Compartmentation and Dampers Are Essential

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In 1939, a landmark study was issued by the National Board of Fire Underwriters (NBFU) concerning the smoke hazards due to HVAC systems.[1] Based on examination of NFPA fire data from January 1936 to April 1938, the study recommended that during a building fire the HVAC fans be shut down and dampers in the HVAC system should close to interrupt the passage of smoke, flame and heat.

In subsequent years, these recommendations formed the basis of code requirements for HVAC systems during a fire. With the exception of engineered smoke control systems, HVAC fan shutdown is now common practice. For the NBFU study, the justification of the recommendations was property protection. Today, life safety has become the major reason to interrupt the passage of smoke, flame, and heat in HVAC systems.

A fire damper is a device, installed in an HVAC system, that closes automatically upon detection of heat to interrupt the airflow and restrict the passage of heat in accordance with Underwriters Laboratories (UL) Standard UL 555. A smoke damper is a device installed in an HVAC system to control the movement of smoke in accordance with the UL 555S Standard. Combination fire and smoke dampers meet the requirements of both. This article shows that, even with the considerable advances in sprinkler technology, these dampers are still needed to prevent smoke movement through the HVAC systems to locations remote from the fire.

Smoke Movement

While we most commonly think of smoke as rising during building fires, smoke flow is a complex process resulting in horizontal and even downward flow. This complexity is due to the forces that can move smoke through the many flow paths in buildings. These flow paths include shafts, holes in floors, holes in walls, gaps around doors, and HVAC ductwork *without* smoke dampers. A detailed description of the forces of smoke movement including mathematics is presented by Klote and Milke.[2] The forces of smoke movement include buoyancy of combustion gases, expansion of combustion gases, elevator piston effect, HVAC fans, stack effect, and wind effect.

Wind Effect: Wind can have a pronounced effect on smoke movement. Over most types of terrain, wind velocity increases with elevation. In cities, structures can block wind flow, and the wind can have eddies and various secondary flows. Because of the complexity of wind patterns in cities, prediction of smoke movement due to wind effects requires computer modeling based on reliable information about local wind patterns. Further, local wind patterns in cities are virtually impossible to predict, except by wind tunnel tests. For a few projects, the wind tunnel test data needed for the structural engineering analysis has been used for smoke control system design calculations. It can be stated that an open window, broken window or other opening on the windward side of a building will result in smoke being forced to locations remote from the fire.

Stack Effect: When it is cold outside, there is frequently an upward movement of air within building shafts. These shafts include stairwells, elevator shafts, mechanical shafts, and vertical HVAC ducts when the fans are shut down. Air in the building and the shafts is warmer than the outside air. The buoyant force of the warm air causes it to rise in the building shafts. Because this phenomenon is like upward smoke flow in a chimney or smoke stack, it is called *stack effect*. However, when it is hot outside, a downward airflow can occur in air-conditioned buildings, because the inside air is colder than the outside air. Sometimes this downward airflow is called *reverse stack effect*.

The theory of stack effect is well developed and has been proven by experiments. *Figure 1a* shows the airflows resulting from stack effect. In the lower part of the building, outside air flows into the building and into building shafts. The air flows up the shafts. On the upper floors of the building, air flows out of the shafts, through the building and to the outside. This flow results from pressure differences. There is a height where there are no pressure differences and no flows, and this height is called the *neutral plane* as shown in *Figure 1a*.

Smoke movement from a building fire can be dominated by stack effect. When there is stack effect, the smoke from a fire below the neutral plane moves with the building airflow into the shafts, up the shafts, and onto the upper floors of the building as shown in *Figure 1b*. The upward flow is often enhanced by the buoyancy of the hot smoke. The forces of stack effect can also force smoke through construction gaps and other holes in the floors resulting in smoke on some of the floors above the fire floor.

For a fire above the neutral plane, sometimes pressure differences due to the stack effect are sufficient to keep smoke out of the shafts, and smoke only flows through construction gaps and other holes in the floors

