INVESTIGATION OF AN ELEVATED FIRE - PERSPECTIVES ON THE 'Z-FACTOR'

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ABSTRACT

For years, fire scientists have been aware that diffusion flames from identical fuel packages will burn with different flame lengths depending upon their location in a compartment. If a fuel package burns against a wall or in a corner, then the flame lengths tend to elongate due to limited and altered entrainment flows. Efforts at teaching the fire investigation community about these and other scientific- and engineering-related principles began in earnest in the early 1990s. Since then, this and other types of fire behavior reported by prominent fire scientists have been included in documents regularly used by fire investigators.

While investigators often consider such "x-y" placements (in terms of Cartesian coordinates) and their effects, little attention is given to similar variations in a fire's base height, the "z-factor". What happens to a fire's growth rate or the rate of smoke production when the fire starts well above the compartment floor level? How does the fire response to this condition compare with that of a fire burning near floor level? Answers to such questions are not readily available. Even so, many of the effects can be estimated using general fire dynamics principles. As an example, flames from a fire located well above the floor might impact the ceiling while flames from the same-sized fire at the floor would not. Similarly, the rate of upper layer heating for elevated fires would be expected to be different than for floor level fires. Further, any descent of a vitiated upper layer to or below the burning fuel level would likely cause changes in the heat release rate as well as the rate of carbon monoxide production. Each of these factors could be important to investigators.

This paper will describe the use of full scale and computer fire models to examine various hypotheses of burning behavior caused by variations in the "z" factor. A particular case study will be presented as will a recap of the subsequent analyses related specifically to effects on fire behavior from an elevated fire.

INTRODUCTION

Today in the fire investigation profession, investigators apply scientific principles of compartment fire behavior, heat transfer, combustion science, pre-flashover/post-flashover burning, and flame spread to their investigations more than ever before. The processes involved in compartment fire growth that lead to flashover are of particular importance. Understanding timing associated with fire ignition, growth and spread can be crucial to an investigation, particularly one of a suspected criminal fire.

Twenty years ago, the topic of entrainment was virtually unheard of in the fire investigation community. Fires in the center of rooms were looked at in the same manner as fires against walls or in corners. Investigators typically were unaware of how the time to flashover could be varied simply by moving a burning fuel to a different 'x, y' position in a room. In the Cartesian coordinate system, 'x' and 'y' values refer to locations on the x- and y- axes in a two-dimensional space like that shown by the plan view of a compartment. The 'z' axis is the axis perpendicular to both the x- and y-axes and can be thought of as representing the third dimension, height.

Investigators now generally appreciate the differences resulting from two similar-sized fires burning at different x- and y-positions inside a room. What happens when fires burn at different levels along the z-axis (in terms of height) however, is still not well understood and seems rarely considered. Despite its common involvement in actual compartment fires, this “z-factor” does not seem to have garnered much research attention. Results of a literature review suggest most experimental fires are either set at or near floor level or under conditions where smoke layers do not significantly influence the burning behavior. A literature review did not find any studies specifically addressing the effects of elevating fuels along the z-axis. High rack storage fires have been studied but most often for the purpose of establishing effective suppression systems rather than examining related trends in fire behavior.

During the author’s investigation of a fire in 2002 that destroyed a three-story building and caused over $5 million damage, the need for such research became apparent. The fire originated in a restaurant that occupied most of the building’s 7,500 square foot ground floor. Upper floors were used for offices and storage. In the previous three weeks before the large fire, there had been two other small fires in the restaurant. The first fire was quite small and happened when a pile of laundered cotton towels ignited in a plastic bucket. The second fire also started in a pile of freshly laundered cotton towels. It caused extensive smoke spread throughout the building.

Just prior to these fires, the washing machine that had been used for years to wash napkins, tablecloths and other towels for the restaurant was replaced. It was common in normal business operations for those items to be impregnated with cooking oils. The night of the final fire, workers had washed and dried several items and piled them on a table in the laundry room.

During the investigation, fire patterns revealed the worst damage was located near the center of the building outside the laundry room. The most extensive burning was in an open storage area about twenty feet away. Because of the recent fire history, investigators excavated and closely examined the laundry room even though it was clearly separated from the area of most severe damage. After debris from the upper floors was removed, the approximately 100-square-foot room was found filled to its 8-foot high ceiling with burned material that had fallen from above.

