THE IMPACT OF VENTILATION IN FIRE INVESTIGATION

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ABOUT THE AUTHOR

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Some of Mr. Carman's 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.

INTRODUCTION

A basic notion of fire investigation is that the origin of the fire must be correctly identified in order to determine the cause. If an investigator misidentifies the origin, the subsequent causal determination will also be flawed. Not understanding the role of ventilation in a fire's development is a leading factor in mistaking the origin. Attorneys defending clients accused of starting a fire must ensure ventilation effects are properly evaluated and considered to ensure the correct fire origin is identified.

FIRE INVESTIGATION AS A FORENSIC SCIENCE

The field of fire investigation is unique amongst forensic sciences. Many fire investigators, compared with their counterparts in other forensic specialties, have a limited scientific education and background. Although much has been done to improve the profession by establishing a firmer scientific foundation, fire investigation remains too often guided by anecdotal theories rather than by proven scientific principles.

Inaccurate fire origin determinations carry an immense cost. Personal liberty or huge financial burdens often rest directly upon fire investigator opinions. Too often, important decisions have been decided based on what are now known to be "myths" of fire science. Burn patterns and behaviors once widely accepted as abnormal and possibly proof of arson are now understood to be artifacts of natural fire progression.

For years, admission of expert opinions into court proceedings have been based on the level of general acceptance of such theories among practitioners. Because fire investigator training was historically fashioned on an apprenticeship model where elders teach newcomers, "general acceptance" was a relatively easy burden to meet. Although "general acceptance" remains the basis of admitting opinion evidence in some courts, other standards such as those set forth in *Daubert* require a provable scientific basis. Regardless of the standard used, frequent scientific advances affect which opinions are deemed acceptable. It is important that investigators and attorneys keep abreast of these developments.

Considering the pace of improvement in fire science, attorneys should consider employing pre-litigation technical reviews of origin and cause determinations in most cases, especially those with potentially weighty outcomes. Recent advances in fire science can either be used to bolster arguments or weaken them.

Differences in investigators' awareness of fire behavior can be considerable. While most forensic science professionals who work in specialty areas such as DNA, serology and trace analysis are college-trained scientists, most U.S. fire investigators hail from the ranks of firefighters or law enforcement officers. While some may have scientific training, most would not be considered scientists, per se. Though a scientific degree does not guarantee successful fire investigations, sound training emphasizing critical, analytical assessment certainly improves its likelihood.

Regardless of educational differences, it is imperative that fire investigators and other forensic specialists alike adhere to scientifically valid methodologies. The accepted approach that most fire investigators now claim to follow is the Scientific Method. That method dictates that practitioners collect information, analyze it, propose hypothetical scenarios describing where and how a fire occurred, and test or evaluate those hypotheses. While a valid framework for fire investigation, its success requires that the scientific principles relied upon for analysis and hypothesis testing be accurate. For such a methodology to work, investigators must stay abreast of current scientific advancements.

PERSISTENCE OF FIRE INVESTIGATION LORE

For years, anecdotal teachings handed down from one generation of investigators to the next have persisted. A long-held belief about fire behavior is that once a fire ignites, it spreads progressively outward, involving other fuels along its path. Following that theory, it could be argued that by the time a fire is extinguished, its area of origin will have burned longer than all others. Hence, it makes sense that if the origin burned the longest, it should be the most severely damaged, the area of "deepest char".

Another long-standing notion is that flames always burn up and outward. This reasoning led to the teaching that the point of lowest burning would be at a fire's origin. Historically, investigative lore advised that finding the area of lowest burning and deepest char would identify the origin. Investigators realized that when elevated fuels like curtains ignited and dropped, burning to the floor, the ensuing burn patterns could be lower than those from a fire starting higher up. The idea that the fire origin would always be the lowest point of burning has since faded from general acceptance.

In contrast, some fire investigators still reason that the area of deepest char or most severe burn damage marks a fire's origin. While it may seem logical that damage will be greatest where a fire burned the longest, it is simply not always the case, particularly with large fires. Frequently, when fires have become fully involved, the areas of worst burning are distant from their origins.

Another popular idea with many fire investigators is that when examining a fire scene, moving from areas of lesser to greater damage will lead to a fire's origin. While this approach seems logical, in some instances it will actually lead investigators away from the origin rather than towards it.