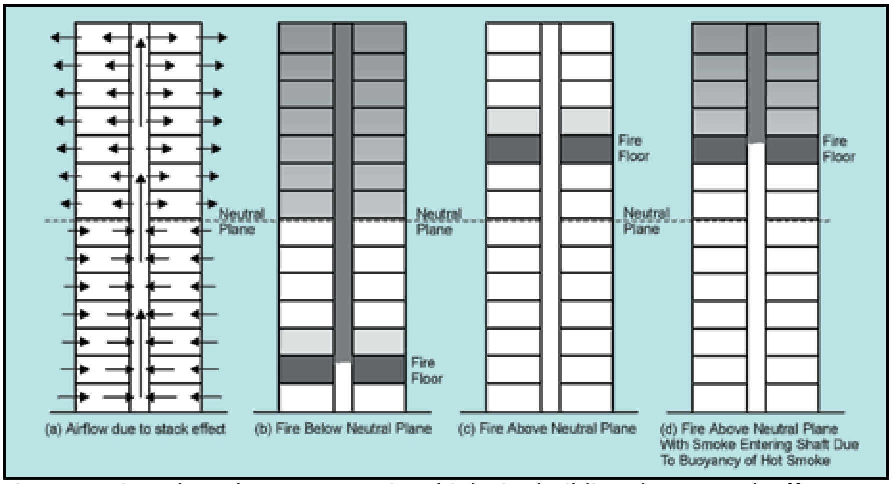

Figure 1: Air and smoke movement in a high-rise building due to stack effect.

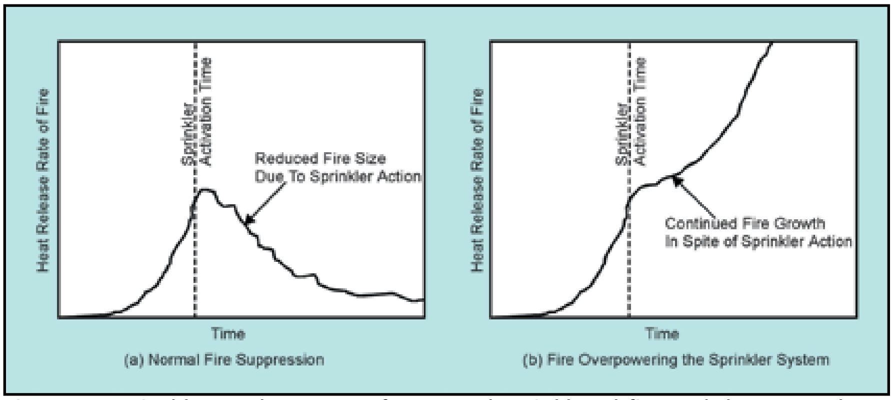

Figure 2: Typical heat release rates for normal sprinklered fire and the unusual case of a fire overpowering the sprinkler system.

as shown in *Figure 1c*. However, the airflow due to stack effect may not be sufficient to prevent smoke from flowing into shafts, and this condition can result in smoke flow into the shafts and onto upper floors as shown in *Figure 1d*.

The previous discussion describes smoke flow that is caused only by stack effect. The presence of other forces of smoke movement can significantly alter smoke flow. Smoke dampers can virtually eliminate smoke movement through HVAC ducts. Because the other forces of smoke movement can result in totally different smoke flow patterns, the neutral plane can be far from the building mid-height or there may be no neutral plane. Thus, smoke dampers are needed at each floor to prevent smoke migration through HVAC ducts.

Smoke Flow Through the HVAC System

As already stated, HVAC system shutdown is common in the event of fire. Dampers are needed to prevent smoke movement through HVAC ducts to locations remote from the fire. When the fans are off, the forces of smoke movement discussed previously will drive smoke through ducts unless smoke dampers are used to stop smoke flow. While we usually think of vertical smoke flow in ducts, research at the U.S. National Institute of Standards and Technology (NIST) showed that the flow can also be horizontal.[3] The forces of smoke movement discussed earlier can cause significant smoke flow in buildings of any height. When fan shutdown fails, dampers can reduce the extent to which the HVAC system can force smoke to locations far from the fire.

Without dampers, significant amounts of smoke can move through ducts to locations far from the fire—endangering life and damaging property. As explained later, significant amounts of smoke can be produced in both sprinklered and non-sprinklered buildings. For these reasons, smoke dampers are needed in the HVAC ducts.

Compartmentation

Compartmentation has a long history of providing protection from the passage of heat, flame and smoke. The protection from the passage of heat and flame is called fire resistance and is well known and implemented by use of walls, floor-ceiling assemblies, doors, dampers, and other building elements with fire resistance ratings of ½ hour, 1 hour, 2 hours, and so on.

While the smoke-resistant capabilities of compartmentation have been relied on for hundreds of years, little has been done to formally analyze and specify passive smoke resistance. It is common sense that smoke leakage is much less for small construction cracks and gaps around doors than for large openings like open doorways or open stairs. Likewise, smoke leakage is much less for a closed damper than for an open duct. In the last few decades, smoke dampers have been developed specifically with the intent of restricting smoke transport. Smoke barriers are a recent innovation intended to restrict smoke movement.

