Chapter 9
Impact of Interior Doors on Residential Fire Safety

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Abstract Doors play an important role in residential fire safety. Research has documented that doors can be an effective means to slow the spread of fire and smoke in home fires and have the potential to increase the available egress time for home occupants. While doors can be used as valuable barriers to the effects of fire, they can also serve as obstacles for detection, occupant notification, and evacuation. The impact of doors in residential fires can be influenced by both human and fire behaviors. Additionally, there may be a risk of pressure peaks during the early stage of the fire that may make it difficult to open doors that do not open outwards. This chapter provides an overview of the role interior doors play in residential fires, including the benefits, inhibiting factors, and unknowns.

Keywords Interior doors · Smoke alarm · Audibility · Evacuation · Compartment fires · Pressure effects

1 Introduction

Doors are a fundamental element in residential dwellings and apartments worldwide. Interior doors define and compartmentalize a home, providing physical, visual, and acoustical privacy. However, interior residential doors have undergone a dramatic change over the last several years. Doors have historically been constructed from solid pieces of wood. But the global shift toward environmentally sustainable products has caused a shift in priorities, including the more efficient use of material and financial resources. To optimize materials resources, the construction materials for interior doors have changed from solid-core wood doors to hollow-core

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composite doors. While doors can act as a physical barrier to fire and smoke, interior residential doors are generally not viewed as strong fire-resistive elements.

2 Doors in Residential Dwellings

While the global residential building stock is diverse, the most common type of residential units can be classified into two categories: single and multifamily dwellings. To quantify the impact of interior doors on residential fires, it is first important to understand the types of doors, their characteristics, and locations within residences.

2.1 Types of Residential Interior Doors

A vast array of doors may be found in residential dwellings, including hinged privacy doors, sliding doors, pocket doors, and folding doors. Interior doors are often characterized by their design, such as flush doors, paneled doors, sash doors, or louvered doors and their construction type – either hollow-core or solid. Today, hollow-core, flush panel doors are becoming increasingly common in interior residential applications. Due to their use of engineered materials, these doors are low-cost, lightweight, and easy to install [18].

Hollow-Core doors

Hollow-core doors consist of a solid wood or composite frame with an essentially hollow interior, which is often constructed of cardboard, arranged in a honeycomb pattern. The specific material, pattern, and density of the core can vary. The outside of the door typically consists of some type of paneling or timber veneer. Hollow-core doors are intended to act as a low-cost, lightweight, and environmentally friendly alternative to solid wood doors. These doors can be styled to replicate the look of solid wood doors, while using less materials. These doors are most commonly used as interior residential doors, due to their reduced strength, insulation, and security as compared to solid doors; however, they can be used as exterior doors under certain circumstances [17].

Solid-Core doors

Solid-core doors utilize an engineered construction method to provide a door that is a hybrid of hollow-core and solid wood doors. This door type uses a solid core that is constructed of engineered or composite wood, like Masonite or Fiberboard. A fine-grade surface wood veneer or engineered wood that is made to give the appearance of a frame and panel door is then glued on top of the solid core.

Solid-core doors that are at least 44.45 mm (1 ¾ inches) thick can offer more fire resistance than other interior doors [17].

Solid-Wood doors

Solid wood doors are constructed entirely of natural woods, such as pine, oak, and maple, among others. While they can be made of a single, unified slab of wood, this is rather rare. They are most often built using the frame-and-panel method of construction, which creates a classic six-panel door that has been used for centuries around the world. While these paneled doors appear to be one piece of contoured wood, these doors consist of a conglomerate of individual panels, mullions, stiles, and rails that secure the six panels together [18].

Fire-Rated doors

A fire door is a door that acts as part of a passive fire protection system to delay the spread of fire and smoke between compartments within a home or structure. Fire doors are classified by their fire-resistance rating, which determines the duration in which the fire door, or passive fire protection system, is designed to withstand the conditions of a standard fire resistance test.

2.2 General Placement of Doors in Residences

In a traditional residential dwelling, there will be a combination of interior and exterior doors.