Once the debris was removed, items in the lower part of the laundry room were found nearly unburned. A hollow-core door into the room had been opened about 20 degrees during the fire. It had burned away at the top but the lower section was intact. Carpeting on the floor under the door and outside the laundry room was also unburned.

There was extensive burn damage to the wooden tabletop where the laundry was piled after being removed from the dryer. On the floor adjacent to the damaged 40-inch high table top was a 24-inch high cardboard box of toilet tissue. The carton had only minor burn damage at its upper level. Many of the paper rolls inside were undamaged. Nearby on the floor, a 16-inch high, plastic-webbed laundry basket had melted near the top edge but was fully intact below with unburned towels and laundry inside.

In the ensuing investigation, two basic hypotheses developed as to fire origin. One theory held the fire started on the table in the laundry room and extended out through the door resulting in more extensive damage elsewhere. Another proposed that the fire could not have started there and extended outward as evidenced by the lack of damage at the lower levels of the laundry room. If it had, it would have resulted from flashover and fully involved burning. It instead must have started in the area of most severe burning and extended into the laundry room.

Investigators were familiar with the concept that one could expect steady flame extension out of a compartment’s vents after the onset of flashover. Those flames could then ignite exterior fuels causing additional fire spread. In this instance, the laundry room clearly had not reached flashover. Further there was no obvious path of fire extension (e.g. trailers) from the room except through the door. The elevated fire level was suspected as being the principal variable responsible for flame extension in the absence of fully involved burning.

COMPARTMENT FIRE BEHAVIOR REVIEW

Numerous references detail the stages involved in compartment fire growth from ignition to flashover and beyond.[1-10] After ignition of a diffusion-flame fire, flames spread over the fuel as gases or vapors are released. The rate and extent of flame spread is dependant upon fuel properties, and in the case of solids, the location of ignition. The rate at which a fire grows is a function of how easily the fuel is pyrolyzed or evaporated.

As the fuel gases burn, the usually luminous flames release heat. Expanding gases then rise in a buoyant plume because of lower density. As the plume rises, air surrounding the plume is entrained or mixed into it. When it strikes a ceiling, it deflects horizontally, forms a ceiling jet and spreads radially outward. If the ceiling jet encounters vertical bounds such as walls that restrict further travel, smoke backs up and deepens into a layer. When the smoke layer reaches open vents, e.g. windows or doors, it flows out of the compartment.

Entrainment of air occurs all along the surface of the plume from the base of a fire to the underside of the descending smoke layer. The higher velocity of the upward-flowing hot gases caused fluid eddies to form between the plume and the cooler, surrounding air. It is through these eddies that air is entrained. Enroute any walls, ceiling jets can also entrain air in this way. Once a smoke layer begins to stabilize due to differences in buoyancy, upward entrainment between the cool air layer and the hot smoke is generally negligible except at the fire plume. Some mixing between the smoke layer and air below may also occur near vents as the incoming cooler air shears against the hot gas layer.[3]

The air entrained into the flame supports combustion of the unburned fuel gases. At the height where enough air has been entrained to burn the fuel, the flame zone ends. More air continues to entrain higher up in the plume. This additional mass both cools the plume and causes it to widen as it rises.

The plume, ceiling jet and smoke layer lose heat to the surroundings by convection and radiation. If a burning fire does not supplement this energy loss, the upper-layer smoke temperature drops. The energy balance between heat release into the compartment and transfer out determines whether a fire will grow or decay.

If a fire continues to grow, heat entering the smoke layer causes the smoke temperature to rise. Should the average smoke layer temperature reach around 500°C to 600°C, radiation from the smoke will ignite the remaining combustibles in the compartment. At such time, the heat flux on the compartment floor is on the order of 20 kW/m^2. The smoke layer then stabilizes at a level where a mass balance is achieved between the hot gas flowing out of openings above the neutral plane and the cooler air flowing in below.

