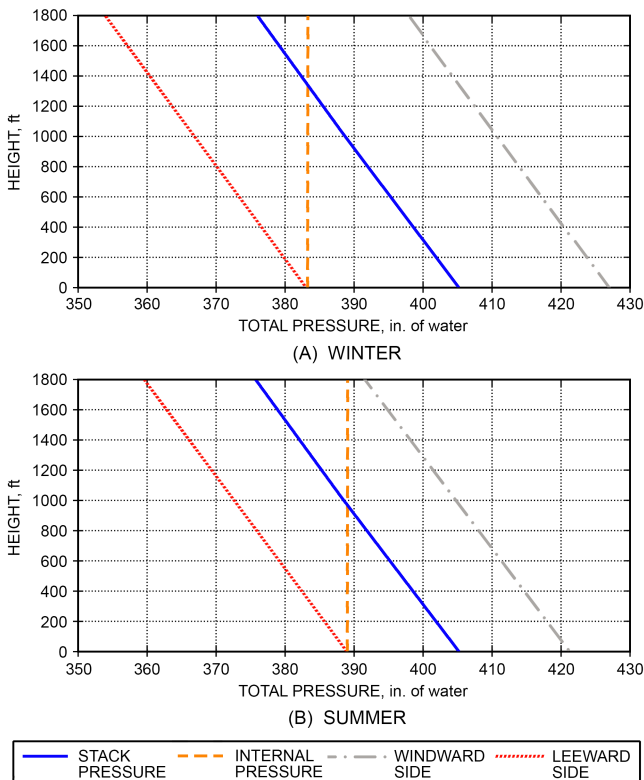


Fig. 3 Climate Data for (A) Bangkok, (B) Beijing, (C) Dubai, and (D) Copenhagen

Table 2 Stack Effect Calculations for Beijing Example Buildings

	Height, ft						
	0	328	668	988	1308	1648	1968
Outdoor air temperature, °F	94.90	92.44	89.90	87.50	85.11	82.56	80.16
Air pressure, in. of water	405.16	399.74	394.18	389.00	383.88	378.50	373.49
Air density, lb/ft ³	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Stack pressure difference, in. of water	0.00	-0.08	-0.17	-0.25	-0.32	-0.40	-0.48
Wind pressure, in. of water	1.07E-02	2.30E-02	2.95E-02	3.46E-02	3.91E-02	4.35E-02	4.73E-02
Total pressure, in. of water	405.14	399.64	394.00	388.75	383.56	378.10	373.02
Airflow rate, ft ³ /s	828.08	826.17	824.18	822.30	820.42	818.41	816.52
Internal pressure, in. of water	389.08	389.08	389.08	389.08	389.08	389.08	389.08
Wind speed, mph	14.90	21.97	24.99	27.18	29.03	30.76	32.23
Windward side, in. of water	421.19	415.70	410.06	404.81	399.62	394.16	389.08
Leeward side, in. of water	389.08	383.59	377.95	372.70	367.50	362.05	356.97

**Fig. 4 Stack Effect for Beijing Example Building**

pressure increases along the building height; in summer, it decreases along the height. In addition, when the building gets taller, its NPL on the windward side rises: the extreme is for a building height of 1969 ft, for which the NPL on the windward side is almost on the top of the building. For a 328 ft building, the windward-side pressure is almost the same as the stack pressure.

For the climate in Beijing, which is cold and dry in the winter and warm and humid in summer, stack effect is much more intense than in warmer climates. Stack effect during cold outdoor conditions may cause problems, such as elevator doors not closing properly because of the pressure differential across the doors, causing the doors to stick in their guideways enough that the closing mechanism cannot overcome it.

Another difference of Beijing compared with other cities is that the wintertime NPL is slightly lower, or below the middle of the building. During winter in a 1969 ft building in Beijing, the NPL is

Table 3 Parameters for Bangkok Example Building

	Summer	Winter
Outdoor temperature, °F	96.7	67.4
Indoor temperature, °F	75	68
Relative humidity, %	56	56
Height above sea level, ft	13	13
Wind speed, mph	10	10
Air pressure, in. Hg	29.77	29.77

slightly below 984 ft, which means the indoor air pressure is much higher at the upper level of the building than in the following cities. Therefore, for upper levels of the building, air leakage is much greater in Beijing than other, warmer cities, the airflow rate is higher, the building function is significantly affected. Address stack effect during design. Architects and engineers must pay close attention to solving the problems associated with stack effect, which are exacerbated in extremely cold climates.

Bangkok. Bangkok has a hot and humid climate throughout the year (Table 3); therefore, in winter, the leeward- and windward-side pressures on the Bangkok building change more from the bottom to the top than those on the Beijing building (Figure 5 and Table 4). Also, because even in winter outdoor air is warmer than the indoor air, internal pressure decreases along the building height.

Because Bangkok's climate is humid and hot throughout the year, winter and summer temperatures are similar (average winter temperature is approximately 80°F, and average summer temperature is approximately 84°F). Stack effect on the building in summer and winter is therefore approximately the same.

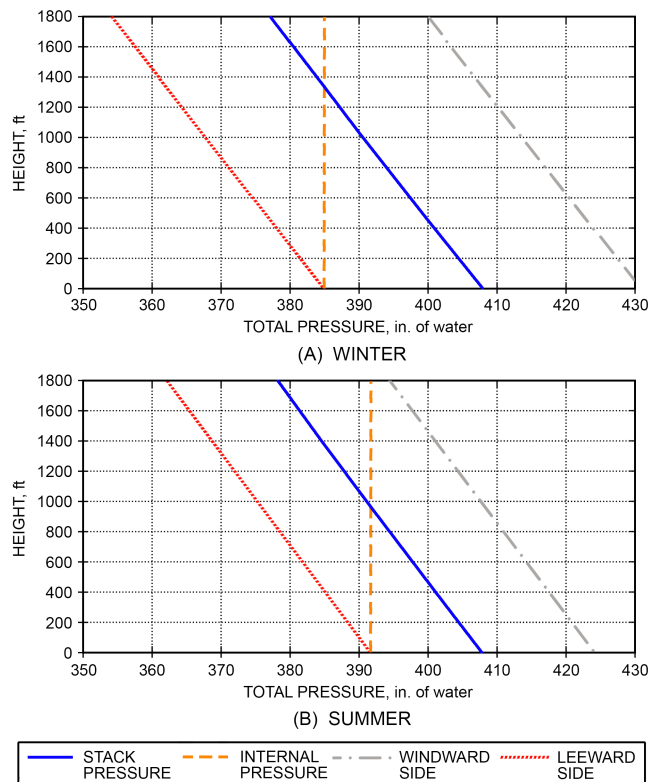
Figures 6 and 7 show air density and wind speed changes along the building height. According to the calculation, wind speed increases from 5 mph at ground level to 22 mph at the top (i.e., more than four times greater at the upper level). On the other hand, air density decreases drastically as building height increases, from 0.0737 lb/ft³ to 0.0696 lb/ft³. Because the wind speed increase along the building height is so great, the airflow rate is much higher at the upper level compared to the lower level. It is crucial for architects and engineers to consider the high wind pressure on the building facade's upper levels.

Dubai. Because Dubai is in a hot and arid climate area (Table 5), the summertime decrease of leeward-side, windward-side, and internal pressures is more obvious, and the NPL on the windward side almost reaches the top of the building (Figure 9 and Table 6). This means the windward side continuously admits air from the outdoors. Even though the temperature in summer is extremely high in Dubai, its winter temperature is lower than Bangkok's and below the building's internal temperature, which means the internal pressure decreases along the building height.

The biggest problem in Dubai is the ambient humidity. In summer, humidity is extremely low, averaging approximately 9% rh, which

Table 4 Stack Effect Calculations for Bangkok Example Buildings

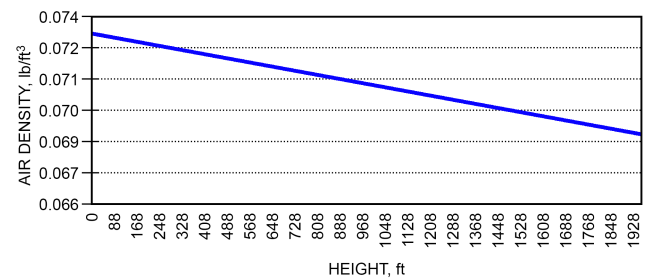
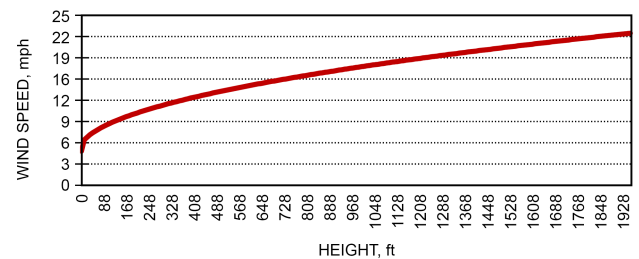
	Height, ft						
	0	328	668	988	1308	1648	1968
Outdoor air temperature, °F	96.70	94.26	91.73	89.35	86.98	84.45	82.07
Air pressure, in. of water	407.95	402.49	396.90	391.69	386.54	381.13	376.09
Air density, lb/ft ³	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Stack pressure difference, in. of water	0.00	-0.09	-0.18	-0.27	-0.35	-0.44	-0.52
Wind pressure, in. of water	4.83E-03	1.40E-02	1.92E-02	2.33E-02	2.71E-02	3.09E-02	3.42E-02
Total pressure, in. of water	407.91	402.38	396.70	391.41	386.18	380.69	375.57
Airflow rate, ft ³ /s	829.41	827.51	825.53	823.66	821.78	819.78	817.90
Internal pressure, in. of water	391.74	391.74	391.74	391.74	391.74	391.74	391.74
Wind speed, mph	10.00	17.07	20.09	22.28	24.13	25.86	27.33
Windward side, in. of water	424.09	418.55	412.87	407.58	402.35	396.86	391.74
Leeward side, in. of water	391.74	386.21	380.53	375.24	370.01	364.52	359.40

**Fig. 5 Stack Effect for Bangkok Example Building**

significantly influences the stack effect. As shown in Figure 9, when the relative humidity increases from 9% to 60%, the air temperature at the top level of a 1969 ft building changes from 79°F to 82°F. Air temperature is the most significant factor that affects stack effect. Therefore, architects and engineers should also consider the consequences of humidity on stack effect when designing a building.

Copenhagen. Table 7 gives the parameters for the Copenhagen example building. Stack effect is shown in Figure 10, and the calculations are shown in Table 8.

Stack effect exists in almost every tall building higher than 100 m. Its effect on the building's interior environment or facade is significant because the increased difference between indoor and outdoor air pressure and increased wind speed on the building envelope's exterior cause problems that considerably affect building function. For example, elevator doors may not close because of pressure differences across the door; heating load may be increased

**Fig. 6 Air Density for Bangkok Example Building****Fig. 7 Wind Speed for Bangkok Example Building****Table 5 Parameters for Dubai Example Building**

	Summer	Winter
Outdoor temperature, °F	109.2	57
Indoor temperature, °F	75	68
Relative humidity, %	38	45
Height above sea level, ft	33	33
Wind speed, mph	16.4	16.4
Air pressure, in. Hg	29.77	29.77

by a substantial influx of cold air entering the building through openings at the lower levels. An extreme example would be an extremely tall commercial building whose lower portion is occupied while the top of the building is still under construction. A tall building with an open top has the NPL shifted to the top of the building. This shift causes an extremely high outdoor air pressure on the building at the lower floors, which could result in malfunction of the revolving entry doors.

As demonstrated by the example buildings, it is important to pay attention to the windward and leeward sides of the building, because each side has different pressure differentials between indoors and outdoors. These differences cause different airflow directions in the building, especially in windy areas like Chicago, where wind can place huge pressures on the building facade.

