Analysis of Changing Residential Fire Dynamics and Its Implications on Firefighter Operational Timeframes

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Abstract. There has been a steady change in the residential fire environment over the past several decades. These changes include larger homes, different home geometries, increased synthetic fuel loads, and changing construction materials. Several experiments were conducted to compare the impact of changing fuel loads in residential houses. These experiments show living room fires have flashover times of less than 5 min when they used to be on the order of 30 min. Other experiments demonstrate the failure time of wall linings, windows and interior doors have decreased over time which also impact fire growth and firefighter tactics. Each of these changes alone may not be significant but the all-encompassing effect of these components on residential fire behavior has changed the incidents that the fire service is responding to. This analysis examines this change in fire dynamics and the impact on firefighter response times and operational timeframes.

**Keywords:** Fire dynamics, Firefighting, Tactics, Residential fires

1. Introduction

There is a continued tragic loss of firefighters' and civilian lives, as shown by fire statistics [1, 2]. One significant contributing factor is the lack of understanding of fire behavior in residential structures resulting from the changes that have taken place in several components of residential fire dynamics. The changing dynamics of residential fires as a result of the changes in home size, geometry, contents, and construction materials over the past 50 years add complexity to the fire behavior (Figure 1).

NFPA estimates [3] that from 2003 to 2006, US fire departments responded to an average of 378,600 residential fires annually. These fires caused an estimated annual average of 2,850 civilian deaths and 13,090 civilian injuries. More than 70% of the reported home fires and 84% of the fatal home fire injuries occurred in one- or two- family dwellings, with the remainder in apartments or similar properties. For the 2001–2004 period, there were an estimated annual average 38,500 firefighter fire ground injuries in the US [4]. The rate for traumatic firefighter deaths when occurring outside structures or from cardiac arrest has declined, while at the same time, firefighter deaths' occurring inside structures has

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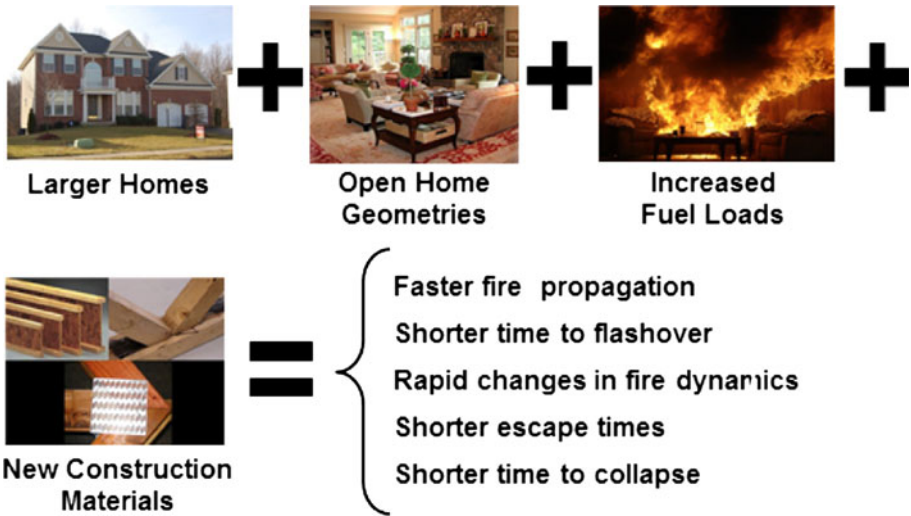
Figure 1. Modern fire formula.

continued to climb over the past 30 years [5]. Additionally, on average firefighters in the United States receive less than 1% of their training on the subject of fire behavior [6]. The changes in the residential fire environment combined with the lack of fire behavior training are significant factors that are contributing to the continued climb in firefighter traumatic deaths and injuries.

As homes become more energy efficient and fuel loads increase fires will become ventilation limited making the introduction of air during a house fire extremely important. If ventilation is increased, either through tactical action of firefighters or unplanned ventilation resulting from effects of the fire (e.g., failure of a window) or human action (e.g., door opened by a neighbor) heat release will increase, potentially resulting in flashover conditions. These ventilation induced fire conditions are sometimes unexpectedly swift providing little time for firefighters to react and respond.

2. Background

While the physics of fire development has not changed over time, the fire environment or more specifically the single family home has evolved. Several factors including home size, geometry, contents and construction materials have changed significantly over the past 50 or more years. Each of these factors will be examined in detail as they pertain to the safety of occupants and the responding fire service.

2.1. Home Size

Many contemporary homes are larger than older homes built before 1980. Based on United States Census data [7] homes have increased in average area from

approximately 144 m^2 in 1973 to over 232.3 m^2 in 2008. Twenty-six percent of homes constructed in 2008 were larger than 278.7 m^2 (Figure 2). In addition to increased area more homes are being built with two stories. In 1973 23% of homes were two-story and that has increased to 56% by 2008. The percentage of single story homes has decreased from 67% to 44% in the same time period (Figure 3).

The larger the home is the more air available to sustain and grow a fire in that home. Additionally, the larger the home the greater the potential to have a larger fire, and the greater the potential hazard to the responding fire service resources if the proper tactics aren't utilized. While the average home size has increased 56%,
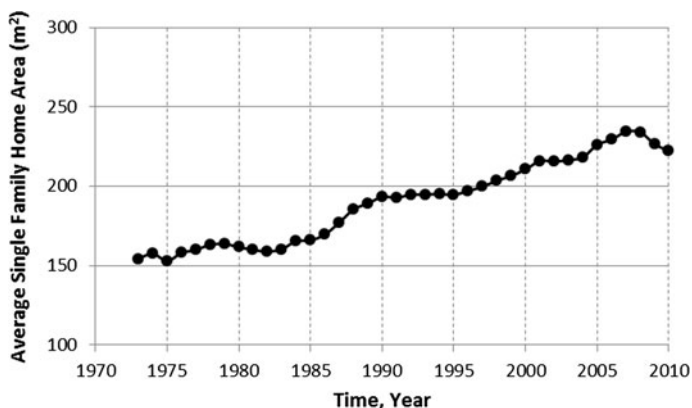
Figure 2. Average area of new single-family homes from 1973 to 2008 [7].
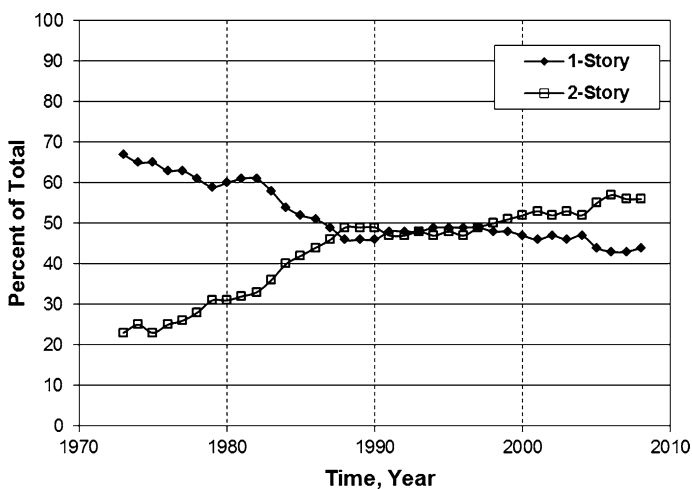
Figure 3. Percentage of number of stories of single family homes [7].

the fire service resources available to respond have not increased proportionally in many areas of the United States. This is emphasized in suburban areas where larger homes are being built but fewer fire service resources are available [8].