The amount of heat energy that can be released in a compartment fire is limited by how much air can enter to support combustion. Before flashover, there is often enough air in or entering a compartment to burn all of the fuel gases being emitted. In this situation, the size of a fire is "fuel limited" - it is limited by the amount of fuel being burned. Adding air under those conditions will not increase the fire size.

After flashover once all the available fuel begins to pyrolyze, the air/fuel balance can be quickly disrupted. In a short time, more fuel gas is available inside the compartment than there is air to burn it. At that stage the fire's size becomes "ventilation limited" since the heat release rate is no longer dependant on the amount of fuel gas but on how much air is available to burn it.

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

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

For fuel limited conditions in which there is more than enough air to burn the fuel gas, $\phi < 1$. Under ventilation limited conditions, there is insufficient air to burn all the fuel and $\phi > 1$. When a compartment fire has transitioned through flashover and become ventilation limited, excess, unburned fuel gas can flow out of vents before burning. Once it encounters sufficient air outside of the compartment, it can ignite. This effect is often mentioned in the literature and associated with post-flashover, fully developed fire conditions. [7-10]

In some early pioneering fire research by Kawagoe dating back to the 1940s, the relationship between burning rates and the size of ventilation openings was first suggested.[6] The terms "ventilation controlled" burning and "fuel controlled" burning were offered. Other researchers have since correlated the heat release rate needed for flashover with this "ventilation factor".[11]

HOW 'X,Y' LOCATION AFFECTS FIRE BEHAVIOR

The upper layer temperature in a compartment fire is one of the crucial factors in determining whether a fire transitions through flashover. Various factors related to fire growth can affect upper layer temperatures. One is an increase in a fire's heat release rate. An increase in the overall compartment energy level can raise the upper layer temperature. As mentioned earlier, two fuel packages with identical heat release rates but different x-y coordinates will also lead to varying rates of upper layer heating. Since air entrainment cools rising gases, reducing the amount of entrained air will reduce cooling thus increasing smoke temperatures.

Zukoski et. al. studied the effect of placing burning objects next to compartment boundaries such as walls or in corners.[2] A wall intersecting the plume reduces the area through which entrained air can enter by approximately one-half. In a corner, available entrainment area is three-quarters less than that for a plume in the open. Higher smoke temperatures near the ceiling will result from less cooling. Temperatures will also increase with restrictions of ceiling jet formation next to walls. In those instances, outward flow does not occur in all directions. This results in less heat being lost by convection.

Lastly, since less air is entrained into the flame zone to support combustion, flame lengths become elongated since the fuel gases rise for a longer time before completely burning. This extension of flames into the upper layer also increases temperatures.

Lee demonstrated that flashover could be reached with lower heat release rates for fires set next to walls or in corners than those burning in the center of a room. In his experiments, a wall fire with a heat release rate of only 84% of a center-room fire could cause flashover. A corner fire needed only 72% of the rate.[12] Mowrer and Williamson predicted even greater differences in the same ratios, $HRR_{fo}(\text{wall})/HRR_{fo}(\text{center})$ and $HRR_{fo}(\text{corner})/HRR_{fo}(\text{center})$.[6, 11-13]

UPPER LAYER VITIATION

In a free burning fire in open air, more than enough air in entrained into the flame than is needed to burn the fuel gases. Even so, some vapors emitted from the fuel are not completely burned and escape the flame.[10] The products can be gaseous or in the form of small carbonaceous solid particles or aerosols that make up soot. With lower oxygen concentrations of the inflowing air, even more unburned fuel enters the upper layer.

In low-level compartment fires with open vents, the neutral plane between the outgoing smoke and incoming fresh air often stabilizes at or above the top of the flame zone. If the flames penetrate the upper layer, they encounter vitiated or smoky air. The result is a build up of unburned fuel gases and particulates accumulating in the smoke. If the fuel concentration becomes high enough, the layer itself may begin to burn. Drysdale notes that as an increasingly hot smoke layer descends and envelopes even more of the flame zone, a rapid change in burning dynamics can occur similar to what happens at the onset of flashover.[17]

Beyler studied the effect on fire behavior of varying the equivalence ratio, ϕ, in a smoke layer.[15] Recall ϕ is the ratio of fuel-to-air concentration compared to that at stoichiometric conditions. It is inversely proportional to how much fresh air enters a plume below the hot layer. Therefore the less clean air available to enter the flame, the higher the values of ϕ.