Table 6 Stack Effect Calculations for Dubai Example Buildings

	Height, ft						
	0	328	668	988	1308	1648	1968
Outdoor air temperature, °F	109.20	106.60	103.91	101.38	98.85	96.16	93.62
Air pressure, in. of water	407.61	402.16	396.57	391.37	386.22	380.82	375.78
Air density, lb/ft ³	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Stack pressure difference, in. of water	0.00	−0.14	−0.28	−0.41	−0.54	−0.68	−0.80
Wind pressure, psi	1.27E-02	2.58E-02	3.25E-02	3.78E-02	4.25E-02	4.70E-02	5.09E-02
Total pressure, psi	407.59	402.01	396.29	390.96	385.69	380.15	375.00
Airflow rate, ft ³ /s	838.69	836.64	834.50	832.49	830.47	828.31	826.28
Internal pressure, in. of water	391.29	391.29	391.29	391.29	391.29	391.29	391.29
Wind speed, mph	16.40	23.47	26.49	28.68	30.53	32.26	33.73
Windward side, in. of water	423.89	418.31	412.58	407.26	401.98	396.45	391.29
Leeward side, in. of water	391.29	385.71	379.99	374.66	369.39	363.85	358.70

Table 7 Stack Effect Calculations for Copenhagen Example Buildings

	Height, ft						
	0	328	668	988	1308	1648	1968
Outdoor air temperature, °F	77.80	75.38	72.87	70.51	68.15	65.64	63.27
Air pressure, in. of water	407.89	402.44	396.85	391.64	386.50	381.08	376.05
Air density, lb/ft ³	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Stack pressure difference, in. of water	0.00	−0.01	−0.02	−0.04	−0.05	−0.06	−0.07
Wind pressure, in. of water	2.62E-02	4.45E-02	5.35E-02	6.02E-02	6.61E-02	7.18E-02	7.67E-02
Total pressure, in. of water	407.89	402.44	396.84	391.63	386.48	381.06	376.02
Airflow rate, ft ³ /s	815.23	813.39	811.48	809.67	807.86	805.93	804.11
Internal pressure, in. of water	391.95	391.95	391.95	391.95	391.95	391.95	391.95
Wind speed, mph	22.90	29.97	32.99	35.18	37.03	38.76	40.23
Windward side, in. of water	423.82	418.37	412.78	407.57	402.41	397.00	391.95
Leeward side, in. of water	391.95	386.51	380.91	375.70	370.55	365.13	360.09

Table 8 Parameters for Copenhagen Example Building

	Summer	Winter
Outdoor temperature, °F	77.8	21.2
Indoor temperature, °F	75	68
Relative humidity, %	58	75
Height above sea level, ft	16	16
Wind speed, mph	22.9	22.9
Air pressure, in. Hg	29.77	29.77

It is therefore, mandatory that stack effect gain enough attention from both architects and engineers when designing high-rise buildings to ensure tight envelopes and means to deal with stack effect infiltration and exfiltration. Knowing its mechanism and calculation requirements can help improve understanding of the distribution of ambient air pressure and temperature, and identify potential problems so that they can be avoided when the building is occupied.

Climate (especially temperature and pressure) also significantly influences stack effect in and on the building. Figure 11 shows the pressure difference in the example cities used previously. In Beijing or Copenhagen, the temperature is extremely low during the winter; the temperature change along building height can cause pressure to change from 407.5 in. of water to 377.4 in. of water. However, in Dubai, which averages higher temperatures during the year than Beijing or Copenhagen, the temperature change along building height causes pressure to decrease from 407.5 in. of water to 375.4 in. of water. In Bangkok, the pressures change from 407.5 in. of water to 374.1 in. of water. This phenomenon must be addressed by architects and engineers when designing tall buildings in warmer cities, where building facades experience greater pressure changes. The upper levels of the building might experience significantly more infiltration (reverse stack effect), which may cause greater heat loss and consequently higher energy consumption.

A high-rise building in Bangkok is more likely to have reduced pressure on the upper levels, which means more infiltration from the external environment to the inside of the building, resulting in higher energy consumption. In Bangkok, it is important to improve the building's tightness to minimize air leakage into the upper levels of the building.

In cities like Beijing and Copenhagen, where tall buildings experience high pressures at upper levels, the opposite of the Bangkok situation occurs in the winter; therefore, when designing the building, increasing indoor pressure is important.

Essentially, in cold climates, designers need to reduce the high pressure at upper levels of a high-rise building, and in warm climates, which have lower pressure at the top level, it is crucial to minimize infiltration by increasing the internal pressure.

The ambient temperature difference along the building height varies from city to city (Figure 12), and interacts with stack effect to influence infiltration/exfiltration. In Beijing, the temperature is low around the top levels of the building, which, combined with a higher pressure, causes increased air infiltration from the outdoors, resulting in increased heating and higher energy consumption. However, in warmer cities like Bangkok and Dubai, the upper-level temperature is warm during most of the year. In winter, this warmth is beneficial; however, in summer, the warmer air can infiltrate into the upper levels of the building, increasing the building's cooling load. It is therefore always beneficial to seal the building tightly to avoid the stack effect.

Minimizing Stack Effect

During design, the architect and HVAC design engineer should take steps to minimize air leakage into or out of (and vertically within) the building. Although it is not possible to completely seal any building, this approach can help mitigate potential problems that could be caused by stack effect.

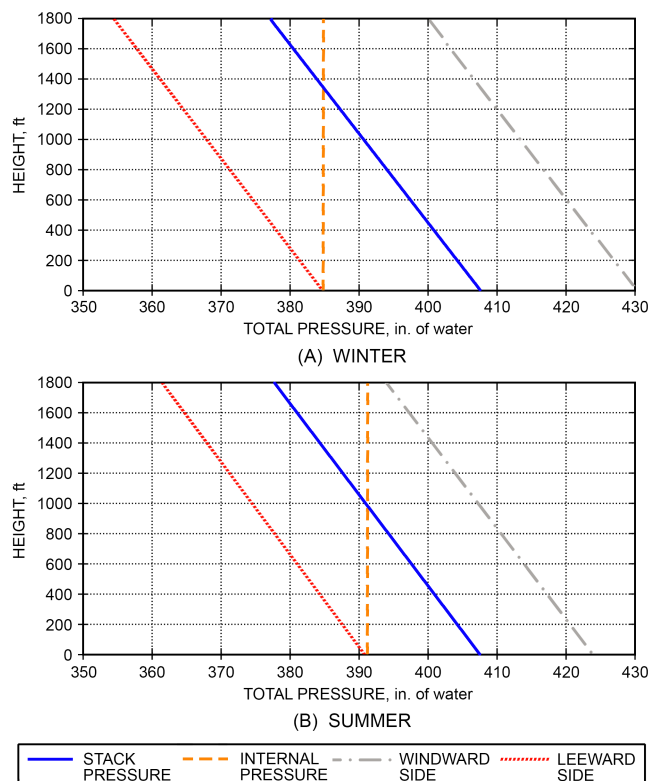


Fig. 8 Stack Effect for Dubai Example Building

A tight building envelope is fundamental to protecting a building against uncontrolled air movement into and out of the building. A tight specification, testing, and careful monitoring during construction are required. Although most curtain walls are traditionally tested in the factory, increasingly more field tests (either spot tests or whole-building pressure tests) are specified in some buildings. A whole-building pressure test is difficult in tall buildings, and currently there is a limit on how many floors can be pressurized. Sectionalizing a tall building is required to perform a localized test.

Outdoor air infiltration points include building entry doors, doors that open to truck docks, outdoor air intake or exhaust louvers, construction overhangs with light fixtures, or other recessed items, located immediately above the ground level and are not properly sealed against leakage or provided with heat, and any small fissures in the exterior wall itself. Internally, the building allows air passage through fire stairs, elevator shafts, mechanical shafts for ducts and piping, and any other vertical penetrations for piping or conduit or at the edge of the floor slab at the exterior wall. All these are candidates for careful review to ensure, as much as possible, that the exterior wall is tight, all shafts are closed, and all penetrations sealed. Vestibules or airlocks can be provided for loading docks with good door seals on the doors to and from the loading dock.

Entrances for tall buildings in cold climates should be revolving doors. Doors of this type are balanced, with equal pressure in opposite directions on the panels on either side of the central pivot, making operation relatively simple and requiring no special effort to turn. Their gasketing also provides closure at all times. Give special consideration to hotel entries where people carry large luggage through; larger revolving doors are required to avoid people bypassing the revolving doors altogether.

Two-door vestibules are acceptable for the loading dock, assuming the doors are properly spaced to allow them to be operated independently and with one door to the vestibule always closed, and sufficient

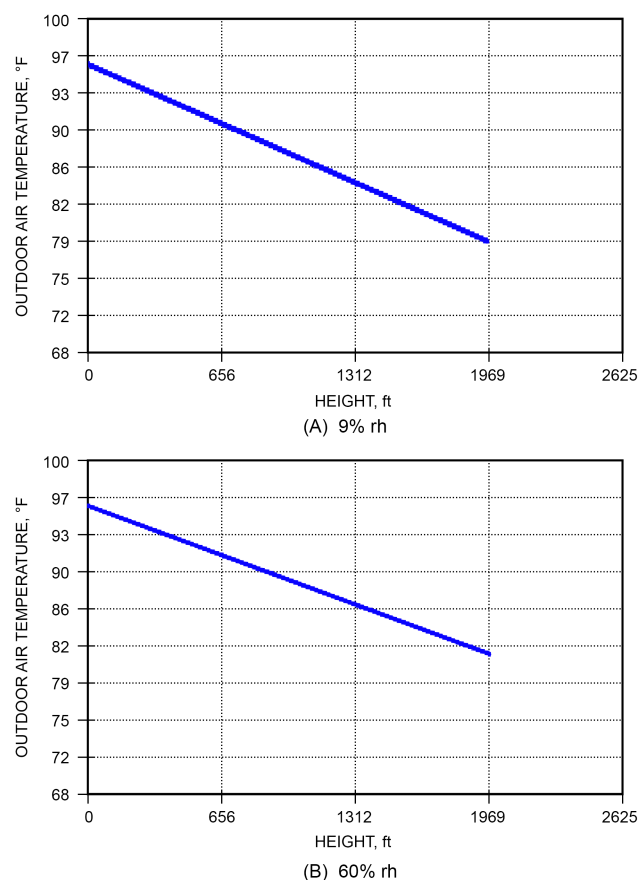


Fig. 9 Atmospheric Temperature for Dubai Example Building

heat is provided in the space between the doors. If properly spaced, simultaneous opening of both doors on either side of the vestibule can be controlled. However, two-door vestibules in cold climates are inadequate for personnel entry because, with large numbers of people entering the building at various times, both doors will be open simultaneously and significant quantities of unconditioned outdoor air can enter the building. In cold climates, revolving doors are strongly recommended at all points of personnel entry.

To control airflow into the elevator shaft, consider adding doors at the entry to the elevator banks. This creates an elevator vestibule on each floor that minimizes flow through open elevator doors.

Elevator shafts are also a problem because an air opening may be required at the top of the shaft. In many tall buildings, however, the elevator hoistways are not vented for smoke, using sprinkler heads instead. Alternatively, some jurisdictions accept the installation of a motorized damper on the hoistway vent; the damper is initiated by a smoke detector and opens immediately when smoke is sensed in the hoistway. All shafts, however, can be sealed in their vertical faces to minimize inflow that would travel vertically in the shaft to the openings at its top.

Elevator cars can act as pistons to increase the pressure in elevator hoistways ahead of the moving cab. Careful sequencing of elevator cabs, especially when multiple cabs are located in a single shaft, must be considered to provide proper relief and sequencing of door openings.