The increase in the number of homes with a second story means a potential for more volume above the fire which allows the smoke layer to remain above the fire and allows a longer time for the fire to grow. It also means more above ground areas for the fire service to access for civilian rescue and egress, potentially increasing the chance of injury.

2.2. Home Geometry

Newer homes tend to incorporate features such as taller ceilings, open floor plans, two-story foyers and great rooms [9]. All of these features remove compartmentation, add volume and can contribute to rapid smoke and fire spread. Commercial building codes require fire and smoke separations to limit the impact of the fire on occupants, there are minimal codes requiring compartmentation in single family homes [10].

A trend in new homes is to incorporate taller ceilings and two-story spaces or great rooms [11]. Much like the impact of having a two-story home, taller ceilings create a longer smoke filling time that allow for more oxygen to be available to the fire for it to grow before being surrounded by smoke filled, oxygen deficient air. The heat release rate of a fire slows down significantly once the oxygen content of the air decreases. Newer homes are being constructed with ceilings taller than the traditional 2.4 m, upwards of 4.3 m to 6.1 m [9]. It is also common for great rooms and open foyers to directly connect the living spaces to the sleeping spaces allowing for smoke generated in the living spaces to rapidly trap potential sleeping occupants.

Another trend in homes is to remove walls to open up the floor plan of the home [12]. As these walls are removed the compartmentation is lessened allowing for easier smoke and fire communication to much of the home. In the living spaces doors are often replaced with open archways creating large open spaces where there were traditionally individual rooms.

Combining of rooms and taller ceiling heights creates large volume spaces which when involved in a fire require more water and resources to extinguish. These fires are more difficult to contain because of the lack of compartmentation. Water from a hose stream becomes increasingly more effective when steam conversion assists in extinguishment, without compartmentation this effect is reduced. The simple tactic of closing a door to confine a fire is no longer possible in newer home geometries.

2.3. Home Contents

The challenge of rapid fire spread is exacerbated by the use of building contents that have changed significantly in recent years, contributing to the decrease in time to untenable (life threatening) conditions. Changes include: (a) the increased use of more flammable synthetic materials such as plastics and textiles, (b) the

increased quantity of combustible materials and (c) the use of goods with unknown composition and uncertain flammability behavior.

Over time home contents have transitioned from being compromised of natural materials to dominated by synthetic materials [13, 14]. Synthetic materials such as polyurethane foam have replaced cotton as the padding found in upholstered furniture. Today more than 95 million kilograms of flexible polyurethane foam are produced in the US, enough to make 140 million sofas [15]. This difference was examined in the early 1980s when oxygen consumption calorimetry was utilized to measure the heat release rate of furniture. A study led by Babrauskas [16] compared different constructions of upholstered chairs. The cotton padded chair covered in cotton fabric produced a peak heat release rate of 370 kW at 910 s after ignition. The foam padded chair covered in polyolefin fabric produced a peak heat release of 1,990 kW at 260 s after ignition. Both chairs had a very similar total heat released 425 MJ for the natural chair and 419 MJ for the synthetic chair.

2.4. Home Construction Materials

Another change that has taken place over the last several decades is the continual introduction of new construction materials into homes [17]. The construction industry is continually introducing new engineered products that provide better structural stability, allow for faster construction time and are more cost effective. Additionally, the market for green or environmentally sustainable building materials experienced a growth rate of 23% through 2006 and is expected to continue growing at a rate of 17% through 2011 according to Green Building Materials in the US [18]. The increased market demand for environmentally sustainable products is driving engineered lumber products to further reduce material mass that could potentially result in even further concern for fire safety in building construction today and in the future. Environmentally sustainable products take into account resource efficiency, indoor air quality, energy efficiency, water conservation and affordability [19]. Life and fire safety are not part of the material selection criteria, while using less material and being more affordable are.

Many home construction materials have changed significantly for numerous reasons such as lack of supply, ease of manufacturing, cost, improved structural or energy efficiency performance, and many other reasons [20]. Home wall linings, structural components, windows and doors are some of the construction materials that have evolved. Table 1 shows some iterations of the evolution.

Table 1
Construction Material Evolutions

Construction material	Legacy $\rightarrow$ Modern			
Wall linings	Plaster and lath		Gypsum Board	
Structural components	Old growth lumber	New growth lumber	Wood trusses	Engineered I-joists
Windows	Single Glazed (Wood framed)		Double glazed (Vinyl Framed)	
Interior doors	Solid core	Hollow core	Composite hollow core	

Evolutions in building materials create changes in the fire environment. How all of these changes compound to impact fire behavior and firefighting tactics is not well understood.

3. Experimental Series

Experiments were conducted to examine the changes in contents and construction materials. Six room fire experiments examined the difference between modern and legacy living room furnishings. Furnace experiments were conducted to quantify changes in wall linings, structural components, windows and interior doors.

3.1. Comparison of Modern and Legacy Room Furnishings Experiments

Six fire experiments were conducted to examine the changes in fire development in a room with modern contents versus a room with contents that may have been found in a mid-twentieth century house. The modern rooms utilized synthetic contents that were readily available new at various retail outlets, and the legacy rooms utilized contents that were purchased used from a number of second hand outlets.

3.1.1. Experimental Description. The experiments were conducted in three pairs of living room fires (Table 2). The purpose was to develop comparative data on modern and legacy furnishings. The first four rooms measured 3.7 m by 3.7 m, with a 2.4 m ceiling and had a 2.4 m wide by 2.1 m tall opening on the front wall. The last two rooms measured 4.0 m by 5.5 m, with an 2.4 m ceiling and had a 3.0 m wide by 2.1 m tall opening on the front wall. All sets of rooms contained similar types and amounts of like furnishings. Weight measurements were not taken for the first set of experiments. However, in the second and third set of rooms, all furnishings were weighed before being placed in the rooms. In the second set of rooms the modern room had a fuel loading of 19.0 kg/m^2 while the legacy room had a fuel loading of 22.9 kg/m^2. The difference was due to the legacy sofa and chair weighing 47% and 31% more than the modern furniture. In the third set of rooms, both the modern room and legacy room had a fuel loading of approximately 11.2 kg/m^2. A similar amount of fuel was in both sets of room

Table 2
Experimental Overview

| Experiment	Description	Room dimensions (m)	Front opening dimensions (m)	Fuel loading (kg/m^2)
1	Modern	3.7 × 3.7 × 2.4	2.4 × 2.1	NA
2	Legacy	3.7 × 3.7 × 2.4	2.4 × 2.1	NA
3	Modern	3.7 × 3.7 × 2.4	2.4 × 2.1	19.0
4	Legacy	3.7 × 3.7 × 2.4	2.4 × 2.1	22.9
5	Modern	4.0 × 5.5 × 2.4	3.0 × 2.1	11.2
6	Legacy	4.0 × 5.5 × 2.4	3.0 × 2.1	11.2

Figure 4. Experiment 1 setup.

experiments however the third set of rooms was 8.4 m² larger. Each experiment was ignited using a candle placed onto the sofa. An array of 0.8 mm gage Inconel thermocouples was located in each room with measurement locations of every 0.3 m from floor to ceiling. Temperatures were sampled and recorded every 1 s.