As values of ϕ increase, so does the concentration of unburned fuel gases leaving the flame. The entrainment of hot smoke (with its lower oxygen concentration) inhibits combustion causing an increase in the amount of unburned fuel gas in the smoke layer.[17] Beyler discovered in his experiments that the smoke layer began burning when ϕ reached about 1.8. [18]

Of particular importance here is that in addition to a build up of unburned hydrocarbons in the smoke, carbon monoxide concentrations also increase. The production rate of carbon monoxide (CO) rises significantly at values of ϕ of 0.6 and above. At around $\phi > 1.2$, CO reaches its maximum level of up to 6%.[19, 20]

Once a fuel-rich layer begins to burn, oscillations can occur in a fire's overall burning behavior.[21] Beyler observed up and down burning rate fluctuations in the fires in general as well as oscillations in the concentrations of CO and total unburned hydrocarbons in the smoke layer.[18]

HYPOTHESIS TESTING

Many of the relationships mentioned above were derived in compartment tests with fires burning at or near the floor. Fire extension out of a compartment has been commonly observed in fires that have reached flashover and transitioned to fully involved burning. As a result, this phenomenon is often associated, perhaps unintentionally, as exclusive to full fire involvement.

Since no studies specifically addressed the correlation of these principles to compartment fires burning at elevated heights, a thorough examination and testing of the restaurant fire hypotheses was challenging. Would elevated fires behave differently than low-level fires in leading to flashover? Would the venting upper layer flow outward as hot smoke or as extending flames?

The author theorized that in the 2002 investigation, the large fire started (like the previous two had) in piles of hot, freshly laundered towels. The towels had been piled on a table approximately 40-inches off the floor. There were indications supporting this theory including a localized area of severe burn damage on the tabletop consistent in size with a typical load of laundry.

Fire dynamics principles suggested a plume would have risen above the burning towels and eventually formed a smoke layer. Recall a partially opened door (open about 20°) was found in the entrance to the room. The soffit over the door spanned from 80 inches (2.0m) above the floor to the ceiling height of 96 inches (2.4m). If the layer descended to the door, smoke could vent through the upper gap in the doorway and incoming air could enter at the bottom.

Based upon the size of the laundry room, it seemed likely the smoke layer would have descended to the upper flame zone. This would have not only increased the buildup of partially or unburned fuel gas in the upper layer, but would have also tended to mix the layer through turbulent flow. The rate of entrainment of clean air into the plume would have slowed (since the distance between the base of the fire and the layer was shorter). This would have limited the mass flow into the layer causing temperatures to be higher than if the fire had been burning at floor level and more entrainment was possible.

If the smoke layer descended to the base of the burning rags, choking the flame, the heat flux from the flame to the fuel would be reduced. As a result, the rags' mass loss/burning rate would drop. The exact nature of this mechanism remains theoretical but is envisioned as an oscillating process. As the layer dropped, so would the burning rate. The reduction in heat release and smoke production would result in the layer rising. Once more air entrained, the burning rate would increase leading to yet another layer descent as the cyclic process proceeded towards equilibrium.

In such an analysis, several variables need to be considered. They include a fire's base height, its relative position compared to layer depth, the rate of smoke layer descent, layer temperature development, concentration of unburned fuel in the layer, the mass rate of smoke venting from the compartment and the influx of air (both based in part on the size and location of vent openings), the fuel's combustion properties, presence of combustible compartment linings and fuels above the smoke layer, and any other factors affecting entrainment flow into the plume.

For the described fire, it seemed feasible that the hot gas layer could have developed not only in sufficient depth and temperature but also in the fuel-to-air concentration ($\phi > 1.8$ for layer burning). Had the temperature been hot enough to ignite the smoke layer, flames might have emitted from the top of the doorway. The average temperature in the layer might still have been too low to cause flashover thus leaving combustibles at lower levels nearly unburned. Meanwhile, if a fire ensued outside the compartment and caused fully involved burning, low oxygen concentrations outside the laundry room could have prevented flashover from occurring inside.