While any requirement for fire resistance barriers or door sets is dependent on local regulations, most one- and two-family dwellings are not required to have fire-resistant doors. The most common door type in one- and two-family homes today is hollow-core doors, although solid wood and solid-core doors are still used. However, some regions, like the UK, recommend that single-family dwellings with at least one story exceeding 4.5 m have a fire-resisted, protected stairway. For the stairwell to be protected, all doors leading into the protected stair or hall area would need to have a rated fire resistance per the relevant standard [4].

In an apartment setting, multiple dwelling units typically share a common hall or exit way. In this type of multifamily dwelling, the hallway needs to be a protected exit corridor, therefore the doors leading out of each individual dwelling unit and the exit doors are generally required to be self-closing and have a rated fire resistance per the applicable standards, such as by Boverket's Building Regulations (BBR), NFPA 101®, *Life Safety Code*, or other local or regional standards.

3 Residential Fire Scenarios and Occupant Behaviors

3.1 Residential Fire Scenarios

When examining residential fires from various countries including the United States, Norway, Estonia, Denmark, Sweden, and the Netherlands, living room fires appear to be the leading area of origin for residential fire fatalities, followed by the bedroom [1, 3]. While kitchen or cooking area fires continue to be a leading area of origin in home fires around the world, these fires are less likely to result in fatalities than those in living rooms and bedrooms. Across the board, the largest percentage of fire fatalities occur during sleeping hours. In most countries examined, smoking was a leading cause of residential fire fatalities. Data indicates that single-family dwellings and apartments are the dwelling types that account for the large share of fire-related fatalities. While the overall number of victims per dwelling type is fairly evenly split, data indicate that occupants in apartments may be at higher risk of dying in a fire, particularly in Europe [3].

3.2 Occupant Door Position Habits

When assessing residential fire risks, occupant habits with regard to door position must be understood. A survey was conducted on 304 occupants, predominately located in the United Kingdom, to study door closing habits in their own residential dwellings. While it does not provide an international perspective, it does provide insight into common door positions and the reasoning for one position or the other. Overall, there was found to be a 60% probability of the occupant's bedroom door being closed while sleeping and a 45% probability of the living room door being closed, if present [5]. Occupants having children or pets were more likely to sleep with the bedroom door open. However, the probability of door closure varies significantly with the property type. Hopkin et al. found apartment residents to be 19% more likely to close bedroom doors than those living in one- or two-family dwellings [5].

4 Fundamentals: Role of Interior Doors in Residential Fires

Whether the interior residential doors are used to compartmentalize different areas of a residence or separate a residential unit from a common corridor, they impact several aspects of residential fire safety, with both positive and negative attributes. Doors can influence fire dynamics, detection of smoke, occupant notification, pressure effects in the home, and safe egress. Beyond the physical aspects, human behavior and the decision to close an interior door impacts the role interior doors can play in residential fire safety.

4.1 Fire Performance of Interior Doors

Interior residential doors are typically intended to act as a partition separating rooms and corridors in a residence, rather than as a passive, rated fire barrier. This is particularly true in single-family dwellings. Larger residential complexes may be subject to additional regulations to provide a protected exit corridor, but nevertheless, the interior doors within each individual apartment unit will likely not be made of fire-resistive construction, but rather act as a partition between rooms. Although fire and smoke separations are required in commercial building codes to minimize the impacts of fire, there are limited requirements for residential dwellings [10]. Interior doors can, however, act as a temporary barrier to fire and smoke.

The performance of a fire door or interior partition door assembly can be characterized by the ability of the door to retard the passage of fire and its effects (heat and smoke) into an adjacent compartment. There are several testing standards available that establish the methodology for evaluating the fire performance of door assemblies, including UL 10(B), *Standard for Fire Tests of Door Assemblies,* UL 10(C), *Standard for* Positive Pressure *Fire Tests of Door Assemblies,* NFPA 252, *Standard Methods of Fire Tests of Door Assemblies,* NFPA 80, *Standard for Fire Doors and Other Opening Protectives,* the *British Standard Specification for Fire Tests on Building Materials, and Structures, B.S. 476 Part 1,* EN 1634, *Fire resistance and smoke control tests for door and shutter assemblies, openable windows, and elements of building hardware,* among others. The temperatures within the furnace during the testing are required to comply with the standard temperature-time curve as specified in ASTM E-119 and NFPA 252.

