INVESTIGATING MULTI-COMPARTMENT FIRE BEHAVIOR OF ELEVATED ORIGINS

Steven W. Carman, IAAI-CFI, CFEI, ATF-CFI (Retired)
Carman & Associates Fire Investigations, Dunsmuir, CA

ABSTRACT

Recent efforts have occurred in the fire investigation community to examine the behaviors of elevated fires and their contribution to large blazes. Lab scale research in the 1980s demonstrated the propensity of these fires to produce high levels of carbon monoxide and identified the ignition behaviors of the vitiated upper layer. Full scale testing of these fires has started but remains limited.

A historical review of selected elevated fires demonstrates the threat of death or serious injury these fires pose as well as the difficulties investigators face in accurately identifying their origins. One investigative challenge they pose is the occasional steep, seemingly reversed damage gradient between the room of fire origin and adjacent spaces. Such apparent anomalies can prove vexing to investigators following the commonly accepted methodology of identifying fire origins by moving from areas of lesser to more extensive damage.

In the past eighteen months, several, full-scale, elevated fire tests have been conducted attempting to recreate such conditions. In each test, the fires extended into adjacent spaces and burned beyond flashover. Subsequent examinations showed that in each case, the rooms of fire origin received far less damage than adjoining rooms.

INTRODUCTION

Since most fire fatalities involve exposures to combustion gases, there is emphasis amongst fire investigators to better understand ventilation-limited fires. Of that broad class of fires, elevated fires are particularly interesting. One of the most notable facets is the propensity of elevated fires to produce high concentrations of carbon monoxide capable of causing remote fatalities while generating levels of burn damage near the fire origin similar to fires of only moderate severity.

Research done in the 1980s and 1990s added significantly to the understanding of the production of carbon monoxide in fires. Beyler studied the effect on fire behavior of varying the equivalence ratio, ϕ, in a smoke layer.[1, 2] Later Gottuk et.al. added to Beyler's findings by further examining the effects of varying the plume equivalence ratios of fires burning various fuels.[3] Gottuk's and Beyler's work showed that the production of CO in a compartment fire is primarily dependent on the compartment flow dynamics (i.e., the equivalence ratio) as well as the upper layer temperature. Lattimer, et.al. provided even more insight into CO generation by considering the effects of wood in the upper layers of post-flashover fires.[4]

In 1987, a kitchen fire in a Sharon, Pennsylvania, three bedroom, duplex house resulted in the deaths of three young women.[5] The fire was primarily limited to the first floor kitchen while each of the victims were on the second floor. A broken window in the kitchen allowed the fire to reach flashover. Two of the victims died of carbon monoxide poisoning while the third was burned. The carboxyhemoglobin level of one victim was 91%.

The kitchen in the Sharon fire had wood paneled walls and a combustible ceiling. Following the fire, Harold 'Bud' Nelson and Robert Levine of the National Institute of Standards and Technology conducted full-scale burn tests to simulate the Sharon fire. They also examined the fire behavior using two "zone" fire models. Among their interests was the extent of carbon monoxide production and its ability to spread throughout the building. The test fire fuel load consisted of more than 200 kg of wood cribs and plywood sheets

On December 22, 1999 a fire in a two story duplex house in Keokuk, Iowa claimed the lives of three children and three firefighters.[6] The fire started in plastic materials on top of the kitchen stove on the first floor of the residence. Initially, the front door to the residence was closed. It was forced open by an arriving police officer who found dense smoke conditions in the living room but no flaming.

Two infants were removed from the house and taken to a hospital. Witnesses reported that the living room did not become fully involved in fire until the infants were being transported. As a second fire crew entered the house and began to attack the fire, a firefighter from an initial crew was discovered on the floor of the living room. Later, two other firefighters from the first crew were found on the second floor.

Like the Sharon fire, toxic gases and high carbon monoxide levels killed the civilian victims of the Keokuk fire. The firefighters were overcome by thermal, post-flashover conditions. The dining room located between the kitchen and living room was far less damaged than either of the adjacent rooms. Had witnesses not observed the progression of the fire development, analysis of the burn patterns through the house may have later proved difficult to resolve fire movement.