It can be helpful to interrupt stairs intermittently with well-sealed doors to minimize vertical airflow through buildings. This is particularly useful for fire stairs that extend through the entire height of

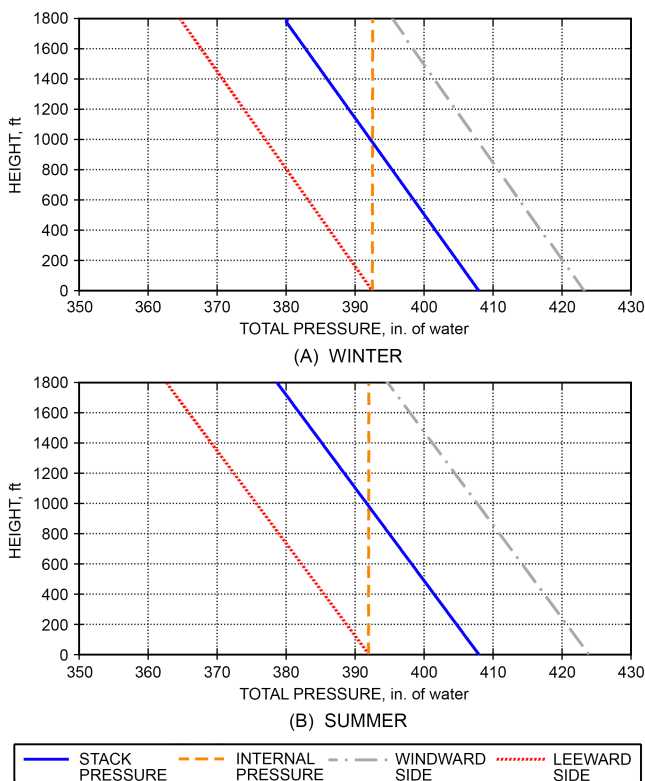


Fig. 10 Stack Effect for Copenhagen Example Building

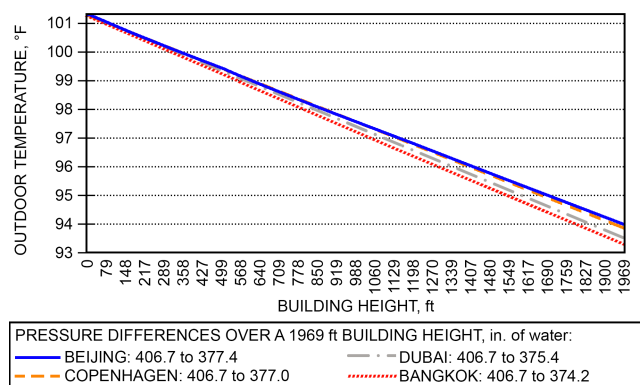


Fig. 11 Air Pressure Difference in Four Example Cities

the building. Entrances to fire stairs should be provided with good door and sill gaskets. (See the section on Door-Opening Forces under Pressurization System Design in [Chapter 53](#) for guidance on ensuring doors in fire stairs can be opened during an emergency.)

The last key item is to ensure a tight exterior wall through specification, proper testing, and hiring a contractor to erect the wall.

The preceding precautions involve the architect and allied trades. The HVAC designer primarily must ensure that mechanical air-conditioning and ventilation systems supply more outdoor air than they exhaust, to pressurize the building above atmospheric pressure. This is true of all systems where a full air balance should be used for the entire building, with a minimum of 5% more outdoor air than the combination of spill and exhaust air provided at all operating conditions, to ensure positive pressurization. In addition, it is good design, and often required by code for smoke control, to have a separate system for the entrance lobby. Although not always required,

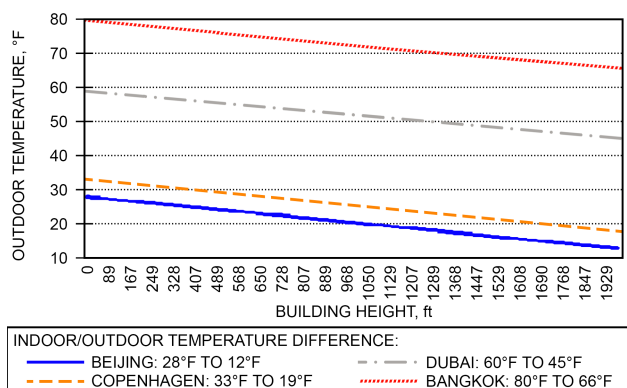


Fig. 12 Air Temperature Difference in Four Example Cities

this system can be designed to operate in extreme winter outdoor air conditions with 100% outdoor air. This air is used to pressurize the building lobby, which is a point of extreme vulnerability in minimizing stack effect. Lastly, if two-door vestibules must be provided, consider pressurizing the vestibule with conditioned outdoor air.

Wind and Stack Effect Pressure Analysis

The world trend toward super- and megatall buildings suggests that both wind and stack effect will greatly affect designs of future tall building and HVAC systems. It is advisable to carry out both wind and stack effect analyses by computational fluid dynamic (CFD) or wind tunnel analysis during concept and schematic design phases of the project, such that advance precautionary measures could be implemented in the early design stage.

2. TYPICAL HVAC DESIGN PROCESS

Design of an HVAC system typically proceeds through multiple phases. The process is subject to economic and time constraints, to availability of or preferences for certain equipment, and to modifications in design criteria as the project progresses. Topics of special concern to tall buildings are discussed here; for a detailed description of the typical design phases, see American Institute of Architects (AIA 2007) and [Chapter 43](#) of this volume.

Program Phase

The functional use(s) of the building, owner and occupant requirements, architectural concepts, and budget limitations are typically determined during this phase. Sometimes called *preliminary design* or *concept phase*, this phase begins when the owner identifies the need for the project and the program is developed.

Schematic Design

In this phase, the designer selects and compares appropriate candidate systems to meet the building's functional needs, and develops recommendations for the owner. This phase typically involves evaluation of the benefits and trade-offs of different design approaches

Preliminary Design or Design Development

During this phase, the mechanical designer coordinates the HVAC system design with the architectural, structural, and electrical systems to resolve potential conflicts. Heat loss, heat gain, and ventilation calculations are refined, equipment sizes and capacities are selected, and system layouts are developed.

Final Design and Preparation of Construction Documents

In this stage, preliminary layouts and equipment selections are fully developed and the final drawings and specifications are

completed. Some projects require preparation of alternate designs, with bids solicited for all options. In such cases, the primary option generally receives the most effort during the design.

Construction Phase

The design engineer's responsibilities during this phase typically include reviewing shop drawings, observing construction, and conducting or witnessing system performance tests.

Acceptance or Commissioning Phase

The term "commissioning" is often used to refer to the start-up and functional performance testing of mechanical systems. However, ASHRAE *Guidelines* 0 and 1 outline a much more comprehensive process for ensuring that an HVAC system is designed, installed, tested, and operated in accordance with the design intent. Experience shows that a comprehensive commissioning procedure is essential to the success of a project.

Postoccupancy Services

Designers may be called upon to help train operating personnel or optimize system operation. These services are often included as part of a comprehensive commissioning process.

Project Team

In some cases, the project team is selected at the beginning of the program phase so the facility concepts can be firmly established with these experts' input early in project development. In other cases, the full project team may not be selected until the program phase is completed, after the owner has chosen the preferred type of system and the design intent statement has been completed.

Team members may include the owner's team, typical design team members (e.g., architect, engineers, fire protection engineer, landscape and geotechnical experts), construction manager, and/or contractor(s) and may also include specialists in fields such as vibration and acoustics, lighting, security, facades, and computational fluid dynamics (CFD).

During schematic design, preliminary design or design development, and final design/preparation of construction documents, the team follows the procedures outlined in [Chapter 43](#).

During construction, the design engineer's responsibilities typically include reviewing shop drawings, observing construction, and conducting or witnessing system performance tests. Contractors may require guidance to ensure that they follow the project specifications rather than their standard methods.

In the acceptance or postoccupancy phases, designers may be asked to help train operating personnel or optimize system operation. These services are often included in comprehensive commissioning.

Safety Factors

System designers typically apply safety factors at various points in the design process to avoid undersizing equipment. Judicious use of safety factors is good engineering practice. However, safety factors are too often misapplied as a substitute for engineering design, and this practice typically results in grossly oversized equipment. Therefore, care is necessary in applying safety factors.

3. SYSTEMS

Systems used in tall buildings have evolved to address owners' goals, occupants' needs, energy costs, and environmental concerns (including indoor air quality).

[Chapter 37](#) discusses mechanical maintenance and life-cycle costing, which may be useful in the evaluation process with regard to alternative systems. Chapter 1 of the 2012 *ASHRAE Handbook—HVAC Systems and Equipment* provides guidelines for a quantitative

evaluation of alternative systems that should be considered in the system selection process. Chapter 19 of the 2013 *ASHRAE Handbook—Fundamentals* provides means for estimating annual energy costs. Ross (2004) provides a more detailed discussion of systems to be considered.

4. SYSTEM SELECTION CONSIDERATIONS

In a fully developed building (including the core and shell as well as space developed for occupancy), the cost of mechanical and electrical trades (i.e., HVAC, electrical, plumbing, and fire protection) is typically 30 to 35%, and for a high-rise commercial building is usually over 25%, of the overall cost (exclusive of land). In addition, the mechanical and electrical equipment and associated shafts can consume 7 to 10% of the gross building area. The architectural design of the building's exterior and the building core is fundamentally affected by the system chosen. Consequently, HVAC system selection for any tall building should involve the entire building design team (i.e., owner, architect, engineers, and contractors), because the entire team is affected by this decision.

The points of concern and analysis methods do not differ in any way from the process that would be followed for a low-rise building. Possible alternative systems also are very similar, but the choices for high-rise buildings are typically more limited.

Air-Conditioning System Alternatives

Several alternative systems are used in tall buildings. Although the precise system configurations are subject to the experience and imagination of the design HVAC engineer, the most common ones are variations of generic all-air and air/water systems.

Unitary, refrigerant-based systems, such as through-the-wall units, are used in conjunction with all-air systems providing conditioned ventilation air from the interior zone, but this combined solution has been limited to retrofits of older buildings that were not previously air conditioned and smaller low-rise projects. They are seldom used in first-class tall commercial buildings.

Another option is panel-cooling-type systems, including chilled-ceiling and chilled-beam systems. Though not common in the United States, these systems are used in Europe as a retrofit alternative in existing buildings that were not previously air conditioned, because these systems can be installed with minimal effect on existing floor-to-ceiling dimension.

All-Air Variable-Air-Volume Systems. All-air variable-air-volume (VAV) systems in various configurations are one of the most common solutions in tall buildings. Conditioned air for VAV systems can be provided from a central fan room or from local floor-by-floor air conditioning units. These alternative means of delivering conditioned air are discussed in the section on Central Mechanical Equipment Room Versus Floor-by-Floor Fan Rooms. The current section is primarily concerned with system functioning, configurations in use, and possible variations in system design.

VAV systems control space temperature by directly varying the quantity of cold supply air in response to the cooling load requirements. VAV terminals or boxes are available in many configurations; pressure-independent terminal units are recommended. Interior spaces that have a year-round cooling load regardless of outdoor air temperature can use any of the alternative types of VAV boxes:

- A **pinch-off box** reduces supply air volume directly with a reduction of the cooling load. This is a very common terminal in commercial projects, and has the smallest height of any terminal used in office buildings. Usually a stop is used to maintain minimum airflow, for proper ventilation.
- A **series-flow fan-powered VAV terminal** maintains constant airflow into a space by mixing the required amount of cold supply

air with return air from the space. The VAV terminal contains a small fan to deliver constant airflow to the space. The fan operates any time the building is occupied. The primary advantage of the fan-powered box is that airflow in the space it supplies is constant at all conditions of load. This is of particular import if low-temperature air is used to reduce the distributed air quantity and the energy necessary to distribute the system air.