An interior residential door's impact on slowing fire spread from one compartment to another was examined in a study conducted by Gross and Shoub [9] through a series of conventional standard furnace fire tests of 16 interior doors [9]. It was found that a traditional, solid wood, paneled door and frame only acts as a fire barrier for approximately 5 minutes. Since one of the objectives of this study was to assess alternative methods to improve fire performance of wood doors utilized in homes, the study also found that conventional or fire-retardant paints did not appear to have a noticeable impact on fire performance; however, a fire-retardant paint with fiberglass reinforcement extended a wood-paneled doors' ability to act as a fire barrier for an additional 11 minutes.

Similarly, a study by Kerber tested three different types of doors that are reflective of the doors found in residential dwellings today [2]. This study examined a hollow-core oak door, a hollow-core composite door, and a solid wood 6-panel door. Interestingly, the type of wood or material used on the door had little impact on its fire performance. The time to failure for all three doors was approximately 300 seconds, or 5 minutes, which is consistent with the results of the Gross and

Shoub study from 1966. The two hollow-core doors showed similar fire behavior, with relatively rapid fire spread to the unexposed side of the door. Surprisingly, the solid wood-paneled door also failed within approximately the same time frame, with the points of failure being on the paneled sections of the door. Since the relative thickness of the panel was significantly thinner than the rest of the wooden door, the panel areas failed quickly while the remainder of the door stayed in tack. These fire test results show the overall thickness of the door as the primary driver of their respective failure times – where failure is qualified as when the unexposed side of the door sustained burning.

4.2 Notification: Doors as a Barrier to Sound

In any fire scenario, early and effective detection and notification of the fire is essential for safe occupant egress. A closed interior door can be an effective barrier to fire, heat, and smoke; however, it has the potential to impair the alerting of sleeping occupants to fire, particularly if the alarm is located outside of the sleeping room. The risk presented by a closed, interior residential door with regard to notification is two-fold. First, the door could delay activation of a smoke alarm if an alarm is not present in the room of origin. And second, the door could delay occupant notification of the fire due to the audible attenuation by the door. With high-risk fire scenarios likely to occur when occupants are assumed to be asleep, it is essential to minimize delays in detection and occupant notification. Thus, the impact of an interior residential door on detection and notification is important to quantify by an assessment of the passage of smoke through closed doors and sound transmission through doors and other building materials.

4.2.1 Smoke Alarm Activation Delays from a Closed Door

One of the most important performance metrics for residential fire safety is the calculation of the time between alarm activation and the onset of untenable conditions for occupants in the home. Detection can be adversely impacted by closed doors since the barrier has the potential to delay or prevent activation of the smoke alarm, when it is located outside the room of origin. Studies, including Bukowski et al. (2008) and Thomas et al. (2010), have shown that alarm activation and the delay in activation time are strongly related to door position [23, 26].

The quantitative assessment of the potential time delay is dependent on a number of factors, including the location of the fire, the smoke alarm presence and location, distance from the source of the fire to the alarm, the air tightness of the home, sensitivity of the detector, type of door and position, among other variables.

Experiments conducted by Thomas and Bruck on four bedroom fires found that when the door in the fire compartment was closed, the amount of smoke that escaped around the cracks of the door was too low of a concentration to activate the alarms in the hallway [23]. Similarly, experiments by Bukowski showed that the time to untenability was reached before alarm activation in 50% of the closed bedroom door experiments, when no alarm was present in the room of origin [7, 26].

If smoke alarms are not placed inside and outside the bedroom or the residence does not have interconnected alarms, the delay or lack of smoke alarm activation from a closed interior door can substantially impact the available safe egress time for occupants and compromise safety.

4.2.2 Delays to Occupant Notification by Sound Attenuation

When no obstacles are present, sound travels uniformly in a direct path from the sounder to the receiver, where the observed sound pressure level decreases proportional to 1/distance. But when a barrier is put in its path, the sound is diffracted; some of the sound is transmitted through the barrier and some is reflected. The value by which doors reduce sound pressure levels is dependent on the type of door and its corresponding characteristics. According to Schifiliti et al. (2016), hollow-core flush panel doors with an air gap, hollow-core flush panel doors hung with edge sealing, and solid hardwood doors hung with edge sealing attenuate sound by 14 dBA, 20 dBA, and 26 dBA, respectively [8]. A common stud wall is also estimated to reduce the sound pressure level received on the other side of the wall by approximately 35 dBA [11]. Alternative construction methods and materials can influence the attenuation of sound through respective barriers.