Dan Madryzkowski, Glenn Forney and William Walton of NIST analyzed the Keokuk fire and the conditions that led to the fatalities. Like Nelson and Levine, they used computer fire modeling software to estimate fire behavior. The analysis showed how the fire started in the kitchen and spread hot smoke through the adjacent dining room, into the living room and upstairs where the children were located. When the police officer opened the front door, the living room was smoky but not burning. After, the kitchen window completely failed, the kitchen fire progressed to flashover. Thereafter, the fire extended into the living room and upstairs where it also flashed over. The intervening dining room seemingly avoided flashover resulting in only moderate fire damage there.

FIRE BEHAVIOR REVIEW

In compartment fires, hot gases rise in a buoyant plume until they reach a ceiling or horizontal barrier where they are deflected and spread radially outward in a ceiling jet. If the ceiling jet is bounded by walls that restrict outward spread, smoke backs up and deepens into a layer. If the smoke layer reaches open vents, e.g. windows or doors, it flows out of the compartment.

As a plume rises, surrounding air is entrained or mixed into it. This entrainment occurs all along the plume surface between the base of a fire to the underside of the descending smoke layer. Outside the plume, vertical mixing between the lower, cool air layer and the hot smoke is generally negligible. Some mixing between the smoke layer and the air below may occur near vents as the incoming cooler air shears against the hot gas layer.[7]

Air entrained into the flame supports combustion of the unburned fuel gases. The flame zone generally stops at the height where enough air has been entrained to burn the fuel. Additional air continues to entrain higher up in the plume. This extra mass both cools the plume and increases its volume.

The maximum amount of heat energy that can be released in a compartment fire is limited by the amount of air that can enter to support combustion. Before flashover, there is often enough air in or entering a compartment to burn all of the emitted fuel gases. At that stage of a fire, its maximum size is “fuel limited” - limited by the amount of fuel being burned. Adding air under those conditions will not increase the heat released. Burning more fuel causes an increase.

About the time flashover as all available fuel begins to pyrolyze, the air/fuel balance is quickly disrupted. More fuel gas is released than there is air to burn it. At this stage, the maximum fire size becomes “ventilation limited”. The maximum heat release rate is no longer dependent on the amount of fuel gas burning but on how much air is available for combustion.

The perfect balance of fuel-to-air is known as the stoichiometric ratio and is designated by (fuel/air)stoichiometric. At any point in an fire, the actual fuel-to-air ratio, (fuel/air)actual, is greater or lesser than the stoichiometric ratio. A relationship known as the equivalence ratio, designated by ϕ, is given by the expression,

$$\phi = \frac{(fuel/air)_{actual}}{(fuel/air)_{stoichiometric}}$$

For fuel limited conditions in which there is more than enough air to burn the fuel gas, $\phi < 1$. Under ventilation limited conditions with insufficient air to burn all the fuel, $\phi > 1$. When a compartment fire has transitioned through flashover or become ventilation limited, excess, unburned fuel gas can flow out of vents before burning. If hot enough, once it encounters sufficient air outside of the compartment, it can ignite. This effect is often described in the literature and associated with post-flashover, fully developed fire conditions.[8-12]

Much of Beyler and Gottuk’s research involved evaluating the equivalence ratio of the upper smoke layer. As a smoke layer descends through the flame zone, the entrainment of hot smoke (with its lower oxygen concentration) inhibits combustion and causes unburned fuel gas to enter the smoke layer.[12] It also increases the concentration of carbon monoxide (CO) in the smoke. Beyler’s experiments showed that when ϕ reached about 1.8 a smoke layer can ignite.[1]The production rate of CO rises significantly at values of ϕ of 0.6 and above. At around $\phi > 1.2$, Beyler found that CO in his experimental apparatus reached a maximum level of about 6%. [1,2]