- A **parallel-flow fan-powered VAV terminal** maintains variable airflow into a space and mixes the required amount of cold supply air at minimum flow requirements with return air from the space. The VAV terminal contains a small fan that starts only in heating mode to deliver mixed primary and return airflow to the space. The fan operates only when heating is required to deliver warm return air, mixed with cool primary air when the building is occupied. Unlike the series-flow box, this option delivers increased airflow to the space during heating but can also shut off primary air and operate only the fan to deliver return air during unoccupied periods. A box-mounted heating coil (hot-water or electric) supplements the heat provided by return air when heating requirements increase. The parallel approach does not ensure constant air volume to the space, as can be obtained with the series approach, but it does provide a minimum airflow at significantly lower operating cost.
- An **induction box** reduces supply air volume and induces room air to mix with supply air, thus maintaining a constant supply airflow to the space. These units require higher inlet static pressure to achieve velocities necessary for induction, with a concomitant increase in supply fan energy requirements. Moreover, operational problems have been experienced, especially at reduced primary airflow quantities. Thus, these boxes are now seldom used in commercial projects.

The exterior zone can use any VAV box type, but in geographical locations requiring heat, the system must be designed with an auxiliary means of providing the necessary heat. This can be done by installing hot-water baseboard, controlled either directly by thermostat or by resetting the hot-water temperature inversely with the outdoor air temperature. Other alternatives are thermostatically controlled electric baseboard on the exterior wall, or either electric or hot-water heating coils in the perimeter VAV boxes.

Low-Temperature Air VAV Systems. All of the preceding variations can be designed using conventional temperature differentials (16 and 18°F) between the supply air and room temperature. Buildings have been successfully designed, installed, and operated for decades with low-temperature supply air between 48 and 50°F. This increases the temperature supply differential to approximately 28°F, thus dramatically reducing primary air quantities.

This lower-temperature air can be obtained by operating the refrigeration machines with chilled water leaving at 40°F or by using ice storage. If the chiller supplies 40°F chilled water, operating costs of the refrigeration plant increase and the chiller must operate for a longer time before an economizer cycle can occur. Moreover, the use of absorption refrigeration machines may not be possible, because they are usually not capable of providing chilled water as cold as 40°F.

However, the reduced quantity of air distributed also reduces fan power, which more than offsets the additional energy used by the chiller. This lower-temperature air requires fan-powered VAV terminals or induction-type air supply terminals to avert the problem of reduced airflow at loads less than design, particularly in the interior zone. The air delivery terminals mix room and cold supply air to deliver warmer air to the space to offset heat gain.

Using low-temperature supply air requires elimination of air leaks and proper installation of the correct thickness of duct insulation to prevent moisture condensation. Note that the decrease in

supply duct size when using cold air can make lower floor-to-floor heights more practical.

Air/Water Systems. Air/water systems historically included induction systems, but modern systems quite often use fan-coil units outside the building, with interior spaces typically supplied by an all-air variable-air-volume system. Exterior zones are typically provided with a constant volume of air from either (1) the interior VAV system in sufficient quantities to meet requirements of ASHRAE *Standard* 62.1's multiple-spaces equation or (2) a separate dedicated outdoor air system providing exterior-zone outdoor air ventilation. Fan-coil units in a tall building that requires winter heat are usually designed with a four-pipe secondary water system to provide simultaneous building heating and cooling.

An advantage of the air/water system is it reduces the required capacity of the central supply and return air systems and the size of distribution air ducts, compared to those required with an all-air system (including low-temperature all-air). At the same time, it reduces the air-conditioning supply system's mechanical equipment room space needs. However, air/water systems require space for heat exchangers and pumps to obtain the hot and cold secondary water needed by the fan-coil unit system.

Underfloor Air Distribution (UFAD) Systems. In underfloor air distribution (UFAD) systems, the space beneath a raised floor is used as a distribution plenum. Most installations use manually adjustable supply diffusers or automatically controlled terminal units beneath the floor to control air delivered to the space above. (In contrast, for more traditional systems, terminal units are installed above the ceiling and supply air is delivered from above.) When properly designed, either underfloor or ceiling-mounted air distribution systems can meet occupants' comfort requirements. UFAD systems typically have a higher first cost because of the raised floor, but operating costs are usually lower because less fan power is required. However, if a raised floor is a design requirement for electrical distribution and information technology cabling, UFAD may offer savings in overall first and operating costs.

The UFAD system can use central fan rooms or floor-by-floor fan units. Conditioned air is typically provided at 60 to 64°F in the raised-floor plenum (between the structural slab and the raised floor), but in locations requiring dehumidification, the air must first be cooled to approximately 55°F to remove moisture and then blended with return air (often using an underfloor-mounted series fan powered box or similar arrangement) to achieve supply air temperatures of 60 to 64°F. The suspended ceiling acts as a return plenum but can be reduced in depth because of the absence of supply ductwork.

A major concern with UFAD in tall buildings is the perimeter zone, which has widely varying loads between summer and winter conditions, especially in buildings with large glass exterior elements. Thermostatically controlled fan-coils beneath the floor can be a cost-effective solution. Additionally, extreme caution is needed in sealing all structural floor penetrations to prevent short-circuiting of supply air.

Underfloor air conditioning for a tall building must be selected early in the design process, because it affects architectural (e.g., floor-to-floor heights, exterior facade treatment, stairs, elevators), structural (e.g., depressed structural slabs), and electrical (e.g., plenum-rated cabling) design considerations. All design disciplines must be involved in this decision process.

The combination of system components and the resultant system configuration for a specific building are limited only by the designer's imagination. The chosen alternative is of interest and concern to the owner, architect, and other engineering consultants, and therefore should be subjected to scrutiny and review by the entire design team before final selection is made.

5. DISPLACEMENT VENTILATION

Chilled Beams

Chilled beams are a type of air/water system that has had increasing success in tall buildings. These units are available in both passive and active types, with active units offering higher capacity. Passive chilled-beam units rely on a combination of radiant and convective heat transfer to provide space conditioning from heated or chilled water delivered to the unit. With active units, primary supply air delivered to the unit causes induced room air to circulate through a hot- or chilled-water coil to provide additional conditioning capacity.

Chilled beams allow an overall reduction in the ductwork required to condition the space, because water has a greater heat-carrying capacity than air. Consequently, sheet metal costs and potentially space requirements for supply and return air ductwork can also be reduced. Use caution, however, because chilled-beam units have no latent cooling capacity, and primary supply air must be conditioned to deliver air at a low enough dew point to provide the required dehumidification of the space served.

Radiant Ceilings

Radiant cooling follows the same principles as radiant heating: heat transfer occurs between the space and the panels through a temperature differential. However, unlike in radiant heating, the colder ceiling absorbs thermal energy radiating from people and their surroundings. The major difference between cooled ceilings and air cooling is the heat transport mechanism. Air cooling uses convection only, whereas cooled ceilings use a combination of radiation and convection. The amount of radiative heat transfer can be as high as 55%; convection accounts for the remainder. With cold ceilings, the radiative heat transfer occurs through a net emission of electromagnetic waves from the warm occupants and their surroundings to the cool ceiling. On the other hand, convection first cools the room air because of contact with the cold ceiling, creating convection currents in the space, which transfers the heat from its source to the ceiling, where it is absorbed.

Because air quality must be maintained and radiant panels remove only sensible heat from the space, radiant cooling panels are used in conjunction with a small ventilation system. The panels provide most of the sensible cooling, and the air system provides ventilation and air moisture (latent load) control. To prevent high humidity levels in a room, the supply air must be drier than that of the supplied space, especially when there are additional moisture sources in the room. Consequently, outdoor air must be dehumidified, which is usually done by cooling to a dew point of approximately 59°F. If the environment is dry, the ventilation system is used to humidify the air. Because the ventilation system is used only to maintain the air quality and to regulate the latent load, the airflow required is small relative to conventional cooling systems. Best results are usually attained with a straight displacement ventilation system with no air recirculation. This system typically supplies air through outlets near or at the floor, at temperatures below that of the room air; this approach provides a uniform layer of fresh air at floor level. In turn, people and other heat sources create a passive convective flow of fresh air to the ceilings, where it can be exhausted. This reduced airflow and radiant panels' relatively high surface operating temperature (mean temperature of 61°F) make radiant cooling a more comfortable way of cooling a space than conventional systems.

A cooled ceiling operates in direct proportion to the heat load in the room. Typically, a person sitting at a desk emits 130 W of energy, whereas a computer emits 90 to 530 W to its surroundings. The greater the number of people and/or appliances and exposure to sunlight, the greater the temperature gradient (and therefore greater increased capacity of the cool ceiling). Generally, cool ceilings can handle between 10 and 20 W/ft² with up to 50% of the ceiling space used for cooling.

Condensation Control

Condensation on the surface of the panels is not a problem with radiant cooling. Because condensation of water occurs when the dew-point temperature is reached, proper water temperature control helps avoid any condensation. The space dew-point temperature should be monitored by a sensor linked to a controller, which modulates the inlet water temperature accordingly. Therefore, if there is risk of condensation, the water temperature is raised or water flow is shut off. However, the lower the panel's inlet temperature is, the more work the panels do; the inlet temperature should be as close as possible to the room's dew-point temperature. Consequently, the cooling capacity of a radiant cooling system is generally limited by the minimum allowable temperature of the inlet water relative to the dew-point temperature of the room air.

Variable-Frequency-Drive (VFD) Fan-Coils

Fan-coil units, either vertical stacked or horizontal, are often used in tall hospitality or residential buildings. Built-in variable-frequency drives provide an energy advantage to the overall building energy consumption, as well as improving temperature control in spaces conditioned by these units. For details, see the section on Fan-Coil Unit Systems in Chapter 20 of the 2012 *ASHRAE Handbook—HVAC Systems and Equipment*.

These units can be either complete with cabinets (which can be exposed in the space) or built into the general construction (less obtrusive to building aesthetics). Vertical units are even available with vertical pipe risers factory installed, reducing field-installed piping and overall construction costs. Although these internal components are generally designed and tested for elevated pressure capabilities, the actual pressure on these components for a particular building height should be investigated.

Variable-Refrigerant-Flow (VRF) Systems

VRF systems for heating and cooling are becoming more prevalent for reducing energy consumption in space conditioning. This system option is viable for use in tall building, particularly the newly available water-cooled condensing unit option. Air cooling may also be viable, but requires significant amounts of space outside the building, and tall buildings typically have small roof areas and space on the ground. In addition, the refrigerant lift available from these units is limited, which typically makes air-cooled options less desirable. For details, see Chapter 18 of the 2012 *ASHRAE Handbook—HVAC Systems and Equipment*.

6. CENTRAL MECHANICAL EQUIPMENT ROOM VERSUS FLOOR-BY-FLOOR FAN ROOMS

Project needs for conditioned air can be met by one or more central mechanical equipment room(s) serving multiple floors, or by systems installed in separate, local fan rooms on each floor, supplying air only to the floor on which the system is installed. Either chilled-water cooling or self-contained air-conditioning units in the floor-by-floor scheme can be used. The choice of any of the three alternative schemes is one of the most fundamental decisions made during the conceptual design phase. This issue concerns the owner, each member of the design team, and the constructing contractors, because it affects space requirements, space distribution, standard versus custom HVAC equipment, and piping and electrical distribution costs.

Central Fan Room (Alternative 1)

In central fan rooms, the supply of conditioned air for each office floor originates from multiple air-handling systems located in one or more central fan room(s), which are frequently identified as central mechanical equipment rooms (MERs). Each air-handling system can

be provided with an outdoor air economizer through minimum and variable outdoor air dampers, as dictated by the annual ambient temperature and humidity conditions and building code requirements. Multiple systems in a fan room can be interconnected by delivering supply air into a common discharge plenum from all supply systems on that floor.

Air from the central fan room(s) is distributed to each floor by means of vertical duct risers in fire-rated shafts (typically 2 h rated) within the core of the building. At each floor, horizontal duct taps are made into each riser. This horizontal duct tap contains a fire damper or a fire/smoke damper, as required by the local building code, that must be installed where the supply air duct exits the rated shaft enclosure. In many situations, an automatic, remotely controlled two-position damper, which can be rated as a smoke damper, provides individual-floor overtime operation and smoke control. The position (open or closed) is typically controlled by the building management system either on an occupancy schedule or by occupancy sensor or manual reset switch.

Return air from each floor's ceiling plenum also enters the vertical shaft through a return air fire damper at each floor.