The first set of rooms was 3.7 m by 3.7 m. The modern room (Experiment 1) was lined with a layer of 12.7 mm painted gypsum board and the floor was covered with carpet and padding (Figure 4). The furnishings included a polyester microfiber covered polyurethane foam filled sectional sofa, engineered wood coffee table, end table, television stand and book case. The sofa had a polyester throw placed on its right side. The end table had a lamp with polyester shade on top of it and a wicker basket on its lower shelf. The coffee table had six color magazines, a television remote and a synthetic plant on it. The television stand had a color magazine and a 37 inch flat panel television. The book case had two small plastic bins, two picture frames and two glass vases on it. The right rear corner of the room had a plastic toy bin, a plastic toy tub and four stuffed toys. The rear wall had polyester curtains hanging from a metal rod and the side walls had wood framed pictures hung on them (Figure 5).

The legacy room (Experiment 2) was lined with a layer of 12.7 mm painted cement board and the floor was covered with unfinished hardwood flooring (Figure 6). The furnishings included a cotton covered, cotton batting filled sectional sofa, solid wood coffee table, two end tables, and television stand. The sofa had a cotton throw placed on its right side. Both end tables had a lamp with polyester shade on top of them. The one on the left side of the sofa had two paperback books on it. A wicker basket was located on the floor in front of the right side of the sofa at the floor level. The coffee table had three hard-covered books, a television remote and a synthetic plant on it. The television stand had a 27 inch tube television. The right front corner of the room had a wood toy bin, and multiple wood toys. The rear wall had cotton curtains hanging from a metal rod and the side walls had wood framed pictures hung on them (Figure 7).

The second set of rooms was also 3.7 m by 3.7 m with a 2.4 m ceiling and a 2.4 m wide by 2.1 m tall opening on the front wall. Both rooms contained identical furnishings with the exception of the sofa and the chair. The first room (Experiment 3) had a polyurethane foam filled sofa and chair with microfiber
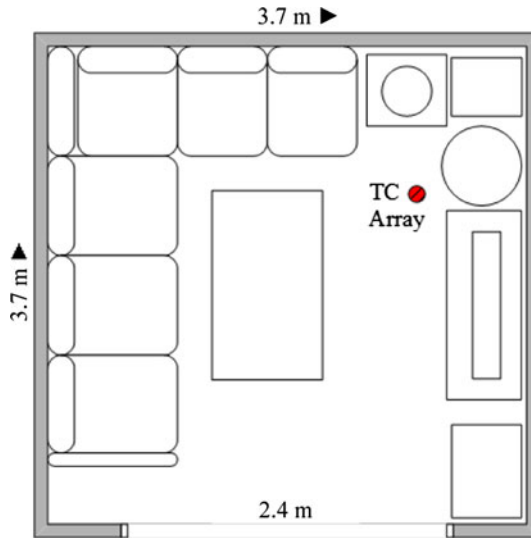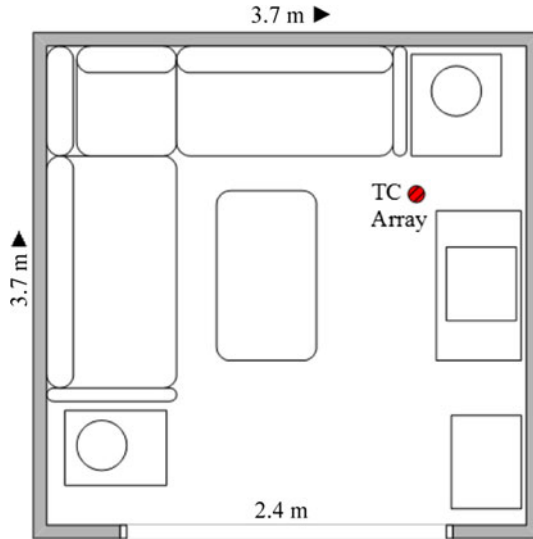
Figure 5. Experiment 1 furniture layout.

Figure 6. Experiment 2 setup.

fabric covering (Figures 8, 10). The second room (Experiment 4) had a cotton padded, innerspring sofa and chair with cotton cover fabric (Figures 9, 11). The contents were similar to those used in the first modern room. The floors were covered in polyester carpet over polyurethane foam padding. The contents included an engineered wood coffee table, two end tables, television stand and book case. The sofa had a polyester throw placed on its left side. The left end table had a lamp with polyester shade on top of it and the right end table had a television remote, candle and vase filled with synthetic rose pedals. The coffee table had four color magazines and a synthetic plant on it. The television stand had a 37 inch flat panel television. The book case had two baskets and a picture frame on it. The left side of the room had a plastic toy bin, a plastic toy tub and four stuffed
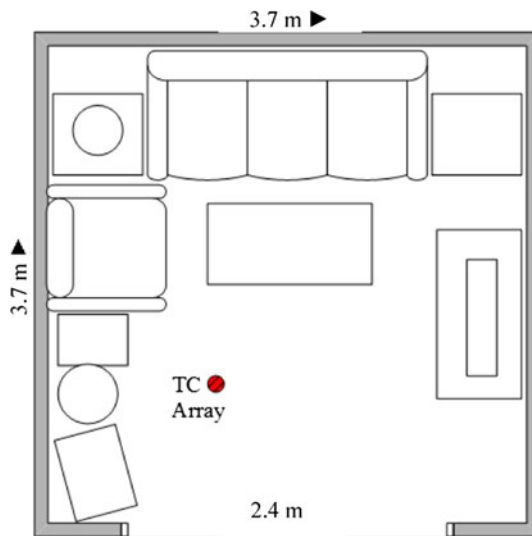
Figure 7. Experiment 2 furniture layout.

Figure 8. Experiment 3 setup.

toys. The rear wall had polyester curtains hanging from a metal rod and the left side walls had a wood framed picture hung on it.

The third set of rooms was larger and measured 4.0 m by 5.5 m. The modern room (Experiment 5) was lined with a layer of 12.7 mm painted gypsum board and the floor was covered with nylon carpet and polyurethane padding (Figure 12). The furnishings included a polyester microfiber covered polyurethane foam filled sofa, two matching chairs, engineered wood coffee table, end table, television stand and book case. The sofa had a polyester throw placed on its left side and two polyfill pillows, one on each side. The end table had a lamp with polyester shade on top of it. The coffee table had three color magazines, a wicker basket and a synthetic plant on it. The television stand had two picture frames
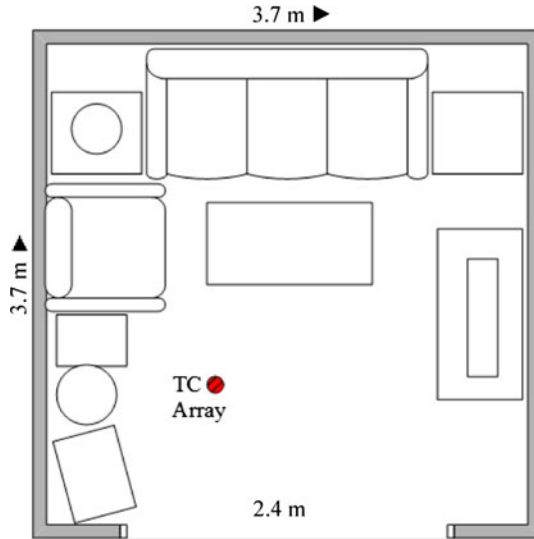
Figure 9.   Experiment 4 setup.