The autoignition temperatures of many hydrocarbon gases are below 500 °C.[22] The autoignition temperature of carbon monoxide is 609°C.[23] Even though these temperatures are close to flashover temperatures, the CO and unburned gases could still ignite without flashover ever occurring if pilot flames reached them up in the layer.

This analysis seemed to support the possibility of flames extending from the compartment without the fire ever reaching flashover. To test the hypothesis further, it was decided that full-scale burn tests were in order.

A fire was set in a compartment similar in geometry to the laundry room. It had a 40-inch high wooden tabletop, an 8-foot ceiling, a combination of combustible and non-combustible walls and a hinged door. A pile of cotton towels and cloths was placed on the table and lightly sprinkled with lighter fluid to facilitate ignition but not greatly increase the heat release rate. Two large, plastic bags containing shredded paper were used to represent the carton of toilet tissue. They were placed on the floor adjacent to the table. After ignition, the door was closed to an angle of around 20° like in the laundry room.

(Fig. 1) Pile of rags on tabletop near plastic bags filled with shredded paper

(Fig. 2) Shortly after ignition.

(Fig. 3) Light grey smoke early in fire

(Fig. 4) Flame replaces smoke

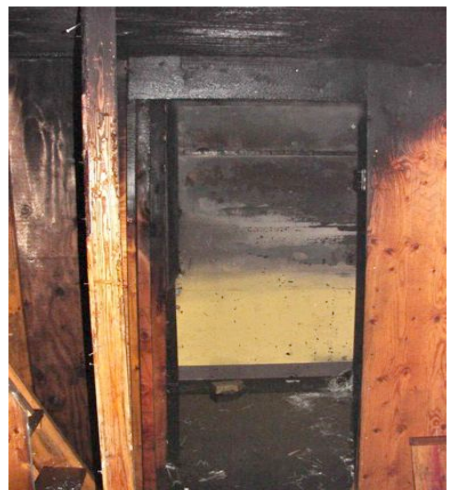
(Fig. 5) Smoke replaces flames during the oscillations between smoke and fire

(Fig. 6) Upper layer ignites and extends well away from the compartment

Though no cameras were used to observe the fire test from inside the compartment, a slow buildup of smoke was seen from the outside followed by slight pulsing of smoke through the upper doorway. The initially light grey smoke darkened and within minutes, small flames appeared at the top of the door. They then retreated into the room, replaced by more and darker smoke. Larger flame soon blew through the upper doorway and extended well outside and over firefighters' heads. Suppression quickly followed.

Of particular interest in the test was the limited amount of low-level damage resulting from the fire. As expected, the tabletop had charred around the edges of the rags and the wooden barrier at the back of the table had begun to burn. As seen in the photos, the walls at and above table level were covered with dark smoke staining and in some cases, charred. The lower portions however, were virtually undamaged.

(Fig. 7) Upper layer damage extending down only to base level of fire

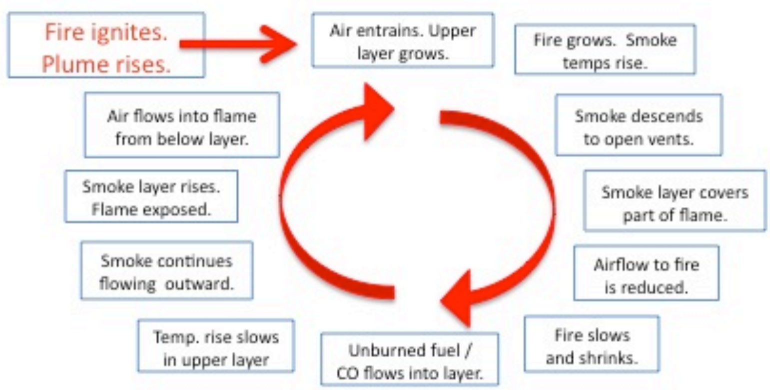


(Fig. 8) View of undamaged lower layer below base level of fire

The plastic bags with paper placed on the floor adjacent to the fire origin had only moderate heat damage. The plastic had started to shrink, leaving holes and exposing the paper, which though discolored, had not burned. During suppression, hose streams scattered the bags and paper about the room. The plywood outside the doorway erected to simulate an 8-foot high ceiling had ignited and received moderate burn damage.