Return air is often not ducted within the shaft, so the air is carried back to the central fan room in the 2 h rated drywall shaft. In each central fan room, multiple return air fans draw return air from the return air shafts and deliver it to a headered return air duct system in the central room and then to each air-handling unit.

With an outdoor air economizer, return air is either returned to the supply air system or exhausted to atmosphere, as determined by the relative dry-bulb temperature (or enthalpy) of the return air and the outdoor air being provided to the building. Quantities of outdoor and return air depend on the season and the resultant outdoor temperature and humidity. In warmer geographic areas where the systems operate on minimum outdoor air at all times, return air is always returned to the supply air system except during morning start-up or where the fans are operating under a smoke control mode.

A typical central fan room and supply and return air shaft arrangements are shown in Figure 13.

Floor-by-Floor Fan Rooms with Chilled-Water Units (Alternative 2)

The air supply for each office floor under this alternative originates from a local floor fan room, typically located in the building core. This room contains a chilled-water air-handling unit with a cooling coil, filters, and fan(s). Morning heating at start-up in cold climates can be provided by a heating coil in the air-handling unit, a unit heater installed in the local fan room, or heating coils in the VAV or fan-powered VAV (FPVAV) boxes. The unit on a given floor usually only supplies the floor on which the unit is installed. Typically, one unit is installed on each floor, but multiple units may be used with interconnected air systems on large floors. Chilled water for the cooling coil is provided by a central chilled-water plant in the building, sized to meet the combined capacity requirements of all of the cooling and heating needs. The supply air fan in the air-conditioning system serves to both supply air and return it from the zone served. The return air is typically directed to the fan room through the ceiling plenum, but the return may be either ducted or unducted in the fan room. In most cases, however, the fan room acts as a return air plenum.

This system typically operates on minimum outdoor air during all periods of occupancy. Outdoor air for the system is provided by an air-handling unit serving as a dedicated outdoor air system (DOAS), located on the roof or in a central mechanical equipment room. This unit provides conditioned outdoor air to the unit on each floor by a vertical air riser routed to each air-handling unit. The outdoor air unit may include preheat and cooling coils to treat incoming outdoor air, and should contain filtration to clean this air. Alternatively, this unit can contain heat recovery to precondition the outdoor air by recovering heat or cool from exhaust air.

Although chilled water is typically provided by a central refrigeration plant, economizer requirements can be provided by cooling the chilled water in mild weather by the condenser water from the cooling tower. During periods of low wet-bulb temperature, the condenser water cools the chilled water through a heat exchanger in the central chilled-water plant or by refrigerant migration through the refrigeration unit.

A typical local fan room supply, return, and outdoor air arrangement is shown in Figure 14. The unit heater shown provides morning heat. It can use electric energy or hot water as its heat source.

As shown in Figure 14, the walls around the local floor fan room are not fire-rated because the duct penetration serves only this floor. The vertical shaft that contains the outdoor air duct from the central fan room, and perhaps the smoke exhaust ducts, constitute a fire-rated shaft. Accordingly, fire dampers are only provided at the point where ducts penetrate the shaft wall, not as they leave or enter the local floor fan room itself. Although fire dampers are shown in the smoke exhaust ducts, many codes prohibit their use in an engineered smoke control system to avoid the possibility of having a closed damper when smoke removal is required.

Floor-by-Floor Fan Rooms with Direct Expansion Units (Alternative 3)

A second variation of the floor-by-floor alternative consists of a floor-by-floor air-conditioning supply system that is virtually identical to that in the chilled-water alternative. In this alternative, a packaged, self-contained, water-cooled direct-expansion (DX) unit, complete with one or more refrigeration compressors and water-cooled condensers, is used to produce the cooling. The heat of rejection from the compressor is handled by a circulating condenser water system and cooling tower. If geographic location dictates an economizer, it can be met by a free-cooling coil installed in the packaged unit that will only operate when condenser water delivered to the unit is cold enough to provide effective cooling. The only central cooling equipment is a cooling tower, condenser water pumps, and the central outdoor air supply unit. If an open tower system is used, consider providing a way to remove particulates from the circulating condenser water. Depending on the size of anticipated particles, typical options include sand filtration, media filtration, and centrifugal separators. For an open system, condensers should be cleanable. Bear in mind that significant water will end up on the floor during condenser cleaning, so it is important to ensure that the room has a recessed floor drain and that the floor is moisture sealed.

The physical arrangement of the supply air unit does not differ from that shown in Figure 14, except that the chilled-water risers are replaced by condenser water piping.

Floor-by-Floor Units Located on an Outer Wall

A popular variant location for a packaged floor-by-floor unit is on an outer wall. This location obviates the need for a separate outdoor air unit in a central fan room. Outdoor air can be directly introduced to the floor-by-floor unit through a louver and automatic louver damper for each unit. Moreover, this arrangement may allow use of an air-cooled condenser to handle heat of rejection. If the location requires an economizer, include a minimum and variable air damper behind the outdoor air louver.

Several precautions are necessary. If an outdoor air economizer is used, the return air spill damper must be located carefully to ensure that outdoor air and spill air do not mix. Similar care must be taken to avoid air-cooled condenser intake air mixing with air previously spilled to atmosphere. There must be no possibility of mixing heated discharge air with either the condenser intake air or the outdoor ventilation air for the supply air-conditioning unit. This can become a complicated arrangement, which may necessitate locating the air-cooled condenser remote from the local fan room.

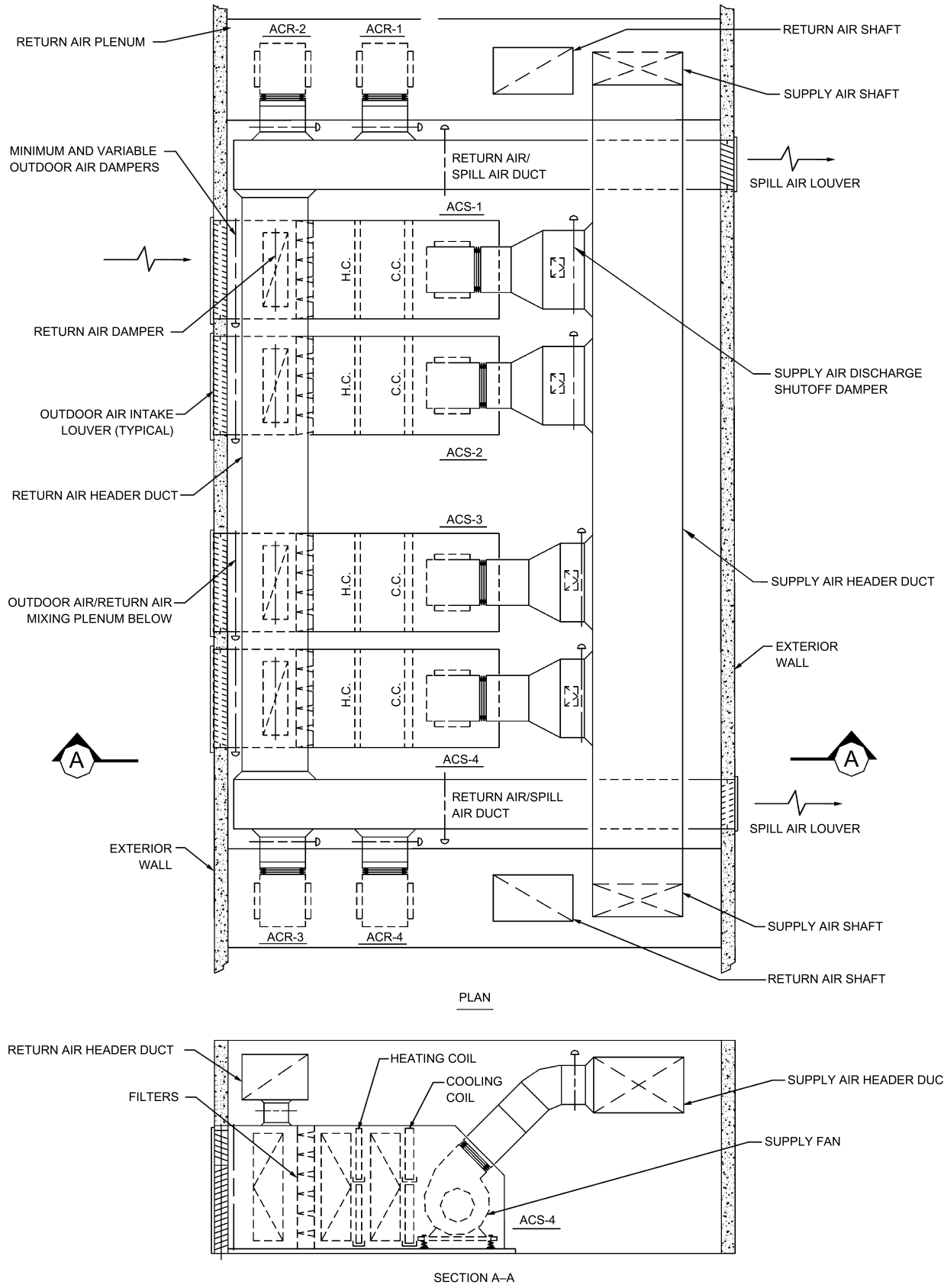


Fig. 13 Central Fan Room Arrangement
(Adapted from Ross 2004)

Comparison of Alternative Schemes

An accurate comparison of alternative schemes can only be made with a developed set of schematic plans in sufficient detail to allow a cost estimate to be completed by the contracting team or a professional estimating service. For an example, see [Table 9](#).

Acoustics

Acoustical criteria should be established for the various types of occupancy that are expected in the building. For example, open-plan office space can be designed to meet a noise criteria level of NC-40, whereas private and executive offices or conference rooms should be no higher than NC-35, and may be required to be even lower. The acoustical engineer on a project sets these levels, and it is the responsibility of the HVAC designer to work with the acoustician to see that the criteria established are achieved in the final installation. (For details on sound levels, see [Chapter 48](#) in this volume and Chapter 8 in the 2013 *ASHRAE Handbook—Fundamentals*).

Equipment and system selection affects the required sound treatment and resultant noise levels in occupied areas. It is important that project acoustical standards and the final design are reviewed by the acoustical consultant to ensure that the desired noise levels can be achieved, particularly when floor-by-floor fan rooms are used.

7. CENTRAL HEATING AND COOLING PLANTS

Many, but not all, tall buildings require a central plant to provide chilled and hot water or steam to meet the cooling and heating needs of the building. If packaged direct-expansion equipment is used on a floor-by-floor basis, as discussed previously, then a chilled-water plant is not required. Similarly, in climates where heat is necessary in colder weather, if electric resistance heat (either along the base of the outer wall or in an overhead fan-powered air conditioning terminal supplying the periphery of a building) is used, then central hot-water or steam boilers are not required. In some locations, chilled water and/or steam or hot water are available from a central utility.

For most other installations, a central chilled-water plant with refrigeration machines and a central boiler plant are required. Factors that should be considered when deciding the type and location of the heating and cooling plant include the following:

- Weight, space requirements, and effect on structural system
- Effect on construction schedule
- Specific changes in mechanical equipment room detailing and slab construction
- Acoustical considerations
- Ease and cost of operation and maintenance
- Available energy sources
- Annual operating costs and possibly life-cycle costs of each alternative

Calculation of owning and operating costs is discussed in [Chapter 37](#). Alternative refrigeration technologies are detailed in Chapters 1 to 3 of the 2014 *ASHRAE Handbook—Refrigeration*, and boilers are covered in Chapter 32 of the 2012 *ASHRAE Handbook—HVAC Systems and Equipment*. Useful reference information is also contained in ASME (2013).

Plant Economic Considerations

Detailed analysis is needed to determine the cooling method that should be installed in a project. The choices are usually limited to either centrifugal refrigeration or absorption chilled-water machines, although recent developments have made screw chillers more relevant for use in tall buildings. Centrifugal machines can be electric drive or steam drive; screw machines are available only with electric motor drives, and both are almost always water-cooled. The absorption machines can be single- or double-effect, but the latter require high-pressure steam to achieve their lower energy costs. High-pressure steam is rare in today's commercial projects unless the steam is available from a central utility.