Figure 10.   Experiment 3 furniture layout.

and a 32 inch flat panel television. The book case had a plastic basket on it. The right rear corner of the room had a plastic toy bin, a plastic toy tub and four stuffed toys. The rear wall had polyester curtains hanging from a metal rod and the side walls had wood framed pictures hung on them (Figure 13).

The legacy room (Experiment 6) was lined with a layer of 12.7 mm painted gypsum board and the floor was covered with finished hardwood flooring (Figure 14). The furnishings included a cotton covered, cotton batting filled sofa, two matching chairs, solid wood coffee table, two end tables, and television stand. The sofa had a cotton throw placed on its left side. Both end tables had a lamp with glass shade on top of them and a wicker basket. The coffee table had a wicker basket filled with five books and two glass vases. The television stand had a 13 in
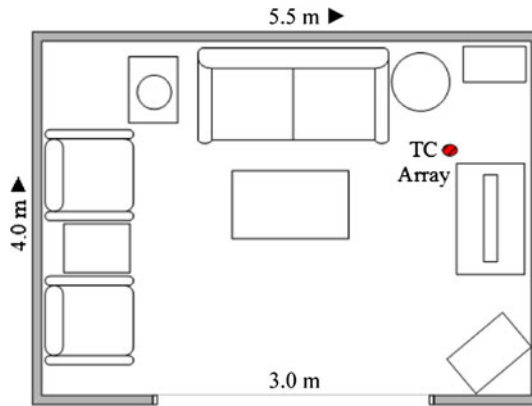
Figure 11. Experiment 4 furniture layout.

Figure 12. Experiment 5 setup.

tube television with a plant on top of it. The right rear corner of the room had a wood/wicker toy bin, and multiple wood toys. The rear wall had cotton curtains hanging from a metal rod and the side walls had wood framed pictures hung on them (Figure 15).
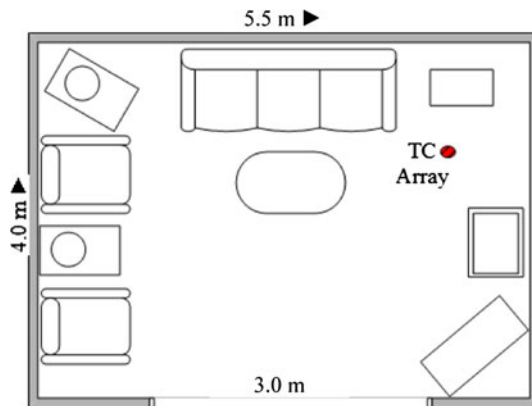
3.1.2. Results. The fire in Experiment 1 grew slowly for the first minute as the candle flame extended to the polyester throw blanket and sofa cushion. At 2 min the fire had spread to the back cushion of the sofa and a black smoke layer developed in the top two to three feet of the room. At 3 min approximately one half of the sofa was involved in the fire, the carpet had begun to burn and the hot gas layer was thickening and flowed out of the top third of the room opening. The modern room transitioned to flashover in 3 min and 40 s (Figure 16). Time to
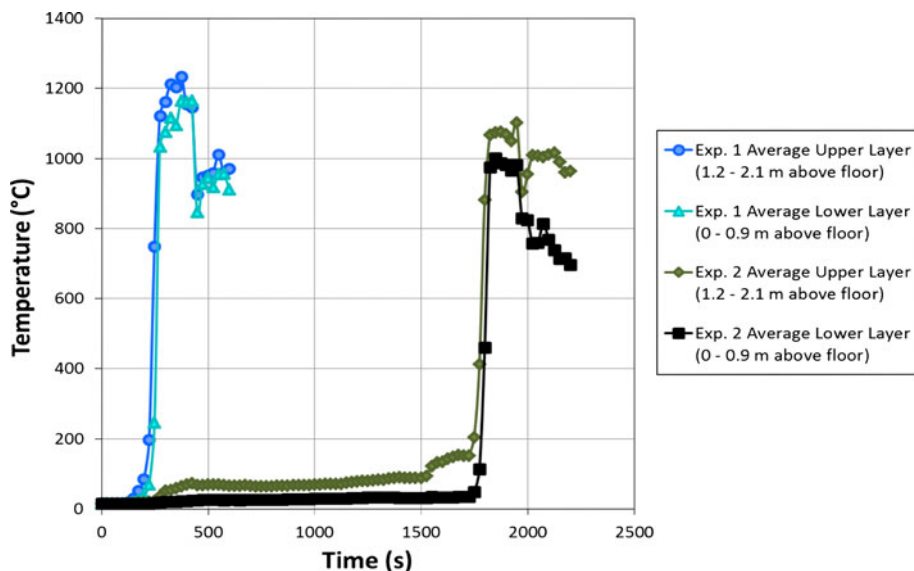
Figure 13. Experiment 5 furniture layout.

Figure 14. Experiment 6 setup.

Figure 15. Experiment 6 furniture layout.

flashover was indicated by ignition of the flooring just inside the opening of the room as a result of the heat flux from the flames coming out of the top of the opening.
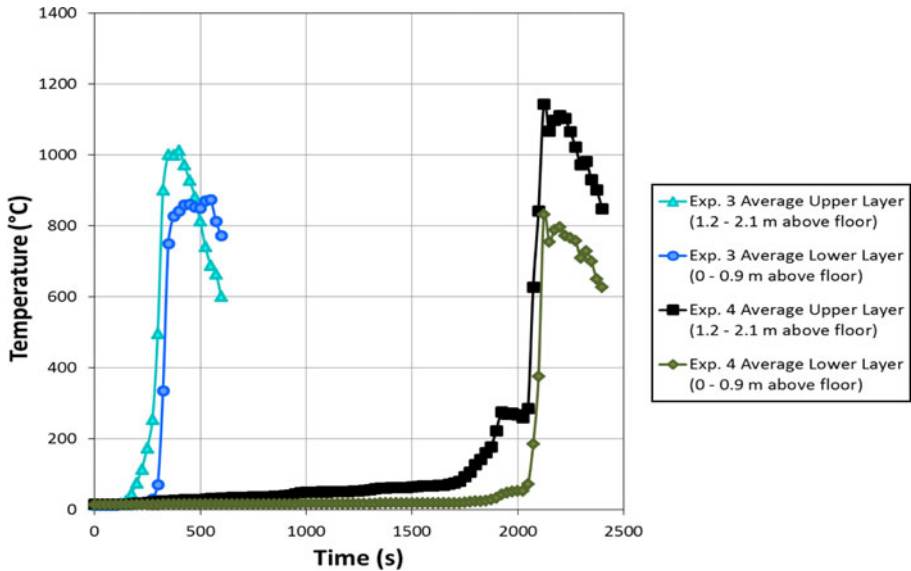
Figure 16. Experiment 1 and 2 room temperatures.