Sprinklers

Successful sprinkler operation results in controlling or suppressing a fire, and such a controlled fire often continues to burn and produce smoke until the fire burns itself out or it is put out. Hasemi[4] indicates sprinkler success rates in Japan of 98% for well-maintained systems and 96% for poorly maintained systems. For Australia and New Zealand, Marryatt[5] indicates a sprinkler success rate of 99% or greater for most occupancies. In the absence of comprehensive sprinkler performance data for the United States, we may consider that in the U.S. sprinklers have a failure rate between 1% and 4%. Based on NFPA[6] fire data, a 2%

failure rate would result in about 1,100 sprinkler failures in high-rise buildings and about 2,000 sprinkler failures in mid-rise buildings in the U.S. over a decade.

Based on Marryatt and Hasemi's reports, most sprinkler failures can be placed into one or more of the following groups (1) an inadequate or no water supply, (2) failure of one or more sprinkler system components, and (3) a fire overpowering the sprinklers.

Loss of water supply can result from a broken water main. Two causes of broken water mains are earth- moving equipment and earthquakes. Large earthquakes are a special situation, because water is often lost for a large number of buildings and the number of fires can severely tax the capabilities of the fire service. For large fires with many open sprinkler heads and fires in multiple buildings, the pressure in the city main can drop such that the water supply is inadequate.

Sprinkler system component failures include shutting off the sprinkler system and sprinkler head failure. Recent advances in monitoring have reduced the potential of an incorrectly closed valve shutting off water to the sprinklers. However, buildings have been completely lost due to uncontrolled fires that developed when sprinkler systems were shut off during firefighting by someone who may have thought that the fire was completely out. In some arson cases, the arsonists have shut off the sprinkler systems before setting a building fire.

The author has seen sprinkler heads fail to open in large-scale fire tests. In a room protected by only one head, such a head failure can result in a large fire. In March 1998, the U.S. Consumer Product Safety Commission (CPSC) filed a complaint against a sprinkler manufacturer seeking the recall of about 10 million Omega sprinkler heads based on six fires where Omega heads allegedly failed to operate.[7] A somewhat related issue involves the contractor fraud in California of gluing sprinkler heads to the ceiling rather than connecting them to sprinkler pipe.[8]

Fast growing fires, shielded fires and fires starting in unsprinklered spaces can overpower a sprinkler system. The extent to which entire buildings are sprinklered today reduces the potential of fires starting in unsprinklered spaces. Some fires grow so fast that by the time the sprinkler activates, the fire is so large that the sprinkler droplets evaporate before they reach the fire. An example of a shielded fire is high shelving filled with paper records or stuffed animals blocking sprinkler heads of a light hazard sprinkler system. Typically, these overpowering fires happen when the use of the space is inappropriate for the sprinkler system.

Another example would be a food grill fueled by bottled propane added to a hotel lobby. Generally, in the United States, the fire service does not have authority to require fire inspections or require corrective measures of privately owned buildings. Thus, when the materials in a space are inappropriate for the sprinkler system, the occupants often are unaware of the unsafe nature of the situation and the condition continues.

These sprinkler failures represent only a small fraction of sprinkler performance. The sprinkler industry, the fire service and the fire protection community are continually striving to improve sprinkler reliability whenever causes of sprinkler failure become known. In our world of ever-changing organizational functions, materials, construction methods and architectural designs, it is reasonable to expect that new failure situations will arise. For these reasons, sprinklered buildings need other fire protection features to ensure an adequate level of protection in the event of sprinkler failure.

Smoke Production in Sprinklered Fires

While a great deal is still unknown about fire and smoke production, it can be said that the amount of soot particulates and toxic gases produced by fire depend on the size of the fire, the burning conditions and the materials that are burning. In fire science, the size of a fire is usually thought of in terms of a heat release rate (HRR). Burning conditions include the size, shape and orientation of the burning materials, as well as, whether the burning is smoldering, flaming in normal air, or flaming in a smoky reduced oxygen environment.

Mulholland[9] provides methods to estimate the visibility through smoke. If the airborne soot particulates produced by burning an upholstered armchair filled with 9 lbs (4 kg) of polyurethane foam were uniformly distributed throughout an 1,800 ft^2 (167 m^2) apartment, a person would not be able to see his own hand held at arm's length in front of his or her face. The typical apartment has much more in it than just one armchair, and almost all other occupancies also have large amounts of materials that can burn. While the codes have control of construction materials, there is little to stop occupants from bringing whatever materials they want into a building.

Some full-scale fire tests have been done on the effect of sprinkler spray on fires at NIST,[10] the National Research Council of Canada,[11,12,13] and the BHP Laboratory in Australia.[14] From *Figure 2a* it can be seen that when sprinklers successfully suppress a fire, the fire can be expected to continue to burn and produce soot particulates and toxic gases. For the less frequent cases where the fire overpowers the sprinklers, *Figure 2b* shows that the fire continues to grow and can be expected to produce amounts of soot particulates and toxic gases that significantly increase with time.