To determine the sound received at a specific point in an enclosed space, the calculation methods outlined by Schifiliti can be applied [8]. This calculation accounts for factors such as the emitted sound pressure level, distance from the source, and the characteristics of the compartment, including the type and quality of the finishes and furnishings. When the alarm is located outside the area of concern, additional factors such as directional considerations, distance from the alarm to the partition (e.g., door), the sound attenuation through the wall or door, and the distance to the receiver on the other side of the partition (e.g., at the pillow in the bedroom) need to be considered.

The audibility of an alarm signal by occupants is dependent on a few variables: alarm characteristics, sound pressure level of the alarm, location of the alarm with respect to occupant location, and the sound transmission loss through building elements such as doors and walls, and occupant characteristics. Regulations like NFPA 72, *Fire Alarm and Signaling Code,* and the British Standard, *BS 5839-Part 1* require a minimum sound pressure level of 75 dBA to be received at the pillow when a smoke alarm is sounding. However, research has found 72.5 dBA (±17.7 dBA) to be the average awakening threshold of sober, normal hearing adults in response to a high frequency alarm [7].

Several studies [7, 10, 24, 25] have examined the impact of the position of a hollow-core door on the received sound pressure level inside a bedroom from 85dBA and 90 dBA alarms outside the bedroom. Some analyzed an alarm placed directly outside the bedroom door, while others examined the impact of an alarm

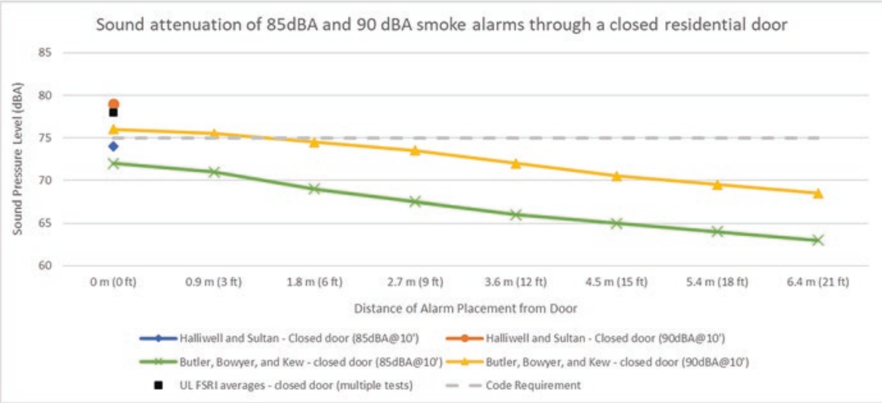

Fig. 9.1 Sound attenuation of 85dBA and 90dBA smoke alarms through a closed interior door

being placed at varying distances down a hallway. These results are depicted in Fig. 9.1. As shown, when the door is closed, an 85 dBA smoke alarm directly outside the bedroom will generally not meet the 75 dBA requirement at the pillow; a 90 dBA alarm may be acceptable for up to 1.5 m (5 ft) from the bedroom door. The Butler et al. [24] study showed that the sound pressure level received at the pillow could be 10–15 dBA lower than the required 75 dBA sound pressure level, as the distance of the smoke alarm from the closed bedroom door exceeds 6 m (~20 ft).

Through further alarm audibility testing by Thomas and Bruck, five unique residential geometries were studied with representative alarm frequencies. In the results, they found that an 85 dBA alarm located in the hallway resulted in audibility that ranged between 40.0 and 74.8 dBA in a bedroom with an open door and 37.4 dBA and 55.9 dBA when the bedroom door was closed[1] [23]. While the percentage by which the door reduces the sound level received in the bedroom will depend on a number of characteristics, research indicates that the value can be significant in some cases.

Given that only about 55.6% of occupants wake to a sound pressure level of 75 dBA, and only 33% wake to 64 dBA, a closed door can present significant risks in terms of achieving adequate notification [7]. Although requirements for bedroom alarms and the interconnection of alarms are increasing, this is currently not common practice. Most of the residential housing stock where alarms are installed likely only have an alarm in the hallway, thus the impact of a closed bedroom door on the received sound levels does introduce risks that can delay occupant notification, and in turn, egress.