Though this fire test supported the theory that an elevated-fire in the restaurant may have led to flame extension apart from flashover, it was still felt that tests at the proper scale were needed. Engineers and technicians at the Bureau of ATF's Fire Research Lab in Ammendale, Maryland built a compartment matching the laundry room size, materials and contents. Two fires were set to further test the theories.

In each test the smoke layer descended to the tabletop and base of the fire. When that occurred, the burning rate appeared to drop. Small oscillations in the layer height followed and eventually settled near the level of the fuel's base height. With time, the fire intensity appeared to stabilize somewhat below the peak-burning rates. Upper layer temperatures continued to rise through the tests and unburned fuel gases collected in the smoke layers. In each test, the smoke ultimately ignited, extending flames out of the compartment.



(Fig. 9) Proposed mechanism for the cyclic behavior during elevated fire tests

The above graphic represents the cyclic mechanism believed to have occurred in the elevated fire tests as the fires developed towards relatively steady-state conditions. It was observed to varying extents during the different tests. In each, it led to flames extending out of the vent. After the initial layer descent in each fire, subsequent rises and drops in layer height seemed progressively smaller before the layers stabilized at or just slightly below the base level of the fires. A plot of layer height vs. time would likely have appeared as a dampening sinusoidal wave.

Depending on compartment geometry and the fluid dynamics involved with an elevated fire, such a process may go through just a few or several such cycles. Even after reaching near steady-state conditions, further changes in layer heights might happen depending on factors such as changes in ventilation, fuel consumption, burning items falling through the layer and onto the floor, etc.

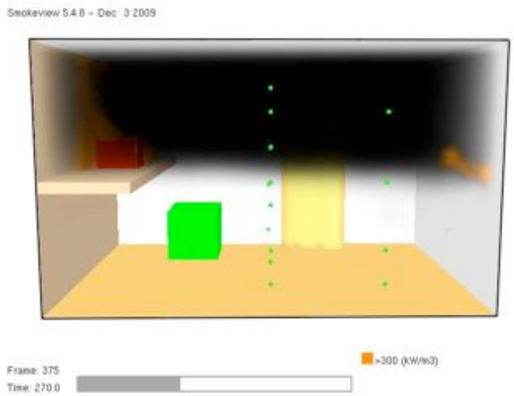
FIRE MODELING ANALYSIS

After completion of the full-scale tests, the computational fluid dynamics (CFD) computer model, Fire Dynamics Simulator (FDS), developed by the U.S. National Institute of Standards and Technology, was used to further evaluate elevated fire behavior. Runs were made for a 4m x 3m x 2.4m compartment with a standard interior doorway opened approximately 20° as in the above-mentioned fire and tests. The compartment layout was similar to that of the first fire test. Steady state fires with a constant heat release rate per unit area value were used. The base height of the fires varied between 0.1m and 1.2m.

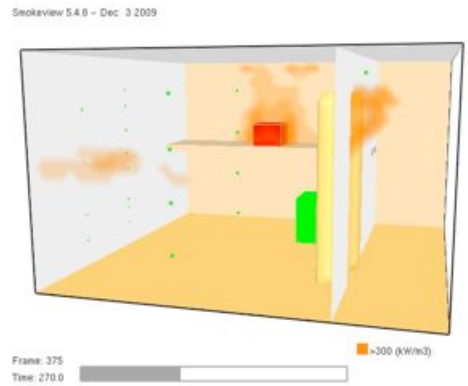
The calculations showed that for fires positioned higher in the compartments, the rate of upper layer temperature increase was higher than for fires at the floor. While early temperatures peaked more quickly and at higher values in the elevated fires, the descent of the gas layer to the base of the fires dampened the overall burning rate. As a result, upper layer temperatures eventually trended slightly lower than for fires burning at the floor.