A 1997 NFPA study,[15] examined the fire data from 1986 to 1995 to evaluate the extent of flame and smoke spread in sprinklered and non-sprinklered buildings. For high-rise buildings, the study showed that 11.4% of fires in sprinklered buildings resulted in smoke damage beyond the fire floor, while 15.4% of fires in non-sprinklered buildings resulted in smoke damage beyond the fire floor. For mid-rise buildings, 15.7% of fires in sprinklered buildings resulted in smoke damage beyond the fire floor, while 34.4% of fires in non-sprinklered buildings resulted in smoke damage beyond the fire floor. The study considered buildings between three and six stories as mid-rise, and buildings seven stories or taller as high-rise. While the study was unable to define the severity of this smoke damage, it is significant that so many fires in sprinklered buildings had smoke damage beyond the fire floor. Information was not available about the extent to which these buildings had dampers, but the presence of dampers may have reduced smoke spread in these fires. If smoke dampers were eliminated in buildings, the spread of smoke during fires almost certainly would increase.

Balanced Design

Traditionally, fire protection has consisted of different systems used together to ensure an adequate level of life safety. A NIST study examined a *balanced design* approach to fire safety evaluating different protective measures for residential, commercial, and institutional facilities.[16] The study looked at the benefits of suppression, detection, and compartmentation alone and in combinations with each other. In general, it can be said that combinations of two of these measures provided better life safety than any one alone, and all three measures together provided the highest life safety.

A balanced design is one that includes fire-safety features that form a total building life-safety system. Buildings should have balanced protection including compartmentation to ensure a level of life-safety protection in the event of sprinkler failure.

Even though sprinklers are highly effective and reliable, total reliance on sprinklers can result in buildings that are unsafe when the sprinkler system is shut down for repairs or modifications or in the event of a sprinkler failure. During sprinkler system shutdown or a sprinkler failure, compartmentation, including fire and smoke dampers, provides important protection. While the probability of sprinkler failure is small, there is a significant potential for a major building fire with multiple deaths during a sprinkler failure if we have total reliance on sprinklers. This situation is similar to the small probability of an airplane crash that has the potential for major loss of life, and the reason that airplanes have backup or complementary safety features.

Sprinklered fires produce significant amounts of soot and toxic gases that can hamper fire evacuation and threaten life. Without smoke dampers, smoke can flow through HVAC ducts to threaten life and damage property far from the fire. Compartmentation, including walls, floor-ceiling assemblies, doors, fire dampers and smoke dampers is needed to provide an adequate level of protection in buildings of any height.

In recent years, there has been a growing interest in the idea of performance-based codes that would allow a design to be based on engineering calculations rather than on prescriptive requirements of the codes. The author has been keenly interested in this topic since his participation as a visiting expert for the 1989 pioneering study of performance-based design at the University of Sydney in Australia.[17] As performance-based design technology develops, engineering analyses that incorporate the potential for component failure, realistic fire scenarios and appropriate safety factors will numerically show the need for passive protection consisting of compartmentation including smoke and fire dampers. Without such passive protection, there can be significant smoke movement far beyond the fire floor even for “cold” smoke from sprinklered fires.

In the event of a sprinkler failure, a fire in a building with inadequate passive protection could result in major loss of life. The relatively small cost savings of permitting inadequate compartmentation and inadequate fire and smoke damper protection in sprinklered buildings can hardly justify the potential disaster that can result from a major fire when there is a sprinkler failure.

Summary

Smoke Movement: Smoke flow due to building fires is a complex process due to the many forces that can move smoke through shafts, holes in floors, holes in walls, gaps around doors, and HVAC ductwork without smoke dampers. Even for “cold” smoke from sprinklered fires, the forces of smoke movement can cause significant amounts of smoke to flow through HVAC ducts without dampers to locations beyond the fire floor.

Sprinklers: Sprinklers have a high success rate, but there have been and will continue to be sprinkler failures. Most sprinkler failures can be placed into one or more of the following categories (1) an inadequate or no water supply, (2) failure of one or more sprinkler system components, and (3) a fire overpowering the sprinklers.

Passive Protection: Compartmentation with fire and smoke dampers can minimize smoke migration during sprinklered fires and during sprinkler failures. As already stated, the relatively small cost savings of permitting inadequate compartmentation and inadequate fire and smoke damper protection in sprinklered buildings can hardly justify the potential disaster that can result from a major fire when there is a sprinkler failure.

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