[1] Note: This study took measurements inside the bedroom, diagonal from the bedroom door, at pillow height. This additional distance could correlate to lower sound pressure levels than some other referenced studies.

4.3 Occupant Tenability: Doors' Impact on Temperature, Smoke Spread, and Gas Exposure

Once occupants are notified of the fire, whether from an alarm or by other means, there is a limited amount of time in a residential fire before the conditions become untenable. The time and severity of the conditions are dependent on the fire scenario, layout of the home, the vulnerability of the occupants, the location of the occupants in relation to the fire, and the occupant's ability for self-rescue or reliance on the fire brigade.

Occupant tenability, defined as an occupant's ability to survive in a fire setting, is a critical parameter in residential fire scenarios. Occupants are exposed to numerous airborne contaminants and physical hazards in a fire environment and during egress, namely, thermal effects and toxic gas exposures, like carbon monoxide (CO), carbon dioxide (CO_2), hydrogen cyanide (HCN), among others [29]. Exposure to adequate doses of these toxic by-products can cause incapacitation and death through narcosis and irritancy. These fire products can impede egress by causing painful stimuli to the eyes, nose, throat, and lungs, which can lead to inflammation of the lungs, ultimately restricting breathing and leading to death. Additionally, escape can be slowed or hindered by smoke, visually obscuring the egress path, or by thermal barriers such as skin pain, burns, or hyperthermia that may result in death during or after exposure [29].

The effects of sensory irritation, visual obscuration by smoke, and thermal exposure are generally present immediately upon exposure and the ultimate hazard is dependent on and proportional to the concentration. Recommended tenability limits for visibility through smoke is OD/m 0.2 for small enclosures and 0.08 for large enclosures [31]. The widely accepted tenability limit for skin exposure to radiant heat is approximately 2.5 kW/m^2. This exposure corresponds to a 200 °C hot gas layer and can be tolerated for a few minutes by most occupants [31]. Threshold exposure concentrations of common asphyxiant gases at which serious impacts to occupant health and safety are expected have been defined in various studies [29–31] and are summarized in Table 9.1.

Over the years, research on occupant tenability in residential applications has highlighted the important role interior doors can play in protecting or slowing occupants' exposure to the toxic by-products of fire, and in turn, lowering their

Table 9.1 Tenability limits for incapacitation or death from exposures to common asphyxiant gases [31]

	5-min exposure		30-min exposure	
	Incapacitation	Death	Incapacitation	Death
CO	6000–8000 ppm	12,000–16,000 ppm	1400–1700 ppm	2500–4000 ppm
CO_2	7–8%	>10%	6–7%	>9%
HCN	150–200 ppm	250–400 ppm	90–120 ppm	170–230 ppm
Low O_2	10–13%	<5%	<12%	6–7%

probability of experiencing an incapacitating dose prior to escape or fire department rescue [19–22, 27, 28].

Madrzykowski and Weinschenk conducted a series of twelve experiments where a fire was ignited on the basement level, and measurements on compartment temperature and concentrations of oxygen and carbon monoxide were captured in bedrooms with an open and closed door on the first story of a single-family dwelling [27]. Through these experiments, it was found that the oxygen concentrations behind the closed interior doors remained at acceptable levels (above 20%), while the open-door scenarios had oxygen concentrations ranging between 0.3% and 19.5%, which created negative health implications in the majority of the tests [27]. The experimental data also suggest a strong correlation between a closed interior residential door and the ability to keep the CO concentrations to survivable levels in the room behind the closed door. With a closed interior door, the CO levels were consistently around 0.1% (1000 ppm), which has an effect of slight heart palpitations, whereas when the door was open the CO concentrations ranged from 0.2% (2000 ppm) to 3.3% (33,000 ppm). A 0.2% CO exposure for 30 min can cause slight heart palpitations, while concentrations between 0.32% and 3.3% can result in death, for short periods of exposure. In most of the experiments, the open bedrooms experienced elevated temperatures and reached fatal CO exposures and oxygen concentrations below survivable levels, while the rooms protected by a close door maintained tenable conditions [27].