Fuels that are already partially oxidized such as wood tend to produce higher levels of CO. Lattimer et.al. showed that, “Tests with wood in the compartment upper layer produced compartment global equivalence ratios in the range of 5.2 to 5.6. These equivalence ratios are over two times greater than those measured in tests with no wood in the upper layer. Inside the compartment with a window opening, the CO concentrations were measured to increase from an average of 3.2% dry without wood in the upper layer to an average of 10.1% dry with wood in the upper layer.”[4]

Following Nelson and Levine’s work on the Sharon, Pennsylvania fire, Pitts, et.al.[13] also investigated the contribution of upper layer wood to the production of CO. In their tests of a reduced-scale compartment with the ceiling and upper portion of the walls lined with wood, they measured CO levels as high as 12%. That was four times greater than CO concentrations in room fires with no wood in the upper layer.

Another factor related to CO concentration is the smoke temperature. In a fire, CO is often an intermediate product of combustion. It can further oxidize in the presence of oxygen to form CO_2. Gottuk showed that smoke layers with temperatures below about 600°C (875 K) freeze out the conversion of CO to CO_2 in the upper layer.[3] In other words, once CO is present, even in the presence of adequate oxygen the CO will not oxidize further. So for fires like elevated fires that create high amounts of CO, once it flows out of the room of origin, unless the adjacent rooms are above 600°C, it is likely that the CO will not oxidize further until spreading throughout the building.

ELEVATED FIRE BEHAVIORS

The distance between the base of an elevated fire and lower level of the smoke layer is less than for similar fires burning lower in a room. Accordingly, it follows that the CO production from an elevated fire will occur sooner and be much greater than for an identical fire burning at floor level. The likelihood of CO production from elevated fires is greater than that from similar sized fires starting lower in a room. For fires in rooms with wood in the upper layers, the risk is even greater.

A recent report by the U.S. Fire Administration[14] stated that from 2003 to 2007, cooking caused approximately 40 percent of residential structure fires in the United States. Since most cooking occurs at an elevated level above the floor, and since most kitchens have upper, wood-based cabinets, it follows that if these fires are able to grow, they pose a significant risk of CO generation and possibly of death to people located even remotely to them.

Previous work by the author showed that flame extension is possible from the room of origin of an elevated fire without the fire ever reaching flashover.[15] In several elevated fire tests in which the only vent in the rooms of origin were single doorways, the fires did not achieve flashover yet flames extended out from the rooms. Even though upper layer temperatures may have reached and exceeded the 600°C level typically associated with flashover, only minimal fire damage occurred low in the rooms. Had there been windows, the high temperatures would likely have caused them to fail and the additional ventilation would have likely led to flashover.

If elevated fires were limited to just one room, identifying their origin would be relatively easy. The smoke layer generated by the fire would not descend far below the level of the burning fuel. As the smoke enveloped the flame, the smoky, entrained air would slow the combustion. Further layer descent would also slow and the smoke level would stabilize or oscillate at or slightly above the base of the flames. Similar burn damage limited to areas high in a room is often looked upon as having been caused by hot smoke flowing into the room from a fire burning elsewhere.

In the past two years, fire tests were designed and conducted to create scenarios where the rooms of fire origin would have significantly less damage than adjacent spaces. By examining the scenes of such fires, it was hoped that techniques might be developed to better recognize how the fires spread. The commonly employed practice of locating the area of origin by moving from areas to lesser damage to more damage would be ineffective in such cases and might lead investigators away from an origin rather than towards it.

The fire tests involved elevated fires. It was anticipated that even absent flashover, flames would extend out of the room of origin and into an adjacent room. If the fires then burned in the secondary rooms with adequate ventilation, those rooms might reach flashover. Previous work[16, 17] discussed challenges of interpreting burn patterns in post-flashover fires. In such investigations it is important to recognize that burn patterns from the most intense burning are typically located in or near areas of adequate ventilation, sometimes far from the origin. Equating the most severe damage with the longest period of burning could lead to improper origin determinations.

Inboth the Sharon, Pennsylvania and Keokuk, Iowa fires, the rooms of origin eventually reached flashover. Each time, when windows in the rooms of origin failed, adequate ventilation enabled the transition. If elevated fires occurred in rooms without the extra ventilation from an open window, the most severe burning could be in rooms distant from the room of origin. The burn damage near the origin might appear more typical of that caused by exposure to fires starting elsewhere and smoke flowing into the room. It could be limited to moderate smoke staining in the upper portions of the room.