Air-cooled refrigeration machines have been installed in tall buildings, but infrequently: commercially available sizes of air-cooled refrigeration equipment are limited, and space requirements

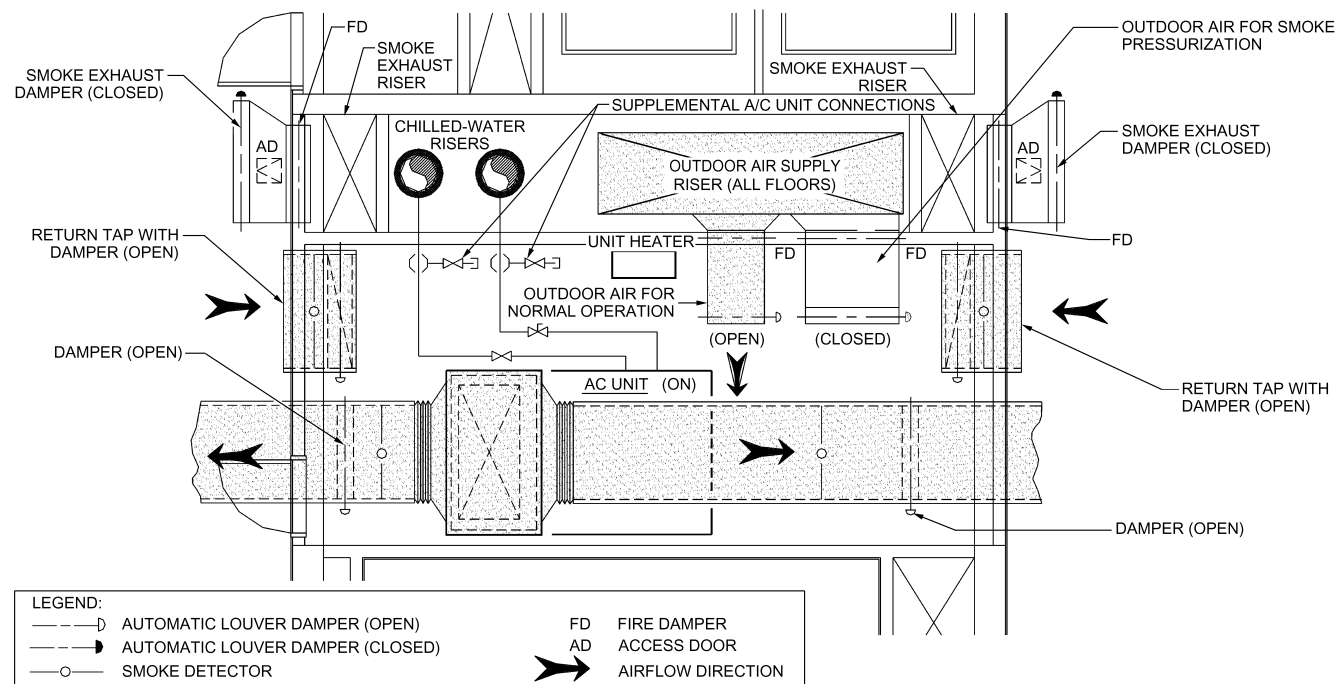


Fig. 14 Floor-By-Floor Air Conditioning Unit Layout (Normal Operation)
(Adapted from Ross 2004)

Table 9 Comparison of Construction Alternatives

Alternative 1	Alternative 2	Alternative 3
Central Fan Systems Central Chilled Water	Floor-by-Floor Fan Systems Central Chilled Water	Floor-by-Floor DX Systems Central Cooling Tower
First-Cost Considerations		
HVAC		
Fewer units, field erected.	More units, factory-fabricated and assembled.	More units, factory-fabricated and assembled.
More complex and expensive duct systems.	Simpler ductwork.	Simpler ductwork.
More complex field-installed controls.	Field-installed control system.	Factory-installed control system.
Central chilled-water plant.	Central chilled-water plant.	No central chilled-water plant; cooling tower only.
Building Management System		
Complex controls and interface with building management system (BMS) and smoke control system.	Controls are relatively simple but field installed. Interface with BMS and smoke control system less complex.	Unit controls provided by manufacturer. Interface with BMS and smoke control system simple.
Electrical		
Electrical loads concentrated in central location. Probably lowest electrical cost.	Minor cost premium for distributed fan motors. Probably higher electrical cost than alternative 1.	Additional cost for electrical distribution to local DX units. Highest electrical cost.
General Construction		
Additional gross floor space needed. No separate outdoor air or smoke exhaust shaft.	Additional cost of sound treatment of local floor-by-floor fan room. Need separate outdoor air and smoke exhaust shaft.	Additional cost of sound treatment of local floor-by-floor fan room. Need separate outdoor air and smoke exhaust shaft.
Construction Schedule		
General Complexity of Installation		
Central mechanical equipment room space and complex construction technology for both chiller plant and fan systems locations. Requires piping of a major chiller plant. Chiller plant location critical to construction schedule. Heavier slab construction at central mechanical equipment room. Extensive complex ductwork in central mechanical equipment room.	Chiller plant space is required, with need for more complex construction technology. Requires piping a major chiller plant. Chiller plant location critical to construction schedule. Heavier slab construction for chiller plant only. Limited ductwork, repetitive fan room arrangement on each floor.	Areas that contain complex construction technology are limited. No major chiller plant. Cooling tower only. Chiller plant is not required. Very limited special slab construction. Limited ductwork, repetitive fan room arrangement on each floor.
Owner Issues		
Marketing/Electric Metering		
Tenant lights and small power can be metered directly. Fan energy and chiller plant energy, as well as heating energy, operating costs are allocated unless heating is by electric resistance heat. Other common building operating costs are allocated.	Tenant lights, small power, and fan energy can be metered directly for any floor with a single tenant. Multitenanted floors require allocation of fan energy only. Chiller plant energy, as well as heating energy, operating costs are allocated unless heating is by electric resistance heat. Other common building operating costs are allocated.	Tenant lights, small power, fan, and cooling energy can all be metered for any floor with a single tenant. Multitenanted floors require allocation of fan energy and cooling energy only. Heating energy operating cost must be allocated unless heating is by electric resistance heat. Other common building operating costs are allocated.
Operating Costs		
For normal operating day, operating costs for all floors occupied are lower than alternative 3. Approximately equal to alternative 2. Overtime operation requires the chiller plant to operate in the summer. With variable-speed fan control and headered supply and return fans, energy costs equal to alternative 2. Operation more cumbersome. Fan and chiller plant costs must be allocated.	For summer operating day, operating costs for all floors occupied are lower because of lower energy consumption than alternative 3. Approximately equal to alternative 1. Overtime operation requires chiller plant to operate in summer but otherwise is simple. Chiller plant cost must be allocated.	For the summer operating day, operating costs for all floors occupied are higher due to higher energy consumption than alternatives 1 or 2 because of less efficient DX compressors. Overtime operation simplest but probably higher in cost than alternatives 1 or 2. Single-floor tenant cost for cooling tower only must be allocated.
Equipment Issues		
Equipment Maintenance		
All equipment is installed in central mechanical equipment room with centralized maintenance.	Requires more maintenance than alternative 1 but less than alternative 3, because of larger number of units with filters, motors, fan drives, bearings, etc. Chiller is in central mechanical equipment room, allowing centralized maintenance.	Requires more maintenance than alternatives 1 or 2 because of larger number of units with filters, motors, fan drives, bearings, etc., plus compressor equipment on each floor.

Table 9 Comparison of Construction Alternatives (Continued)

Alternative 1	Alternative 2	Alternative 3
Equipment Redundancy and Flexibility		
Can operate in reduced mode in case of limited failure due to headered fan arrangement. Can handle changing cooling loads and/or uneven cooling loads on a floor-by-floor basis within limits. Can usually turn down system operation to supply air to a single floor.	If unit fails, floor is without air conditioning. Cannot handle changing cooling loads or uneven cooling loads on a floor-to-floor basis without building in additional system capacity at design.	If unit fails, floor is without air conditioning. Cannot handle changing cooling loads or uneven cooling loads on a floor-to-floor basis without building in additional system capacity at design.
Equipment Life Expectancy		
Life expectancy of equipment is in excess of 25 years.	Life expectancy of equipment is in excess of 25 years.	Compressor life expectancy is probably approximately 10 years. Remainder of installation life expectancy is in excess of 25 years.
Architectural Issues		
Building Massing		
Central fan rooms usually require two-story MER.	Local fan room fits within floor-to-floor height of the office floor.	Local fan room fits within floor-to-floor height of the office floor.
Chiller plant room usually requires two-story MER.	Chiller plant room usually requires two-story MER.	No central chiller plant room required.
Usable Area		
Takes the least area per office floor.	Takes a greater area per floor.	Takes a greater area per floor.
Maximum usable area per office floor.	Less usable area per office floor than alternative 1.	Less usable area per office floor than alternative 1.
Gross Area		
Takes more gross building area than alternatives 2 or 3.	Takes more gross building area than alternative 3 but less than alternative 1.	Takes less gross building area than alternatives 1 or 2.

are comparatively excessive. The largest air-cooled refrigeration machine that currently can be purchased this time is approximately 400 tons. Tall buildings, by nature, are typically large, and the number of air-cooled refrigeration machines and relatively large equipment space that would be required usually make air cooling not viable. In addition, air-cooled equipment's operating costs may be higher because of higher condensing temperatures developed by the refrigeration equipment caused by outdoor dry-bulb temperatures that are higher than the coincident wet-bulb temperature. Water-cooled equipment's refrigerant condensing temperature, on the other hand, is driven by the lower outdoor air wet-bulb temperature. This operating cost difference exists even though there is no cooling tower fan or condenser water pump.

Air-cooled equipment may, however, find application in tall buildings where water for cooling tower makeup either is not available or is prohibitively expensive.

For tall buildings that do not use electric resistance heat, the fuel-fired heating plant includes boilers fired by oil or gas, by both fuels (with oil as a standby fuel), or by electricity. These boilers provide hydronic heat and low-pressure steam for distribution to spaces in the building, or act as supplements to heat pumps or heat recovery systems. Choosing the correct solution for a building is subject to an economic analysis that considers space requirements, first cost, and operating expense.

Central Plant Location

Further complicating the energy transfer source decision is the location of the equipment within the building. This affects structural costs, architectural design, construction time, and availability of cooling or heating relative to the initial occupancy schedule. A below-grade location could potentially provide early heating availability, but also could complicate the design process and result in higher overall project costs. Locating cooling and heating plants on floors above grade, up to and including space immediately below the roof, is common and may be desirable for simplicity of construction and ease of providing the necessary ventilation air and

other services to the equipment. Moreover, the two types of plants need not be installed at the same level in the building, because there is usually no direct interconnection of the two plants.

Virtually any location in a tall building can be used for the heating and cooling equipment. When choosing the location, consider the following:

- If a boiler is installed above grade, fuel (i.e., oil, gas, electricity) must be brought to the boiler and a flue and combustion air, in the case of a fuel-fired boiler, must be taken from the boiler to atmosphere.
- Boiler plant location should be determined by analysis following previously outlined parameters.
- Regardless of where it is installed, the design must include appropriate acoustical design considerations and vibration isolation.

Considerations for the refrigeration plant location are more complex. Not only must electricity, gas, oil, or steam be brought to the machine to operate the equipment, but chilled and condenser water also must be pumped from the refrigeration plant to the air-conditioning supply equipment. In addition, the cooling tower and the working pressure of the refrigeration machines, piping, fittings, and valves must be reviewed based on the static height of liquid above this equipment, as discussed in Ross (2004) and Chapter 40 of the 2012 *ASHRAE Handbook—HVAC Systems and Equipment*.