Similarly, the benefits of a closed door inside the premises of the fire compartment with respect to occupant tenability were confirmed by Kerber [28]. Given a living room fire in a single-family one-story dwelling, measurements were captured in two side-by-side bedrooms where one door was closed and the other was open. The oxygen level never dropped below 19.5% in the room with a closed door, whereas it dropped below 10% in the open bedroom [28]. Similarly, the temperature in the hallway outside the bedroom was 900 °C, while the temperature in the room with the closed door was only 125 °C, over seven times lower.

It should be noted that when an occupant is exposed to toxic gases in a fire atmosphere, they inhale and are exposed to a mixture of toxic products of varying concentrations; therefore, the exposures are normalized by the concept of fractional effective concentration (FEC) or fractional effective dose (FED), where the exposure concentration of any by-product during a fire is quantified as a fraction of the dose predicted to give a negative effect (e.g., incapacitation, loss of consciousness, etc.). The ultimate impact on the occupant is dependent on the sum of the received dose of each toxic gas exposure.

ISO 13571 [6] specifies a methodology to estimate the fractional effective dose (FED) – the time to incapacitation from either thermal or gaseous effects of fire. A FED value of 1 is intended to indicate that a healthy adult has obtained a sufficient dose of fire-related toxicants and exposures to cause incapacitation. However, there is wide variation in occupant's susceptibility. For instance, young children, the elderly, and unhealthy adults are significantly more susceptible to the impact of fire effluents than healthy young adults. So, to ensure the majority of the population will be able to escape, a safety factor is commonly applied by setting the acceptable FED at 0.3 [21].

Trainia et al. (2017) conducted a series of seventeen experiments in a one- and two-story single-family dwelling that investigated the impact of structural geometry, fire location, and door position on occupant tenability [10]. The results of the one-story experiments indicated that in both living room origin and bedroom origin fires, the time to untenability (FED = 0.3) in the bedroom with a closed door was approximately 2.5 times longer than the other rooms in the home, and a FED exposure of nearly 46 times less than other areas of the home. With fire department intervention occurring within approximately 6 min in the one-story home and approximately 10 min in the two-story home, all rooms had exceeded the FED for susceptible populations prior to fire department intervention, except for the bedroom with the door closed. The average time to untenability in all open rooms was 5 min and 32 s in the one-story home and 9 min 36 s in the two-story home experiments. In the various experiments, occupants in the room behind closed doors had between 11 min and 22 min to escape prior to the room becoming untenable, depending on the scenario. Crewe et al. found similar results for time to untenability in rooms with closed doors [21]. When considering that egress time from residential structures can range between 2 and 16 min, according to a study by the National Resource Council of Canada, a closed door can significantly increase an occupant's probability for safe egress.

While Bukowski found that a closed door can extend available egress time by approximately 10 times [26], it should be recognized that tenability in areas of the home not protected by closed doors will likely be poor [27, 28] and may require the occupant to depend on fire department rescue.

4.4 Pressure Peaks: Doors' Impact on Egress

Beyond the concerns of detection, notification, and tenability, we must also consider the potential for the door to act as a barrier to egress. In an egress situation, occupants must be able to open the doors that are on their way to safety. In addition to the behavioral and smoke-induced physiological challenges, fire-induced pressure may prevent the door's use if the door opens inwards and is relatively air-tight. Interior doors are usually not airtight and are therefore unlikely to face the pressure-related opening problems.

The possibility of pressure-related door opening challenges has long been recognized in the context of smoke control. The design standards for pressurization systems, such as NFPA 92, *Standard for Smoke Control Systems,* and EN 12101–6, *Smoke and Heat Control Systems*, calculate the critical force by balancing the moments of pressure and handle pulling forces: $F = \Delta P \times A \times (W/2)/(W-d)$, where ΔP is the pressure difference, A is the door leaf area, W is the door width, and d is the distance from the doorknob center to the edge of the door nearest to the knob. Possible door closers would increase this force. For typical measurements of

A = 1.8 m^2, W = 0.9 m, and d = 7.5 cm, we get an approximate formula for the required opening force: $F \approx \Delta P$, when ΔP is in Pa and F in N. Most standards seem to propose a critical force in the range of 110 to 130 Pa. This means that the critical overpressure of the fire compartment is somewhere between 100 and 200 Pa.