The fire in Experiment 2 also grew slowly in the first minute as the candle flame spread to the cotton throw blanket and sofa cushion. At 5 min the fire involved the arm of the sofa and extended to the curtains behind the sofa. At 10 min the fire had spread to approximately one-third of the sofa. From 10 min to 20 min the fire continued to spread across the sofa and began to develop a hot gas layer in the room. The legacy room transitioned to flashover at 29 min and 30 s after ignition (Figure 16).

Experiment 3 was ignited on the right hand corner of the sofa where the arm, seat and back joined. The fire involved the right 1/3 of the sofa at 3 min and 45 s. The fire spread to the television stand at 4 min and the left arm of the sofa ignited from radiant energy from the gas layer at 4 min and 16 s. Flames began to come out of the top of the front opening at 4 min and 20 s and flashover occurred at 4 min and 45 s. Room temperature was measured with a thermocouple array placed 0.9 m inside the opening and 1.5 m from the left wall (Figure 17). Flashover was observed at 285 s after ignition.

Experiment 4 was also ignited on the right hand corner of the sofa. At 5 min after ignition the fire was still in the corner where it was ignited. By 10 min the fire involved 2/3 of the right arm of the sofa and back cushion and only ¼ of the right seat cushion. At 20 min the fire spread to the second back and seat cushions, and the flames were burning behind the seat cushion and extending 0.3 m above the back of the sofa. The end table and television stand became involved in the fire 30 min after ignition. The room transitioned to flashover at 34 min and 15 s after ignition (Figure 17).

Heat release rate was also measured during Experiments 3 and 4 utilizing an oxygen consumption calorimeter. Figure 18 shows Experiment 3 peaked at approximately

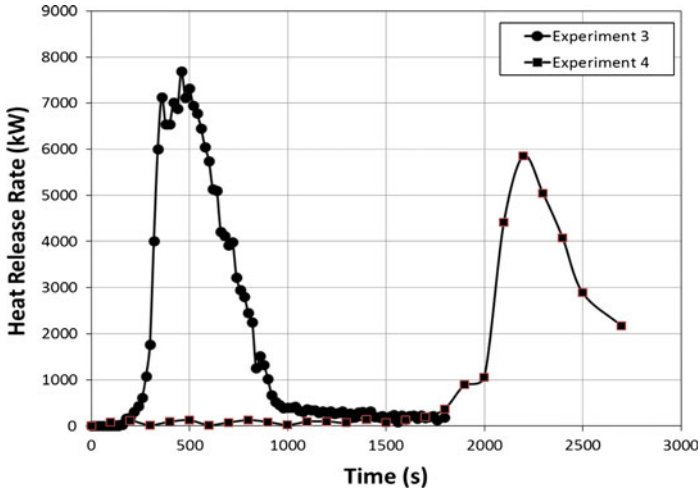**Figure 17. Experiment 3 and 4 room temperatures.**

7.5 MW at 450 s after ignition, while Experiment 4 peaked at approximately 6 MW at 2,200 s after ignition. Both experiments released approximately the same amount of energy over the duration of the experiments. Experiment 3 released 3.2 MJ and Experiment 4 released 3.5 MJ.

   Experiment 5 was ignited and the fire spread to the sofa cushion and pillow by the 1 min mark. By 2 min the fire involved approximately one-third of the top of the sofa and spread to the lamp shade. At 3 min the top of the entire sofa was on fire and the carpet began to burn adjacent to the sofa. The modern room transitioned to flashover in 3 min and 20 s (Figure 19).

   Experiment 6 was also ignited on the left side and it spread to the throw blanket and sofa cushion by 1 min. By 5 min the fire involved the left side of the sofa and spread to the curtains burning the left panel away. At 10 min the entire surface of the sofa was burning and by 15 min the fire involved the entire sofa including the underside. The flames reached the ceiling but did not extend to the adjacent furnishings. The fire burned down and never transitioned to flashover so it was extinguished at 30 min after ignition (Figure 19).

3.2. New Construction Materials

3.2.1. Wall Linings. UL conducted a series of floor furnace experiments to examine modern and legacy construction practices [21]. Two of the experiments compared a dimensional lumber floor system with different protective linings. The first was lined with 12.7 mm unrated gypsum board that is used in most homes. The second was lined with a plaster and lath lining. Both assemblies were identical with the exception of the lining and had the same loading and bearing conditions.

Figure 18. Experiment 3 and 4 heat release rate comparison.
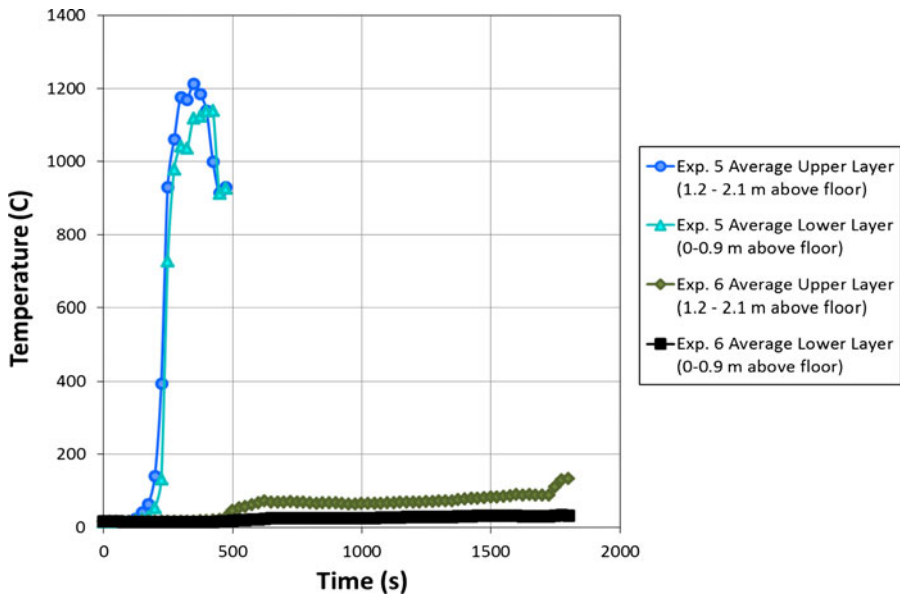
Figure 19. Experiment 5 and 6 room temperatures.

The gypsum board protected assembly exceeded the deflection criteria of L/240 at 35 min and 30 s after ignition and the plaster and lath protected assembly exceeded the same criteria at 75 min and 45 s. The gypsum board protective membrane was breached at 23 min and 30 s while the plaster and lath was breached at approximately 74 min.

In many other experiments conducted at UL that utilize gypsum wallboard to line walls for room fire experiments like those described in Section 4 it is observed that the gypsum wallboard fails at the seams. As drywall compound is heated it dries and falls out exposing a gap for heat to enter the wall space and ignite the paper on the back of the wallboard and the wood studs used to construct the walls. Gypsum wallboard also shrinks when heated to allow gaps around the edges of the wallboard. Plaster and lath does not have the seams that wallboard has and therefore does not allow for heat penetration as early in the fire. This change in lining material allows for easier transition from content fire to structure fire as the fire has a path into void spaces.