Models were run both with combustible and inert ceilings. The general upper layer temperature trends remained consistent. With combustible ceilings, oscillations in burning rates occurred once the upper layer became stable. The extra fuel led to scattered flames near the bottom of the layer. The effect was more pronounced in runs with the elevated fires. Smokeview results showed a "puffing" type of behavior where flames at the bottom of the layer would appear then burn away. Flame extension through the doorway also occurred much sooner with elevated fires.

Figures 9 and 10 show Smokeview screenshots of a fire with a raised base at 1.2m, halfway up to the ceiling. The burn time is 270 seconds. Flames can be seen extending through the door and burning under the smoke layer at the right side of the diagram, well away from the original fuel.



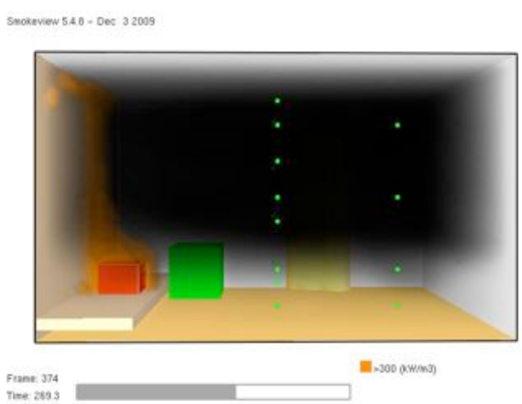
(Fig. 10) 270 sec - Smoke layer extends to base of elevated fire. Flames visible at right side below the layer.



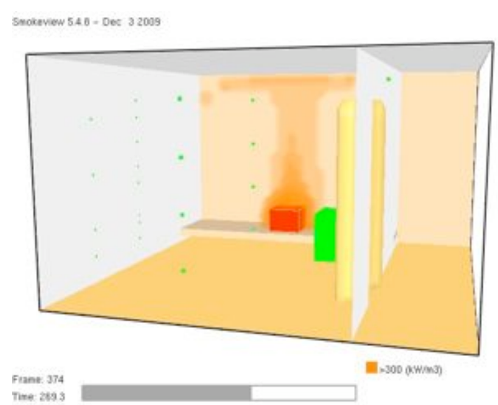
(Fig. 11) Smoke layer removed and view rotated to show flames through door.

Figures 12 and 13 depict a similar fire in the same sized compartment with its base 0.1m above floor level. The displayed time is again 270 seconds. By that time, no flaming had occurred at or through the doorway. None of the model runs developed smoke layer temperatures or floor level heat fluxes high enough to cause flashover.

Further modeling study in this area is recommended using fires in which the burning rate decays after the upper smoke layer descends to the fire's base and then increases again once the layer rises. Such work would naturally be of an iterative nature and require a large time investment. Since variable burning rates were not used in these runs, the above-theorized effects of smoke layer depth oscillation were not observed.



(Fig. 12) 270 sec - Smoke layer does not reach the upper edge of the fuel. No flames developed apart from the main fire.



(Fig. 13) Smoke layer removed and view rotated. Note the lack of flame extension through the doorway.

CLOSING COMMENTS

Since fires at elevated heights (e.g. stovetop fires, kitchen counter fires, upper level electrical wiring/appliance failures) are fairly common, it would benefit both the fire safety and investigation communities for researchers to examine the "z-factor" effect in future studies. In residential fires especially, the danger of increased CO production and flame extension beyond the room of origin prior to full involvement seems significant.

Investigators need to become familiar with the various differences in fire behavior caused by elevated fires. This is particularly important when investigating pre-flashover fires with substantial room-to-room fire spread. Instances of high CO levels or extensive burning at locations distant from a perceived origin might potentially be explained by such factors as flame zone vitiation and smoke layer ignition, especially if combustible materials (e.g. wooden kitchen cabinets) were present in the upper layer.

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Mr. Carman retired as an ATF Senior Special Agent / Certified Fire Investigator in July 2008. He holds a B.S. degree with High Honors in Physical Science from the U.S. Coast Guard Academy. Mr. Carman's previous works include, "High Temperature Accelerant Fires", "Behavior of High Temperature Incendiaries", "Improving the Understanding of Post-Flashover Fire Behavior", and "Clean Burn Fire Patterns". He has lectured internationally on various aspects of fire science and investigation including fire dynamics, fire chemistry and fire modeling.

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