A key event that made researchers and fire authorities aware of the fire-induced pressure problem took place in Cologne, Germany, in 2013. The fire ignited in the living room of a 'Passivhaus' in the night. The occupant woke up, tried to extinguish the fire but failed, and decided to escape, just to notice he could not pull the door open. After a moment, he managed to open a balcony door and survived to report about the event. The doors were later tested and found to be in good working conditions. In their investigation of the incident, Brohez and Duhamel carried out CFAST simulations of the fire, showing peak pressures of 500 Pa [12].

Soon after the Cologne fire, Finnish firefighters observed a similar situation in their training, where they tried to attack an apartment fire but could not open the inwards-opening exterior door due to the high internal pressure. Likewise, occupants inside the apartment also would not have bee able to overcome the high pressure forces on the door to egress either. This conclusion was later confirmed by Kallada, Janardhan, and Hostikka in a scientific experiment where a fireman with a breathing apparatus ignited a polyurethane mattress inside a 58.5 m^2 flat and 16 s later tried to open the inwards-opening door leading into the stairway. Opening the door was found to be impossible due to the excessive overpressure conditions [14]. According to the measurements 26 s from ignition, the internal overpressure was 800 Pa.

The dynamics of the pressure development inside a closed house or apartment seem to be quite different from the temperature development, which usually follows the HRR with some delay. Figure 9.2 illustrates the HRR and pressure behaviors in a heptane pool fire inside a closed apartment with three different settings of the mechanical exhaust ventilation [14]. Although the HRR reached its peak 70 s from ignition, the pressure peaks were reached already at about 30 s, after which the pressure difference decreased and approached zero despite the continuously burning fire. Sudden extinction of the fire due to the fuel burnout caused another, negative

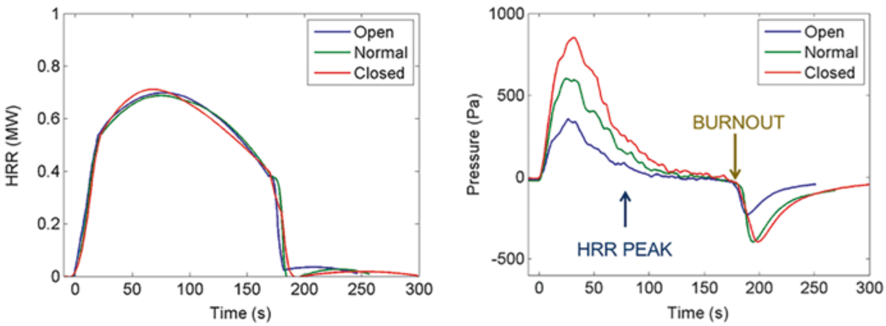

Fig. 9.2 Experimentally measured heat release rate (left) and apartment pressure (right) in the experiments of Kallada Janardhan and Hostikka (2017)

peak in pressure. The magnitude of the pressure peaks showed a clear dependence on the ventilation system condition: using the ventilation system as it was built and used led to a peak overpressure of 600 Pa. Closing the system tightly increased the peak pressure to almost 900 Pa, and opening the ventilation ducts by removing the room dampers decreased it to 300 Pa.

But why was this, rather obvious risk of egress impairment, not noticed until now, after about 50 years of modern fire science? There appears to be two main reasons. First, most of the experimental fire research has focused on temperature as a main fire consequence, and high temperatures are only achieved if the fire is well-ventilated. In most cases, this means open enclosure, where pressure differences cannot be observed. Much fewer studies have been done in closed enclosures, and they have mainly focused on the effects of vitiation. The second reason seems to be the fact that the problem is actually new; it has been created by the increasing air-tightness of the modern buildings, driven by the energy efficiency requirements. In Nordic countries, for instance, the change has been quite dramatic, with air permeability values q_{50} of reducing from the order of 10 m^3/hm^2 for 1970s and 80s buildings [15] to less than 3 m^3/hm^2 in the twenty-first century [16], and now approaching a value well below 1 m^3/hm^2 due to the current building regulations.