3.2.2. *Structural Components.* Engineered floor products provide financial and structural benefits to building construction; however, adequate fire performance needs to be addressed as well. Statistics from 2005 [22] highlight the amount of lightweight construction materials that are on the market. According to the National Association of Home Builders, 46% of single family home floor systems are being built with engineered I joists, 15% with wood trusses and 39% with lumber joists. Adequate fire performance provides a necessary level of safety for building occupants and emergency responders responsible for mitigating fire incidents. Previous research by various organizations, including UL, NIST [23, 24], NFPA [25] and National Research Council Canada [26], provided evidence of the greater risk in structural failure of engineered floor systems in fire events.

In 2008, UL conducted a series of experiments on a standard floor furnace [21], exposing unprotected wood floor systems to the standard time temperature curve (Table 3). Loading consisted of 195.3 kg/m^2 along two edges of the floor to simulate the load from furniture and two 136 kg mannequins that simulated firefighters in the center of the floor. Two unprotected floor systems compared a modern/lightweight floor system compromised of 0.3 m deep engineered wood I joists to a legacy/dimensional lumber 2 by 10 floor system. The engineered I joist floor collapsed in 6 min while the dimensional lumber collapsed in 18 min and 35 s. In the same study two truss floors were tested with a protective layer of 12.7 mm gypsum wallboard, one test had metal gusset plated trusses and the other had

Table 3
UL Study Experiment Description and Collapse Times [21]

Structural element	Type	Ceiling	Allowable deflection L/240 (min:sec)	Fire fighter breach (min:sec)
2 × 10 joist Floor	Legacy	None	3:30	18:35
Wood I joist Floor	Modern	None	3:15	6:00
2 × 10 joist Floor	Legacy	Lath and plaster	75:45	79
2 × 10 joist Floor	Legacy	Gypsum wallboard	35:30	44:40
Wood I joist floor	Modern	Gypsum wallboard	3:30	26:43
Metal gusset truss floor	Modern	Gypsum wallboard	20:45	29
Finger joint truss floor	Modern	Gypsum wallboard	24:00	26:30

finger jointed trusses. They both failed in less than 30 min as compared to the dimensional lumber test with the same protection of 12.7 mm gypsum wallboard, which failed in approximately 45 min.

This study clearly highlights the inferior structural performance of lightweight structural components under fire conditions. Engineered wood floor assemblies have the potential to collapse very quickly under well ventilated fire conditions. When it comes to lightweight construction there is no margin of safety. There is less wood to burn and therefore potentially less time to collapse. The results of tests comparing the fire performance of conventional and modern construction will improve the understanding of the hazards of lightweight construction and assist incident commanders, company officers and fire fighters in evaluating the fire hazards present during a given incident, and allow a more informed risk–benefit analysis when assessing life safety risks to building occupants and fire fighters.

3.2.3. Windows. With increased fuel loads in houses the amount of air available to allow a fire to grow has become the limiting factor and therefore very important. How long it takes for a residential window to fail has not been extensively examined. Most of the previous research has dealt with commercial windows or windows impacted by wildland fires [27]. The object of this series of experiments [28] was to evaluate the reaction to fire of six different window assemblies, by means of fire endurance experiments with the furnace temperatures controlled in accordance with the time–temperature curve presented in the Standard, "Fire Tests of Window Assemblies," UL 9, 8th Edition dated July 2, 2009 [29].

Fire performance experiments were conducted to identify and quantify the self-ventilation performance of windows, comparing legacy to modern, in a fire event prior to fire service arrival (Figure 20). Different window construction parameters assessed include: (1) wood frame and vinyl frame construction; (2) single and multi-pane designs and (3) single and multi-glazed designs. Modern windows are defined as windows that are able to be easily purchased new and that are typically

Figure 20. Window experimental setup.

Table 4
Window Experiment Sample Descriptions

Designation	Description	Type	Size width (m) × height (m)/ glass thickness (mm)
A	Wooden frame, two pane, single glazed, storm	Legacy	0.8 × 1.2/2.4
B	Vinyl clad wood frame, two pane, double glazed	Modern	0.8 × 1.4/2.2
C	Wood/metal frame/nine pane over one pane, single glazed	Legacy	0.7 × 1.5/2.9
D	Premium plastic frame, two pane, double glazed	Modern	0.7 × 1.4/2.2
E	Plastic frame, two pane, double glazed	Modern	0.7 × 1.4/2.2
F	Premium wooden frame, two pane, double glazed	Modern	0.7 × 1.4/2.3

found in houses constructed after the year 2000. The legacy windows used in these experiments were purchased used and are meant to be representative of windows that would be found on houses built between the years 1950 and 1970 (Table 4).

There were a number of different window failure mechanisms and degrees of failure observed during the experiments. In order to have an impact on the fire growth there has to be a passage for air to enter the structure, therefore the failure of interest was the breaking out of the glass as opposed to the cracking of the glass. Failure is defined as a passage through the window of 25% or more of the total glass area. In most cases this was the failure of the top or bottom pane(s) of the window but in some cases the top window sash moved downward, opening the window 25% or more. The two legacy windows with single glazing failed later than the four modern windows with double glazing (Figure 21). The two legacy windows failed at 577 s and 846 s respectively while the modern windows failed at 259 s, 254 s, 312 s, and 270 s respectively (Table 5).

Figure 21. Windows after the experiment (middle window was modern).

Table 5
Window Failure Times

Experiment	Window [mm:ss (sec)]					
	A (L)	B (M)	C (L)	D (M)	E (M)	F (M)
1	6:34 (394)	4:24 (264)	11:49 (709)	3:58 (238)	5:16 (316)	3:39 (219)
2	10:06 (606)	4:38 (278)	14:30 (870)	3:39 (219)	4:26 (266)	5:49 (349)
3	12:11 (731)	3:56 (236)	16:00 (960)	5:05 (305)	5:55 (355)	4:02 (242)
Average	9:37 (577)	4:19 (259)	14:06 (846)	4:14 (254)	5:12 (312)	4:30 (270)

These experiments demonstrated a significant difference in legacy and modern windows exposed to fire conditions. In this series of experiments the legacy single glazed windows outperformed the modern double glazed windows in terms of longer failure times. It is proposed that this occurred for two reasons. First the legacy windows had thicker glazing than the modern windows. The legacy windows had glass thicknesses of 2.4 mm and 2.8 mm, while the modern window thicknesses were 2.2 mm. Second, the method the glass was fixed into the frame differed greatly between the two eras. The legacy window glass was held in place with putty like substance and there was room in the frame for expansion of the glass. The modern glass was fixed very tightly into the frame with an air tight gasket and metal band, to provide better thermal insulation. This configuration did not allow for much expansion and therefore stressed the glass as it heated and expanded.

3.2.4. Interior Doors. Much like structural components, doors have been changed from a solid slab of wood to an engineered approach where doors are made hollow to use less material. To examine the impact of this change on fire resiliency three different interior door designs were exposed to the panel furnace following the temperature curve specified in "Positive Pressure Fire Tests of Door Assemblies," UL 10C, 2nd Edition dated January 26, 2009 [30]. Different door construction parameters assessed include: (1) Hollow and solid core construction; and (2) different wood types (Figure 22).