If an elevated fire occurred in a room with wood in the upper smoke layer, it is conceivable that with the expected production of high levels of CO, fatalities could occur at a distance from the origin. If the room had limited ventilation that prevented it from reaching flashover, flames might extend out into adjacent spaces. If those other spaces were adequately ventilated, it is conceivable they might become fully involved (such as in Keokuk). Investigators moving from areas of lesser damage to more damage to locate the origin might improperly interpret the more severe damage as suggesting the fire started in one of the nearby rooms. Not finding an obvious cause in the secondary rooms, investigators could potentially conclude the fire started there from the application of an open flame, an act of arson. The example fatal fire would then be classified as a homicide.

At least two such scenarios are known to have occurred in the United States in the past ten years.[18] In each instance, an elevated fire at stovetop level is believed to have generated high levels of CO that killed occupants. The damage in each of the rooms of origin was less than that in nearby spaces. Investigators using the methodology for locating an origin of moving from areas of less damage to areas of more damage actually moved away from the kitchens and stovetop origins rather than towards them. Not finding obvious causes near the two presumed origin locations, each investigator concluded open flames had been applied to available combustibles thus causing the fires. Each initially classified the fires as arson and took steps to have fire survivors arrested for murder.

Fortunately in each instance, subsequent reviews by other investigators discovered that the stoves had each been on during the fires and noted severe damage to cooking utensils. Even so, in each of the cases, investigators and prosecutors had initiated steps to file homicide charges. Only through adequate reviews were the processes halted.

SCENARIO TESTING

Denver, Colorado

To try and create a similar fire scenario as that discussed above, a full-scale test was conducted in September 2011 in Denver, Colorado. A two-room structure was built that measured 12 feet by 24 feet overall with an 8 foot high ceiling. Its layout is depicted in Figure 1. Upper and lower cabinets of bare, oriented strand board were built into the 8’ x 12’ smaller room (hereafter referred to as the “kitchen”) was outfitted with. The tops of the lower cabinets were 37” above the floor. The adjacent 12’ x 16’ room was furnished with a queen size bed, bedside table, upholstered chair and dresser. Walls throughout the structure consisted of 1/2” gypsum board over wood studs. The floor was covered with carpeting over plywood sheeting.

A fire was set in the kitchen in a 12-inch deep pot containing cooking oil. Flames from the oil impinged directly upon the upper wooden cabinet above the pan. The test was intended to see if the burning oil would ignite the upper wooden cabinets, filling the upper portion of the kitchen with ignitable fuel-rich smoke. If the smoke layer did ignite, it was anticipated that flames would spread out of the kitchen and ignite fuels in the adjacent room. With an open doorway to the exterior, the second room might later reach flashover eventually causing more severe burning there than in the room of origin.

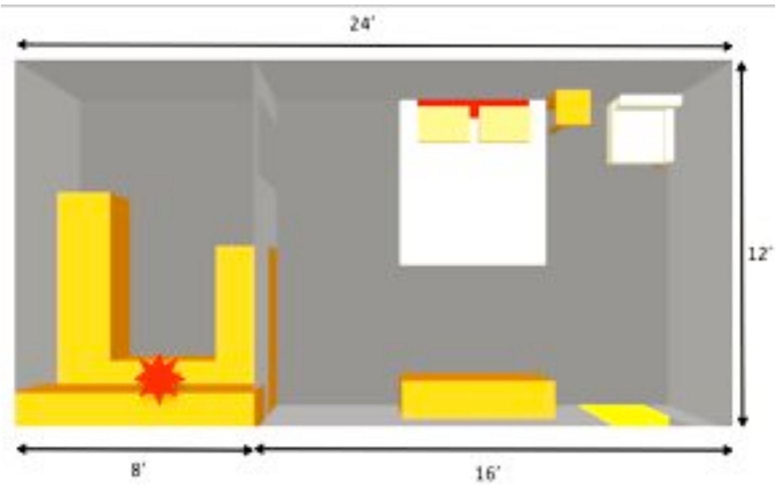

Figure 1 - Layout of Denver test structure. 8’ x 12’ Kitchen to left with open doorway. 12’ x 16’ room to right with open doorway to exterior.