The influence of the building's airtightness on the pressure peak has been studied by numerical simulations. Hostikka et al. [13] used a validated CFD fire model using the data shown in Fig. 9.2 and then used the model to quantify the effects of the apartment envelope airtightness, ventilation configuration, and fire growth rate [13]. The building envelopes were classified based on their q_{50} -values as Traditional ($q_{50} = 3$ m^3/hm^2), Modern ($q_{50} = 1.5$ m^3/hm^2), or Near-Zero ($q_{50} = 0.75$ m^3/hm^2). The ventilation system had a mechanical inlet and outlet and small-diameter (120 mm) ductwork with dampers (closing systems). The three investigated damper configurations represent the situations where (1) there are no dampers, (2) only the inlet branch is closed by a damper, and (3) there are dampers on both branches. Figure 9.3 shows the simulated peak pressures for a 50 m^2 apartment with medium, fast, and ultrafast t^2-fire growth rates. The results indicate that in medium-growth rate fires, the critical pressure would not be exceeded with certainty in traditional buildings and possibly in modern buildings when dampers are not used for both branches. For all the other scenarios, peak pressure could prevent door opening, at least momentarily. The time frames when this occurs for the fast fires were determined by choosing a critical pressure of 100 Pa. With more airtight envelope, the pressure criterion is exceeded earlier, and the duration of the egress impairment is longer. In general, the dangerous period starts between 20 and 80 s from the ignition and ends between 220 and 240 s. Unfortunately, these are the moments when typical home fires develop life-threatening conditions.

In addition to the possible prevention of door opening, high pressure differentials can also open doors that are initially closed if they lack sufficient locking mechanism. This could lead to smoke spread and reduced tenability beyond the room of fire origin. However, little to no research has focused on the pressure resistance of residential doors, to date.

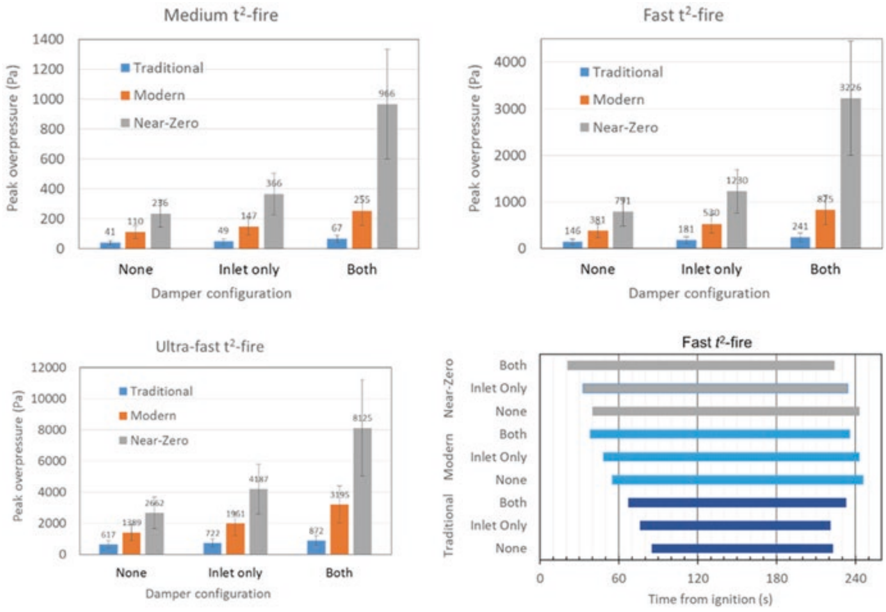

Fig. 9.3 Simulated peak pressures for medium, fast, and ultrafast fires, and no-escape time frames for a fast t^2-fire inside a 50 m^2 apartment with different levels of the envelope airtightness and damper configurations

5 Conclusions

Any closed door, whether hollow-core, solid-core, solid-wood, or fire-rated, can provide protection against the effects of fire, such as heat and smoke, for occupants outside the room of origin. A closed door can extend the tenability time, providing occupants more time to escape and buying time for the fire service to arrive and act on the fire. However, the barrier of a closed door can adversely affect alarm activation and received audibility. The development of the building envelopes and ventilation systems through the modern energy-efficiency norms has also increased the probability of escape impairment through pressure increase, which may prevent occupants from opening an inwards-opening door during the first minutes of a residential fire. The risks and rewards of door position must be taken into account for residential fire safety.

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