There was only one door failure experiment conducted and the failure times are shown in Table 6. Failure was defined to have occurred when the unexposed surface of the door sustained burning. All of the doors failed at approximately 300 s (Table 6). There was very little difference between the two hollow core doors (1 and 2). The fire ignited the unexposed side and quickly consumed what was left of the door. The solid core door (3) had a similar failure time but the mechanism was different. Door 3 burned through at the panels because of their reduced thickness. The thicker portions of the door remained intact at the termination of the experiment (Figure 23). This experiment shows the fire containment ability of interior doors during a well-ventilated compartment fire is approximately 5 min. For the doors evaluated in this experiment it can also be concluded that the type of wood had no noticeable impact on failure time.

Figure 22.   Door samples prior to testing.

Table 6
Door Failure Times

	Door		
Experiment	Hollow Oak	Hollow Composite	Solid 6-panel
7	5:12 (312)	5:15 (315)	5:02 (302)

Figure 23.   Door samples after the test.

The doors evaluated in this experiment demonstrated that the type of wood had no noticeable impact on failure time. The failure time was dictated by the thickness of the door. The hollow core doors had the same overall wood thickness as the panels of the solid core door and therefore the fire breached them at very similar times. Without the panels cut into the solid core door it would have lasted substantially longer as indicated by the amount of wood remaining in the post test analysis of the door.

3.3. Impact on Firefighting Operational Timeframes

The most significant impact of the changing residential fire environment on fire-fighting tactics is the dramatic shift of the safe operational timeline for the fire service. The operational timeframe for the fire service begins with their arrival on scene and ends when the fire is placed under control (Figure 24). To compare the modern and legacy fire environment it is important to examine the time prior to fire department arrival.

The time t_1, depends upon a number of factors such as when the fire is detected after initiation, and the time to call for fire service assistance. This time can vary greatly depending on the source of ignition, item ignited, presence of occupants, presence of fire protection devices and many other factors.

The time t_2, is the time for the 911 operator to call the appropriate fire station to respond. The US national standard NFPA 1221 [31] define the maximum value for t_2 as 60 s.

The time t_3 is the time it takes for the firefighters to get onto the fire apparatus and respond. As per NFPA 1710 [32] this equals 60 s to begin the response.

The time t_4 is the time it takes for the firefighters to drive to the scene of the fire. Following NFPA 1710, the goal for fire emergency response is to arrive at the scene within 4 min after the 911 call is made. That is, $t_2 + t_3 + t_4 \leq 6$ min. Following NFPA 1720 [33], the goal for fire emergency response is to arrive at the scene within 9 min in an urban area ($\sim$384 people/km^2), 10 min in a suburban area (192 people/km^2 to 384 people/km^2), 14 min in a rural area ($\sim$192 people/km^2) and directly related to driving distance for remote areas greater than 8 miles from the closest fire station. Therefore $t_2 + t_3 + t_4 \leq 11$ min to 16 min.

Analyzing the National Fire Incident Reporting System (NFIRS) database yields a very consistent average fire department response time to one and two family detached homes (Occupancy Code 419 in NFIRS) in the United States. Table 7 shows an average response time ($t_2 + t_3 + t_4$) of approximately 6.4 min from 2006 to 2009.

Some international comparisons of fire department response times are available. In 2006, the average response time to dwelling fires in England was 6.5 min [34]. A report comparing residential fire safety in several countries states, "Response time goals in Sweden and Norway are more lenient than in the United States. The Scandinavian nations require the first responding unit to arrive in 10 min, versus a
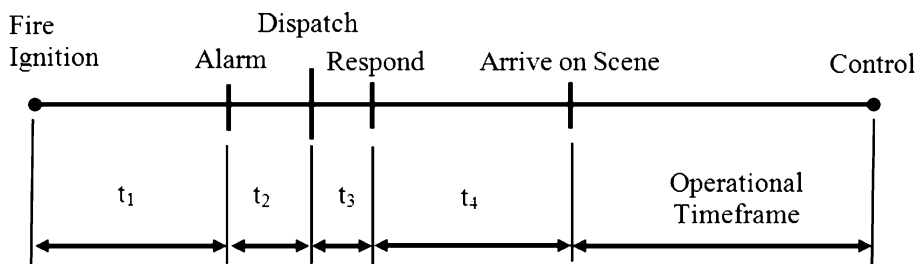
Figure 24.   Fire service timeline.

Table 7
Average Fire Department Response Times

Year	Incident count	Average response time
2006	42,584	6.2
2007	49,664	6.5
2008	50,775	6.6
2009	49,386	6.4

*Note*: Fires in homes >$10,000 in value with >$1 in loss

goal of 6 min in the typical United States city. Scandinavia generally gives more weight to prevention and early extinguishment by homeowners, less to rapid response'' [35]. A report written by a German Fire Officer in 2004 examined response times in Europe by contacting country officials and asking them questions about their acceptable response times and conducting an internet search. Many countries such as Denmark, France, Greece, Ireland, Norway and Sweden had acceptable urban response times of 10 min and response times to suburban or rural areas of 15 min to 30 min [36].

Conservatively assuming the fire is noticed quickly and the fire department is called quickly t_1 could be 2 min. Using the average response time for the US fire service, the operational timeframe would begin at 10 min (Figure 25).

To compare modern and legacy fires as they pertain to the operation timeframe, times to flashover can be added to the respective times to collapse. Times to flashover were taken from the room fire experiments in Section 4. The modern room flashed over in 3:30 to 4:45 and the legacy room flashed over in 29:30 to 34:15. The unprotected modern floor system (Engineered Wood I joist) collapsed in 6:00 (Table 3), and adding a layer of gypsum board increased the collapse time to 26:43. The unprotected legacy floor system (Dimensional Lumber 2 by 10) collapsed in 18:35, and adding a layer of plaster and lath increased the collapse time to 79:00 (Figure 26).

4. Discussion

There has been a steady change in the residential fire environment over the past several decades. These changes include larger homes, more open floor plans and
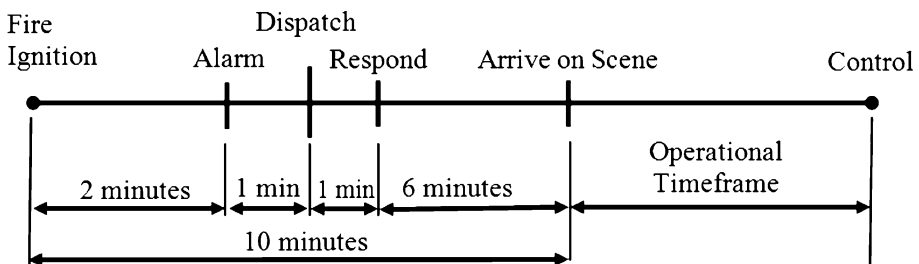
Figure 25. Fire service timeline example.
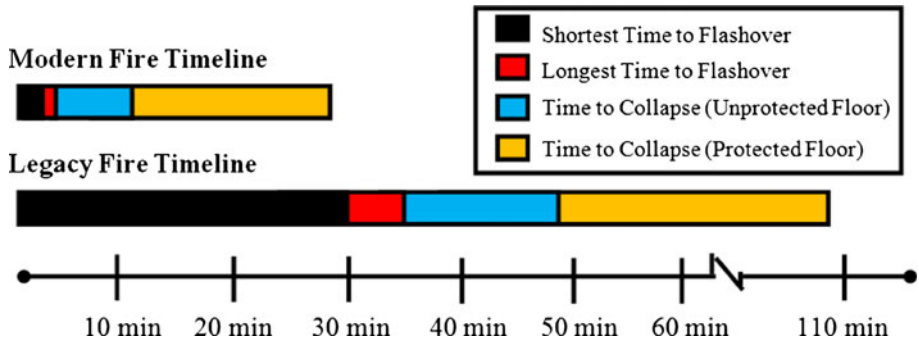
Figure 26.   Modern versus legacy fire timelines.