Though extensive instrumentation was not available for the test, eight Type-K thermocouples were installed in the test building. Four were mounted in the kitchen on TC-1, which was aligned with the door to the larger room. They were installed at 7’6”, 5’3”, 3’1” (lower cabinet height) and 0’6” above the floor. Four additional TC were placed in the larger room, two inside the main door (TC-2) at 7’6” and 4’0” above the floor and two the corner behind the upholstered chair (TC-3) also at 7’6” and 4’0” above the floor.

The flames from the burning oil impinged directly on the upper cabinets and extended about one foot up the face. Even so, the fire in the kitchen was slow to grow. Up until 15 minutes after ignition, the fire caused upper layer temperatures to rise only to near 150°C. To increase the fire growth and add unburned fuel gas to the smoke layer, additional fuels were placed on top of the lower cabinets. They included a plastic basket and plastic sheet positioned next to the burning oil under the upper cabinet along with denatured alcohol squirted on the surface. Even though the fire was ventilation limited, it was thought that additional, faster growing fuels below the upper cabinets might generate sufficient heat to allow the fire to advance. After adding the extra fuel at around minute 15, upper layer temperatures started to rise.

The lower edge of the kitchen smoke layer ignited at about 16 minutes and 15 seconds. At 16 minutes and 40 seconds, the first flames extended from the smoke layer into the adjacent room and the kitchen smoke layer descended to the top surface of the lower cabinets. At about 17 minutes and 15 seconds, the tops of the lower cabinets were engulfed in flames.

Upper temperature reached 600°C at about 18 minutes 40 seconds. The temperature at the top of the lower cabinets at that time was only 250°C but rising. It reached 600°C about 1 minute 20 seconds later. All kitchen temperatures peaked at about 860°C at about 20 minutes 30 seconds and then quickly dropped. Because of the lack of exterior ventilation to the kitchen, once the larger room became involved in fire, the kitchen apparently self-extinguished. Had there been a window to the kitchen, it would have surely failed and flashover in the room would likely have ensued.

Temperatures in the large room had been relatively stable until 17 minutes after ignition. At about 19 minutes and 50 seconds, the first flames extended outside of the main doorway to the exterior. At that time, the temperature 7’6” above the floor behind the upholstered chair (TC – 3) was approximately 400 °C. Steady flaming extended through the outer doorway at 21 minutes and 30 seconds and filled most of the doorway by 22 minutes, about the same time as upper layer temperatures reached 600°C. The fire was extinguished after 2 minutes of post-flashover burning. Temperatures peaked at around 23 to 24 minutes. The highest temperature measured in the living room was about 900°C at 4’0” above the floor behind the upholstered chair. Temperatures near the exterior doorway lagged by about 30-60 seconds.

As expected, the most severe burn patterns in the larger room were along the inflowing air path through the exterior doorway. Large areas of clean burn occurred to the nearby wall and ceiling (see Figure 2). Further back into the large room toward the kitchen (opposite direction from Figure 2), damage lessened as shown in Figure 3. Gypsum walls were smoke stained there but the paper remained mostly unburned below about 3 feet from the floor.

Inside the kitchen, damage was significantly less than that in the large room. Even though countertop temperatures reached 860°C for a short time, in the lower portions of the room, the paper on the gypsum board was only moderately smoke stained as seen in Figure 4. The bare wood face of the lower cabinets experienced only minor damage with some areas receiving only minor discoloration. Closer to the door, the burn pattern on the adjacent gypsum wall was similar to the wall damage next to the exterior entry door (see Figure 5). This kitchen pattern could easily have been interpreted as being caused by hot gases entering from a fire in the larger room. It was actually formed by fuel-rich gases in the ventilation-limited room encountering fresh air entering from the larger room.