Because of the world trend of increasing building height and because tall buildings tend to be mixed use, split chiller and boiler plants are becoming more common: part of the heating and cooling production plant is located at the top part of the building, and part at the basement. The reason for this split is to limit pressure on both halves of the plant distribution systems.

In addition, installing a cogeneration or trigeneration plant in tall buildings to meet green and sustainability initiatives is becoming popular. These facilities use engine or turbine driven generators to deliver electricity to the building and generate either chilled water through absorption chilling and/or heating water.

Acoustical Considerations of Central Plant Locations

Acoustics and vibration also are key considerations during architectural, structural, and mechanical design. The HVAC designer and project acoustician should place mechanical equipment to achieve the desired acoustical levels in spaces above, below, or adjacent to the central plant. Achieving the proper solution involves understanding the characteristics of sound generated by the equipment and the various paths (e.g., through floors, ceilings, walls, building structure) for transmission of that noise and vibration to occupied areas of the building.

Regardless of the type of equipment being installed on a project, it is prudent to specify a maximum permissible sound level for equipment. Sound and vibration generation, transmission, and correction are discussed in [Chapter 48](#) in this volume and in Chapter 8 of the 2013 *ASHRAE Handbook—Fundamentals*.

Effect of Central Plant Location on Construction Schedule

The locations of the boiler and chiller plant also affect the construction schedule. This concern is especially critical for the refrigeration plant, which is a complex installation that involves a significant amount of labor because of the need to complete the chilled-water, condenser water, and possible steam piping as well as provide for the electrical capacity requirements of the machines. The heaviest piping and most difficult installation process for piping in the building occur at the refrigeration plant. As a result, if the refrigeration plant is on the uppermost level of the building, installation of the machines and their associated piping can delay the overall schedule. Accordingly, if the refrigeration equipment cannot be installed in the below-grade level because that space has other priorities (e.g., parking, storage), the refrigeration plant may be best located above the lobby level and below the uppermost levels of the building.

8. WATER DISTRIBUTION SYSTEMS

Water distribution systems for a tall building require special consideration, primarily because the building height creates high static pressure on the piping system. This pressure can affect the design of the piping systems, including domestic water and sprinkler piping systems. This section addresses chilled-, hot-, and condenser water systems.

The chilled- and hot-water systems are always closed systems (i.e., pumped fluid is not exposed to the atmosphere), whereas the condenser water system is usually open. Closed systems contain an expansion tank, which can be either open or closed. An open expansion tank is located at the highest point of the piping system and is open to atmosphere; the exposed surface area of the water in the open tank is insignificant and the system is still considered closed.

In an open system, the pumped fluid is exposed to atmospheric pressure at one or more points in the piping system. The condenser water piping distribution system is typically considered open because the water is exposed to atmosphere by the clean break in the piping at the open cooling tower.

As stated in Chapter 13 of the 2012 *ASHRAE Handbook—HVAC Systems and Equipment*, “one major difference in hydraulics between open and closed systems is that some hydraulic characteristics of open systems cannot occur in closed systems. For example, in contrast to the hydraulics of an open system, in a closed system (1) flow cannot be motivated by static head differences, (2) pumps do not provide static lift, and (3) the entire piping system is always filled with water.”

If an evaporative cooler or dry cooler (commonly called an industrial fluid cooler) were used for the condenser water rather than a cooling tower, the piping system would be closed rather than open. Using evaporative or dry coolers for an entire large commercial

office building is extremely rare. However, they are used in portions of tall buildings to handle the heat of rejection from supplemental cooling systems that may be required for spaces or equipment that require additional cooling capacity.

Hydrostatic Considerations

A major consideration in piping system design for a tall building is the hydrostatic pressure created by the height of the building. This hydrostatic pressure affects not only the piping and its associated valves and fittings, but also equipment in the building; in the chilled-water system, this includes refrigeration machines, casings for chilled-water pumps, cooling coils in air-conditioning systems, heat exchangers, and any fan-coil units at the exterior wall of the building. A similar list of devices beyond piping, valves, and fittings can be developed for other pumped systems such as the condenser water or any hot-water system.

Dynamic pressures created by the pumps also must be added to the static pressure to determine the working pressure on any element in the piping system. This dynamic pressure is the total of the following elements:

- Friction loss through piping, valves, and fittings
- Residual pressure required at the most remote piece of heat transfer equipment for its proper operation (includes pressure loss through the equipment's control valve as well as drop through the equipment itself)
- Any excess pressure caused by pumps operating at reduced flow close to their shutoff pressure

The working pressure of the piping and connected equipment at various elevations in the building must be known. This is found by adding the hydrostatic pressure at the specific location to the dynamic pressure that can be developed by the pumps at that location. The dynamic pressure at any point should include the pump pressure at or close to pump shutoff at full speed, even if variable-speed pumps are used, because it is possible for the pumps to operate at this shutoff point in the event of a VFD failure. This working pressure on piping and equipment invariably lessens as the static pressure at a specific location is reduced.

The trend of ever-greater height makes piping system hydrostatic pressure zoning design very important for both technical and economical reasons. Check the pressure rating of all major air-conditioning equipment to confirm whether the required pressure-rated equipment is economically available in the market.

Effect of Refrigeration Machine Location

The level on which the refrigeration machines and the supporting chilled- and condenser water pumps are located in a building can affect the cost of refrigeration equipment, the pumps, the piping, and the fittings and valves associated with the piping. There is economic impact because of the working pressure to which the equipment, piping, fittings and valves will be subjected by the height of the system above.

[Figure 15](#) shows the effects of three alternative chiller locations in a 70-story, 900 ft tall building: at basement level, a mid-level mechanical equipment room, and a mechanical equipment room on the roof. There is an open expansion tank at the top of the building (the highest point in the system) in all three alternatives. If a closed expansion tank is used, the maximum pressure must be established and considered in the determination of the system's working pressure.

The working pressure on equipment or piping, valves, and fittings at any location in a building is the sum of the hydrostatic height of the water in the piping above the point being considered plus the dynamic pressure created by the pump at the point being analyzed. The hydrostatic and dynamic pressures are determined in feet of water. Their sum, when added together, is the total pressure or working pressure in feet at the referenced point. To determine the working pressure in psig, divide the total pressure in feet by 2.31.

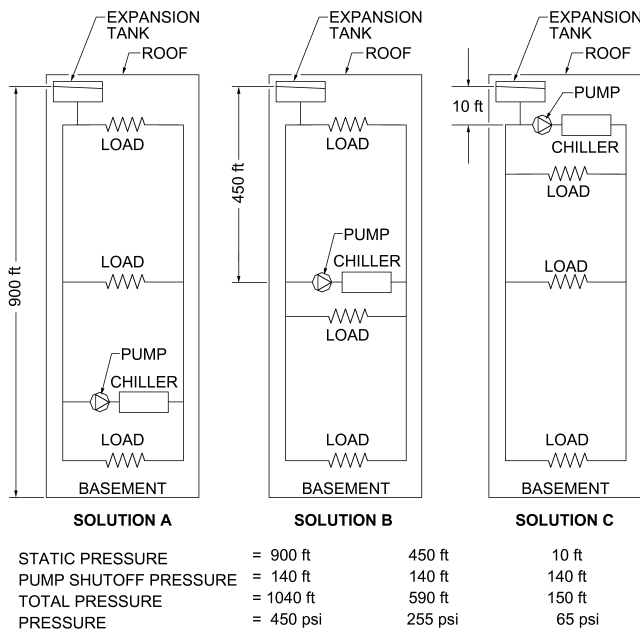


Fig. 15 Chiller Location Versus Working Pressure in 70-Story, 900 ft Building
(Adapted from Ross 2004)

For example, in solution A shown in Figure 16, the vertical height of the column of water above the refrigeration machine is 900 ft. The pump delivering water through the machines has a maximum shutoff pressure of 140 ft. The total pressure is therefore the sum of these two pressures, or 1040 ft or 450 psig.

Calculations for alternative refrigeration plant locations (at mid-level and top of the building) are also shown in Figure 16. Working pressure on the refrigeration equipment at the midlevel of the building is 255 psig, and at the top of the building is 65 psig.

The standard working pressure for coolers and condensers on large refrigeration machines from all of the major manufacturers in the United States is 150 psig. These machines can be manufactured for any working pressure above 150 psig for additional cost. The incremental increase in the cost of a given vessel becomes larger with each unit of increase in the working pressure. Accordingly, it is necessary for the HVAC design engineer to accurately determine and separately specify the working pressure on both the cooler and the condenser of the refrigeration machines.

Working pressure on the refrigeration machine can be reduced by locating the chilled-water pump on the discharge side rather than the suction side. If this is done, the residual pump pressure on the refrigeration machine water boxes is reduced to the sum of the hydrostatic pressure and this nominal value of dynamic pressure from the pumps. This can reduce the cost of the refrigeration machines, but does not alter the pressure on the pump casing and flanges, which must still be the sum of the static and dynamic pressures.

Chilled-Water Pressure Reduction

Pressure on (and cost of) refrigeration equipment can be reduced by locating it above the basement; this, however, will not alter the maximum pressure experienced by the pipe, fittings, and valves at any location that is used. It is possible, however, to reduce the chilled-water working pressure on both the machines and piping by using plate-and-frame heat exchangers, which segregate groups of floors into separate static pressure zones.

In the 900 ft tall example building with the refrigeration machine in the basement, it is possible to break the chilled-water system into three separate zones (Figure 16).

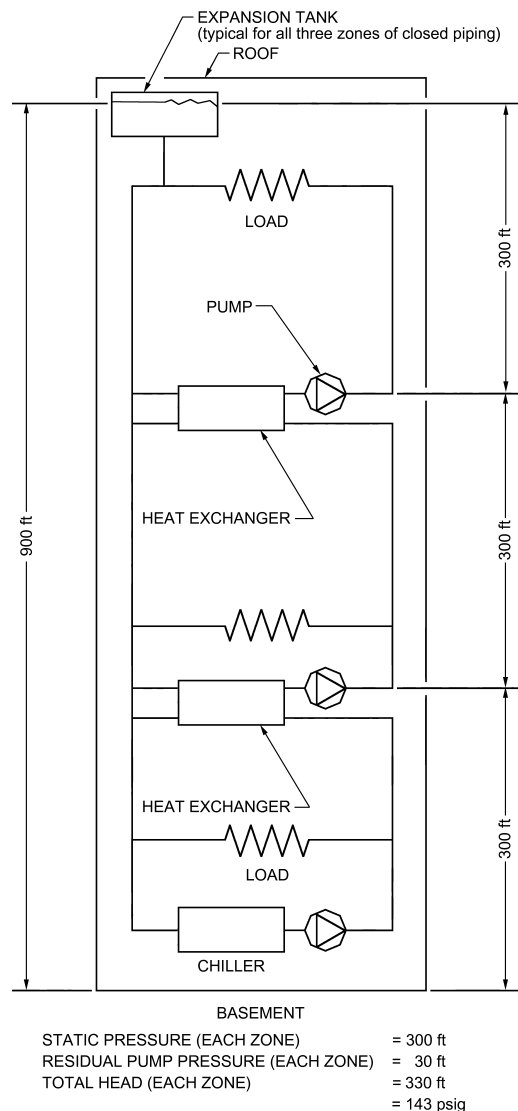


Fig. 16 Zoned Chilled Water for 70-Story, 900 ft Building
(Adapted from Ross 2004)

Each zone has static pressure of one-third of the total building height, or 300 ft. All of the pumps are located on the discharge side of the refrigeration machines or the secondary zone heat exchangers. The result is that the maximum head of each zone is 143 psig, which is below the threshold design pressure of 150 psig, or the point at which an increased pressure rating for the chiller and other heat transfer equipment must be considered.