volumes, increased synthetic fuel loads and new construction materials. The larger the home is the more air available to sustain and grow a fire in that home. Additionally, the larger the home the greater the potential to have a larger fire, and the greater the potential hazard to the responding fire service resources.

Combining of rooms and taller ceiling heights creates large volume spaces which when involved in a fire require more water and resources to extinguish. These fires are more difficult to contain. This also means shorter escape times for occupants as the egress routes may be compromised earlier due to lack of compartmentation.

Comparing the experiments, times to flashover are very similar between the three modern experiments and the three legacy experiments (Table 8). All of the modern rooms transitioned to flashover in less than 5 min while the fastest legacy room to achieve flashover did so at in over 29 min. In these three sets of experiments legacy furnished rooms took at least 700% longer to reach flashover.

Even though the third modern room was 8.4 m^2 larger and had a 1.3 m^2 larger front opening a similar fuel load was able to flash the room over in the same time. The 4.0 m by 5.5 m legacy experiment did not transition to flashover because it did not have enough fuel burning at the same time to create significant heat in the upper gas layer to ignite items that were not adjacent to the sofa. The chairs on the left side of the room and the television and bookcase of the right side of the room were never heated to their ignition temperatures.

The modern rooms and the legacy rooms demonstrated very different fire behavior. It was very clear that the natural materials in the legacy room released energy slower than the fast burning synthetic furnished modern room. The times

Table 8
Comparison of Flashover Times

Experiments	Modern	Legacy
1, 2	3:40	29:30
3, 4	4:45	34:15
5, 6	3:20	Not achieved

to flashover show that the a flaming fire in a room with modern furnishings leaves significantly less time for occupants to escape the fire. It also demonstrates to the fire service that in most cases the fire has either transitioned to flashover prior to their arrival or became ventilation limited and is waiting for a ventilation opening to increase in burning rate. This difference has a substantial impact on occupant and firefighter safety. This change leads to faster fire propagation, shorter time to flashover, rapid changes in fire dynamics, and shorter escape times.

Four examples of new construction materials were examined; wall linings, structural components, windows and interior doors. The change in wall linings now allows for more content fires to become structure fires by penetrating the wall lining and involving the void spaces. This change allows for faster fire propagation and shorter times to collapse. The changes in structural components have removed the mass of the components which allows them to collapse significantly earlier. In these experiments an engineered I joist floor system collapsed in less than 1/3 the time that the dimensional lumber floor system collapsed. Modern windows and interior doors fail faster than their legacy counterparts. The windows failed in half the time and the doors failed in approximately 5 min. If a fire in a closed room is able to get air to burn from a failed window, then it can burn through a door and extend to the rest of the house. This can lead to faster fire propagation, rapid changes in fire dynamics and shorter escape times for occupants as well as firefighters.

Using the conservative value of 10 min as the start of the operational timeframe and comparing it to the modern and legacy fire timelines shows the hazard that the modern fire environment poses to firefighters. It also highlights that the operational timeframe begins after potential flashover. In many cases this means that if sufficient ventilation is available the fire will spread significantly prior to fire service arrival. If sufficient ventilation is not available the fire will become ventilation limited and be very sensitive to initial fire service operations. The potential for fast fire propagation, and rapidly changing fire conditions should be expected in the modern fire environment while arriving at 8 min to a legacy fire, it would still be in the growth stage and less volatile.

Looking beyond fire development and to collapse further hazards are highlighted. In the modern fire environment, after arriving at 8 min, collapse is possible as soon as 1:30 later. Firefighters may not be in the house yet or may be just entering to search for occupants. The legacy fire collapse hazard begins 40 min after arrival of firefighters. This allows for a significant amount of fire operations to take place all while reading the safety of the structure. Figure 27 shows the standard response times for different types of fire departments and the location on the fire development timeline that they arrive in both the modern and legacy fires.

The conditions that firefighters are going to be faced with today and into the future have been significantly impacted by the ever changing fire environment. As society continues to make changes to building materials as a result of the desire to be environmentally conscience and to increase profit the fire environment is going to continue to change and if the current trends continue it will not be in favor of firefighter safety. Therefore it is important that firefighters study this new fire environment and its impact on their safety and tactics. The first component of this is
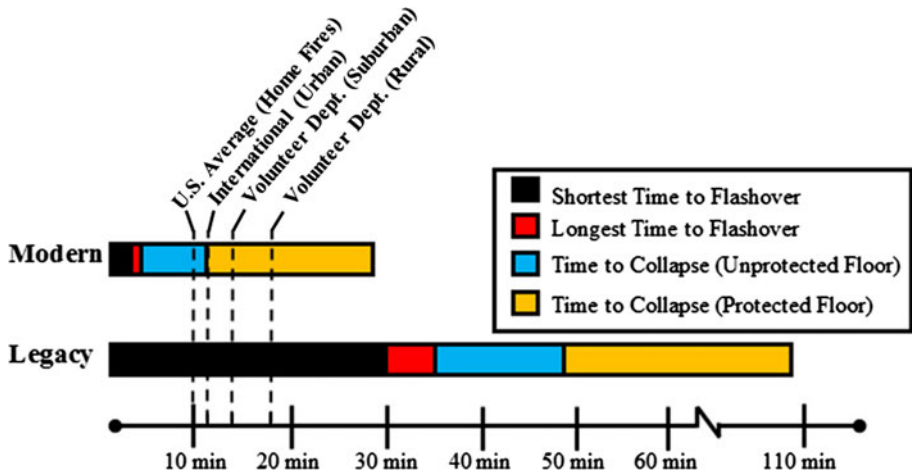
Figure 27.   Fire service arrival times versus fire development.

understanding the conditions they are arriving to are very different than several generations ago. Fire conditions can change rapidly due to the under ventilated fire conditions and floor systems can collapse quickly and with little warning. While operating conditions need to be constantly monitored to understand the impact of the tactics used and the potential need to change them. Ultimately, if the fire environment has changed tactics need to change or be reevaluated to have the greatest opportunity to be most effective on today's fires.

5. Suggestions for Future Research

Research should be conducted to examine the impact of changing fuel loads in full-scale structures especially how it pertains to fire service operations. The impact of ventilation is key to this fire development as well. Experiments need to focus on fire department tactics to make sure that they are still relevant with this evolving fire environment.

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