Figure 2 – Area of severe damage coincides with path of inflowing air

Figure 3 – Opposite end of large room showing areas with less damage. Room of origin is beyond distant doorway

Figure 4 – Minor damage to wood cabinet and gypsum wall board in room of origin

Figure 5 – Pattern on kitchen wall opposite origin. Door to larger room opens to the right

The most severe damage in the kitchen was at the origin. It included burn-through below the upper cabinet as well as an inverted V pattern on the front face of the cabinet where flames directly impinged for approximately 20 minutes (see Figure 6). Even so, the damage was less severe than that near the main doorway in the larger room created during the 2 minutes of post-flashover burning (Figure 2). A circular area of clean burn (visible at the top of Figure 6) on the kitchen ceiling was centered about 2 feet out from the pan of burning oil.

Figure 7 shows a view of the underside of the upper cabinet above the burning oil. The worst charring aligns with the most severe damage to the cabinet face.

Figure 6 – View of area of origin. The pan of burning oil was on the lower cabinet

Figure 7 – Underside of cabinet directly above the origin

Though the post-flashover burning in the large room lasted for only about 2 minutes (10% of the time of direct flame impingement on the upper kitchen cabinet), the intensity of burn damage in the larger room was extensive. Even though the most intense burning was in the larger room, localized damage could still be seen in the kitchen and was inconsistent with mere extension of hot gas from a fire burning in the large room.

The Denver fire was analyzed using Fire Dynamics Simulator, a computational fluid dynamics package created by NIST. Though the time of fire development was significantly shorter in the modeling run than the actual fire, the difference was attributed to inaccurate estimation of the input fire. Rather than using an input fire based on an estimated mass loss rate of oil in a deep pan, a steady state fire was used. The intent of the modeling though was to primarily examine whether the trends in oxygen depletion and air/smoke flow could be simulated. That part of the modeling was successful and suggested such attempts might be useful for hypothesis testing in other similar investigations as to fire movement.

Investigating the origin of such a fire scene by moving from areas of least damage to more damage would be a significant mistake. It would lead investigators away from the origin, not towards it. Such cases demonstrate the importance of incorporating witness statements to identify length of fire involvement and direction of fire travel as well as other techniques such as arc mapping as suggested in NFPA 921, Guide to Fire and Explosion Investigation.

Chico, California

A second, similar fire test was conducted in Chico, California in May 2012. In that test, another two-room, wood-framed building with an open porch on one end was burned. The building was almost entirely constructed of wood and measured approximately 12 feet wide by 24 feet deep. A lateral wall with a doorway separated the two rooms into approximately equal spaces measuring close to 12' x 12'. Unlike the Denver test with gypsum walls and ceiling, the 8-foot high ceiling and walls in Chico were combustible and consisted of either wooden plank or sheets. Newspaper was mounted directly to the wood to simulate wallpaper. The floor throughout the building was a linoleum type sheet mounted to the wooden subfloor. A layout of the building is shown in Figure 8.

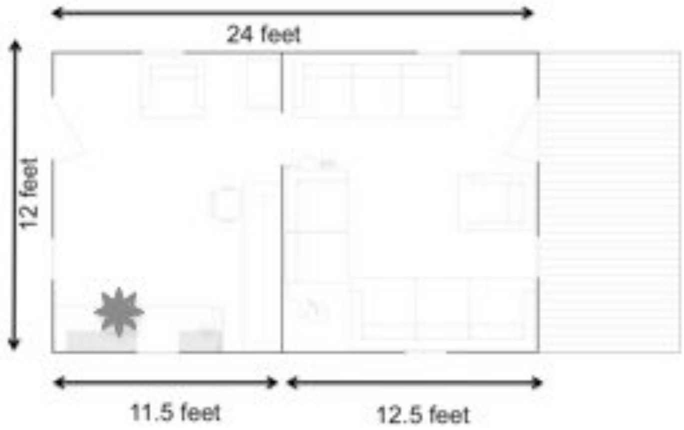

Figure 8 – Layout of Chico burn building. The open porch is to the right.
The left (rear) door was closed. The front was open. The center doorway is open.