The working pressure of the primary chilled-water pump in the basement will not change substantively from that required where no secondary systems were included, because the primary chilled-water pump must now overcome the loss through the flat-plate heat exchanger. In addition, motor-driven pumps are added at each secondary water heat exchanger. Finally, with the addition of the two additional zones and the resultant chilled-water temperature increase, there is a requisite increase in the volume of water flowing through the systems on the upper floors. Accordingly, although there are benefits in the reduction in pressure, there are partially offsetting considerations that must be analyzed to determine the overall cost effectiveness of using flat-plate heat exchangers to reduce the operating pressure on the equipment, pipe, valves, and fittings at a given level.

Use of flat-plate heat exchangers and their location in a chilled-water piping system is subject to an economic analysis by the design HVAC engineer to determine the first cost of alternative arrangements as well as the operating cost differentials, if any, for any scheme.

Using a flat-plate heat exchanger to reduce the working pressure on the condenser, although feasible, is not often considered, because the condenser water piping is usually in a single shaft with minimal (if any) offsets and a resultant small number of fittings. Valves are also only installed at the machines and are few in number. This limited number of fittings and valves may not be sufficient to offset the cost of the flat-plate heat exchanger and its valving as well as the added pump on the secondary side of the heat exchanger. Beyond that, there is an increase in the temperature of the condenser water, which increases the cost of operating the refrigeration machines.

Piping, Valves, and Fittings

The working pressure on the piping, valves, and fittings at various levels in a building must be determined so that proper piping material can be specified. In the United States, with steel pipe, Schedule 40 pipe is the standard wall thickness for pipes up to 10 in. diameter. For pipes 12 in. and larger, the pipe standard that is used has a wall thickness of 0.375 in. Either of these standards would accommodate the working pressures experienced in any expected pipe diameter in any tall building. The allowable pressures for various pipe diameters can be found in ASME *Standard A17.1* and the *Boiler and Pressure Vessel Code* (ASME 2013) and in the publications of various pipe manufacturers. The valves used should be reviewed in the valve manufacturers' literature to ensure their ability to meet the project's requirements.

For steam condensate piping or for condenser water piping, where corrosion is a possible concern, pipe with a heavier wall thickness should be considered, although not because of the working pressure on either system.

Piping materials other than steel are often used. For pipe sizes below about 4 in., in the cases of runouts or in open condenser water piping where corrosion is a concern, copper is the usual choice. Copper pipe is rare, but copper tubing is common. The limiting factor in the use of copper tubing is usually at the joints, where the ability to handle higher working pressure is restricted.

Piping Design Considerations

The design of piping must also consider other factors, including

- Expansion and contraction in the piping and its static and dynamic loads, because they are reflected in the structural steel framing system of the building
- Access to expansion joints and the anchors and guides for the piping, which should be inspected periodically after the building is constructed
- Firestopping between the pipe and the sleeve located at all penetrations of rated slabs, walls, and partitions
- Seismic restraints (if required) on the piping systems and pumps

In addition to expansion and contraction of the piping caused by changes in the ambient temperature or of the pumped fluid in the piping, frame shortening can be a problem in concrete buildings. Concrete shrinks as it cures: over time, this shortening can be in the range of 1/8 in. per floor. Although this movement is relatively small, it amounts to about 9 in. for a 70-story building. This condition requires that pipes above, below, and between anchor points be flexible enough to allow for pipe movement with respect to the structure. To properly design for this condition, the HVAC designer should obtain from the structural engineer the exact amount of movement that the piping system can experience.

Economics of Temperature Differentials

Traditionally, rules of thumb for selecting refrigeration machines in the United States have used a 10 or 12°F temperature differential between entering and leaving water in the chiller and a 10°F differential or 3 gpm per ton of capacity for the condenser. These guidelines are appropriate for small buildings, because they have little effect on project cost, but may be less ideal for large buildings, particularly tall buildings. In projects of this type, the capital costs of piping, valves, and fittings can be substantially reduced, with a possible penalty in refrigeration machine operating cost, by using larger temperature differentials with lower water flow and a consequent reduction in piping diameter.

For a large project with a total cooling capacity requirement of 4000 tons and chilled-water flow at a 10°F temperature differential, 9600 gpm is circulated through 20 in. piping at approximately 10 fps. If a 16°F temperature differential is used, total flow from the refrigeration plant is 6000 gpm and the piping is 16 in. Cost savings on the piping using the greater temperature differential would be significant. Also, although the kilowatts per unit of cooling under both conditions should be studied, with the same discharge temperature, the operating energy consumption probably is unchanged.

For the 4000 ton refrigeration plant with a 10°F differential, the condenser water flow is 12,000 gpm and 24 in. piping is required. If this temperature differential were increased to 15°F, condenser water would be reduced to 8000 gpm, and the piping to 20 in. Again, this change results in a significant first-cost savings, depending on the distance between the refrigeration machines and the cooling towers.

Energy consumption for the refrigeration machines might marginally increase, because the condensing temperature of the refrigerant and the resultant energy usage is largely (but not solely) a function of the leaving condenser water temperature.

9. VERTICAL TRANSPORTATION

The HVAC designer's main involvement with elevators in a tall building is to provide cooling in the elevator machine room to ensure reliable operation. Many codes now require that this machine room be conditioned by a separate HVAC system that is independent of other building systems. This section addresses the possible code requirement of elevator shaft and machine room ventilation to atmosphere.

Elevator Machine Room Cooling

The elevator machine room's cooling loads consist not only of the electric motor that drives the hoisting mechanism but also of extensive heat-generating electronic elevator controls. The electronic components that are part of the system require that the elevator machine room be maintained at a temperature between 80 and 60°F. This can be accomplished by means of a packaged DX condenser water-cooled unit in the elevator machine room; however, because of possible significant operational availability restrictions on the use of water in the machine room, the HVAC designer should review this alternative with the building developer and possibly code officials. Using a packaged DX condenser water unit may be necessary for a low- or mid-rise elevator bank with its machine room in the middle of the building, without easy access to outdoor air unless the remainder of the floor is used as a mechanical equipment room. At the top of the building, the cooling equipment can be air cooled.

The ultimate size of DX units is determined by information provided by the elevator manufacturer. The elevator consultant can provide the necessary general information to allow the design to proceed through bidding. The amount of cooling for this equipment can be significant: as much as 10 to 15 tons for a single elevator equipment room.

Elevator Hoistway and Machine Room Venting

All elevators installed in the United States must conform to ASME *Standard* A17.1, as modified by local authority and applicable building code. One requirement of many codes is to include a vent opening at the top of each elevator shaft that is 3.5% of the plan area of the hoistway or 3 ft² per elevator, whichever is greater. The purpose of this requirement is to allow venting of smoke during a building fire. To accomplish this, a duct must be provided from the vent to atmosphere. This is simple at the top of the building, but for low- and mid-rise elevators, where the elevator equipment room is not located in a mechanical room with perimeter access, extending the connecting duct to atmosphere may be difficult.

Under many codes, including the model *International Building Code*® [IBC (ICC 2012)], for a building that is fully sprinklered, the need for the vent and its extension to atmosphere may be waived for passenger elevators, except for buildings where there is overnight sleeping (e.g., hotels, residences). The vent is typically still required for a dedicated service elevator car.

In addition, under the IBC, the vent may be closed under normal building operating conditions by including an automatic damper in the atmospheric vent or, under some code jurisdictions, by installing a piece of glass that will break in a fire. This damper must open on detection of smoke by any of the elevator lobby smoke detectors. Dampers have a distinct advantage in that they are manually and remotely resettable.

Where elevator speeds are greater than 1400 fpm, vents at the bottom of the shafts may be required by code to allow rapid escape of air when the high-speed car is descending.

Elevator Shaft Pressurization

In super- and megatall buildings, express (or shuttle) elevators are provided to quickly carry occupants to upper-level occupancies, typically in hotels or residential uses. These elevators are commonly used as evacuation elevators in emergency situations. To maintain the safety of these elevators for this use, the elevator shaft(s) should be pressurized to keep the shaft and cars free of smoke. Refer to the section on Smoke Management for more details.

Air-Conditioning Equipment Delivery by Freight Elevators

If part of the chilled-water or boiler plant is located in the top zone of the supertall buildings, the freight elevator should have sufficient capacity and cab size to deliver and transfer all major equipment from the ground level to the area where the upper plant is located, to aid in maintenance of the equipment located there.

10. LIFE SAFETY IN TALL BUILDINGS

Life safety challenges for tall buildings are similar to those of shorter high-rise buildings. It is impractical to rely on stairs as the means of egress to grade. Elevators should play a major role in safe evacuation of occupants and response of emergency forces. Areas or floors of refuge are needed to provide staging points for occupants evacuating and emergency forces responding. Codes have developed means to confront this challenge. The following provides a brief review of those life safety measures.

Codes and Standards

In the United States, the *International Building Code*® (IBC) is the predominant building code; in Canada, it is the *National Building Code of Canada* (NRC 2005). The National Fire Protection Association's (NFPA) *Standard* 5000 generally incorporates NFPA *Standard* 101. These codes do not define a "tall building," but have additional requirements for a high-rise building greater than or equal to 420 ft in height.

Components of Life Safety Systems for Tall Buildings

Tall buildings share many of the code requirements of other high-rise buildings. The IBC (ICC 2012) defines a high-rise building as "a building with an occupied floor located more than 75 ft above the lowest level of fire department vehicle access." Additional requirements are imposed for buildings 120 and 420 ft above grade. No specific definition of "tall building" is contained in the codes.

Key fire safety provisions for tall buildings should include the following:

- Smoke detection for elevator lobbies, elevator machine rooms, and HVAC systems
- Complete automatic sprinkler protection
- Fire standpipe system
- Smoke management system for enclosed exits, stairs, elevators, and areas or floors of refuge
- Emergency power for life safety systems
- Fire department or first-responder elevator
- Redundant exit stair or elevator emergency evacuation provisions
- Area or floor of refuge
- Fire command center

Detection

Automatic smoke detection should be provided in elevator lobbies, elevator machine rooms, mechanical and electrical equipment rooms, and any other spaces not provided with automatic sprinklers. The detection system should be connected to the automatic fire alarm system. Duct smoke detectors should be provided in the main return air and exhaust air plenum of each air-conditioning system with a capacity greater than 2000 cfm. Duct smoke detectors are also needed at each connection to a vertical duct or riser serving two or more floors from a return air duct or plenum.

The smoke detection system should be designed in accordance with NFPA *Standard* 72.

Residential buildings should have smoke alarms in each room used for sleeping purposes and on the ceiling or wall outside of each separate sleeping area. The smoke alarms should be interconnected so that activation of any smoke alarm in the dwelling unit activates all of the smoke alarms in that unit. This does not require activating smoke alarms in other apartments in the building.

Automatic Sprinkler Protection

Complete automatic sprinkler protection should be provided in accordance with NFPA *Standard* 13.

Standpipe System

Standpipe systems should be provided in accordance with NFPA *Standard* 14.

Smoke Management

The essential features of smoke management design are described in [Chapter 53](#). Additional information is contained in NFPA *Standard* 92A.

The IBC requires exit stairs to be smoke protected. One way to achieve this is with a smokeproof tower of pressurized stairs. To enhance egress for buildings 420 ft high or more, the codes require either an additional exit stairway beyond those required by the typical exit calculations, or pressurization of the elevator shafts. To prevent smoke spread through the elevator without elevator shaft pressurization, elevator vestibules with a minimum 1 h fire resistance rating are required.

Codes also require an elevator for use by emergency responders, with access from a vestibule directly connected to an egress stair.

Elevators to be used for occupants in an emergency require special protection, including pressurized elevator shafts, an emergency voice/alarm communication system, elevator lobbies with direct

access to a exit enclosure, and a means to protect the elevator from automatic sprinkler system water infiltrating the hoistway enclosure. Automatic sprinklers are prohibited from the elevator machine room, and shunt trips for elevators shutdown should not be provided.

Emergency Power

All life safety systems are required to have standby power designed and installed in accordance with NFPA *Standards* 110 and 111, as appropriate.

Fire Command Center

A fire command center is required in a protected location at or near grade to monitor all fire safety and emergency systems. It should also have controls for the smoke management system and emergency power system.

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