A lower level wooden cabinet and two upper cabinets were added to the rear room to simulate kitchen cabinets. The room was furnished with a wooden worktable, desk chair, upholstered chair (minus a seat cushion) and a filing cabinet. The front room contained three upholstered sofas with polyurethane foam seating and one upholstered chair.

The open doorway that joined the front and rear rooms aligned with the exterior doors in the front and rear walls. The rear door was closed throughout the fire. The front door was open. All windows were boarded up during the test.

The fire was ignited in a stack of polyurethane blocks on top of the lower cabinet in the rear room. Data from the fire was only collected through video and still photography. Other data recording instrumentation was unavailable. Even so, qualitative analysis of the fire development seemed possible.

The Chico fire burned much more quickly than the Denver test. The upper smoke layer in the rear room ignited at approximately 2 minutes and 40 seconds. Flame appeared throughout the rear room at about 3 minutes. At the same time, steady flames appeared in the open exterior door of the front room. At 3 minutes and 20 seconds, the front room transitioned through flashover. The subsequent post-flashover fire burned 2 minutes and 10 seconds longer before being extinguished. The primary difference in the Chico and Denver test buildings was the combustible upper finish in the Chico rooms. The room of origin in Chico also was about half again as big as the kitchen in Denver. The extra oxygen in the upper part of the room enabled the wooden ceiling to actively burn once heated.

Like in Denver, the Chico fire caused far more severe damage to the secondary room open to the exterior (see Figures 9 and 10). The extent of damage lessened when moving towards the room of origin that was by comparison, only lightly damaged (see Figures 11 and 12). Again, like in Denver, the damage in the room of origin was generally worse at and above the base of the fire. The localized damage at the actual origin though noticeable, was less severe than the generalized destruction throughout most of the adjacent room.

Figure 9 – Left side of front room. Open exterior door to the left. Room of origin is to the right

Figure 10 – Right side of front room. Open exterior door to the right. Room of origin is to the left

Figure 11 – Rear room. Origin at right side of lower cabinet. Top of the wooden table at the left is unburned.

Figure 12 – Opposite side of rear room Front room through door to right

CONCLUSIONS

The tests were part of a preliminary effort to examine the potential effects of elevated burning in terms of fire investigation. They demonstrated that such fires could create fire patterns that would be improperly deciphered if only examined with historically accepted methods for estimating fire movement. Severity of damage cannot be equated with the amount of time a fire burned. While the mechanism of fire spread between the rooms of origin and the adjacent rooms was not conclusively identified, it may be due to ignition of the upper smoke layer rich with CO and unburned hydrocarbons.

For investigations of fatality fires in which victims remote from the fire succumb to CO exposure, investigators must consider the manner in which the CO was generated. While post-flashover burning is known to create high levels of CO, underventilated burning by elevated fires and/or fires involving wood and other oxygenated fuels immersed in the smoke layer may also be responsible.

Use of a methodology involving examination of a fire scene from areas of lesser damage to areas of more extensive damage should not be relied upon as a means by which a fires origin can be identified. In cases like this, that type of analysis may lead the investigator not to the origin but away from it.

ABOUT THE AUTHOR

Steven W. Carman, IAAI-CFI, CFEI, ATF-CFI (Retired)
Carman & Associates Fire Investigation, Dunsmuir, California

Mr. Carman retired from the U.S. Bureau of Alcohol, Tobacco, Firearms and Explosives in July 2008 as a Senior Special Agent / Certified Fire Investigator. He holds a B.S. degree with High Honors in

Physical Science from the U.S. Coast Guard Academy. He is on schedule to receive a M.S. degree in Fire Protection Engineering from California Polytechnic University, San Luis Obispo in the Spring of 2013. His previous works include, "High Temperature Accelerant Fires", "Improving the Understanding of Post-Flashover Fire Behavior", and "Progressive Burn Pattern Development in Post-Flashover Fires." He has lectured internationally on various aspects of fire science and investigation including fire dynamics, fire chemistry and fire modeling.

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