Attorneys who encounter such reasoning behind origin and cause determinations should consider it suspect. While these precepts may hold for simple fires, they often fail to explain behaviors of larger, compartment fires. Arguments like these should be closely examined and challenges considered.

VENTILATION IN COMPARTMENT FIRES

An important aspect of fire science that has gained recognition in recent years is the leading role ventilation plays in a fire. Ventilation may be the most important variable linked to the generation of severe fire damage. The theory of the "Fire Triangle" is one of the earliest principles of fire behavior taught to fire investigators. It states that in order for a fire to burn, adequate fuel, oxygen and heat must be present, each of which form a leg of the triangle. If any of the three legs are missing or are present in insufficient amounts, the triangle collapses and burning cannot proceed. Perhaps because of its simplicity and ease of comprehension, the theory's clear-cut connotations are often overlooked. This may be due to people basing their understanding of fire behavior upon years of watching things burn such as in a fireplace, a campfire ring, or even on television. When a fire is in clear view, people's focus on flame production tends to center on what and how much fuel is burning. It seems that oxygen levels are rarely considered.

Deliberating over oxygen concentration is needless with many fires. Most fires that people watch burn, those in the open, have plenty of oxygen. Unlike those fires however, the oxygen level in a building fire is an important consideration.

Areas that have plenty of oxygen early in a fire may end up with almost no oxygen later. Fire behaviors during the two periods can vary tremendously.

COMPARTMENT FIRE BEHAVIOR

To understand the significance of oxygen levels in structure fires, it is necessary to be aware of how building fires develop. When a fire ignites and grows, hot combustion gases are produced and rise in a plume due to their buoyancy. Upon reaching a barrier like a ceiling or roof, the gases' upward movement stops and they are deflected laterally. If the lateral flow is constrained by walls, a smoke layer develops. Additional smoke causes this upper hot gas layer to grow in depth and volume. If the fire keeps growing and spreading, the upper smoke layer becomes hotter and deepens. If there are open windows or doorways (or other vents), smoke will flow outward once it reaches the top of the openings.

This stage of burning is known as Pre-flashover burning. For fires extinguished in this stage, burn damage is centered on the fire's origin. The room's upper layer will be stained from the buoyant, hot smoke and the most severe damage will likely consist of charred wood, melted plastics and other destruction near the area of fire origin.

Years of testing have shown that if an upper smoke layer in a room becomes hot enough (generally around 1,000°–1,100°F (550°-600°C)), the energy radiated outward to other parts of the room can cause unburned fuels to pyrolyze and emit fuel gases. Under such conditions, a fire burning in a small part of a room can evolve into one in which the entire room starts to burn. This transition is known as flashover. It is such a significant part of fire development that most fire behavior training and reference materials discuss it.

To different parties, flashover bears different significance. For fire suppression personnel, it is the state in which firefighters cannot survive its intensity. For engineers it's the start of the phase of burning that most seriously threatens a structure. For investigators, it generally marks the ignition of all available fuels. It is also the phase of burning in which fire behavior dramatically changes.

Scientists and engineers have known for years that fire behaviors change around the time of the transition to flashover. Before flashover, a fire's size can increase only if more fuel becomes involved. Under such conditions, a fire is said to be "fuel-limited". Its magnitude is dependent on the amount of burning fuel. Pre-flashover fire behaviors are perhaps the most familiar. The pre-flashover phase after all, is the phase in which all fires burn in the open.

In compartment or building fires, a different burning phase occurs after flashover. In the post-flashover phase, the largest a fire can become is dependant on how much oxygen is available to burn the fuel. Adding extra fuel into a compartment in this phase will not increase the fire size. For the fire to grow, more oxygen must be introduced. This phase of burning is said to be "ventilation-limited".

Most fire investigators are generally familiar with the idea of post-flashover burning (or "full involvement" as it is sometimes described). Few er are conversant in the concepts of ventilation limited burning however. In recent years, the lack of training in post-flashover and ventilation-limited burning has become evident. It is extremely important that investigators understand the differences between pre- and post-flashover fires. Inappropriate use of pre-flashover investigative techniques on post-flashover fires can lead to inaccurate origin determinations.

STATE OF POST-FLASHOVER TRAINING

The extent of the training fire investigators receive in post-flashover behavior became clear at a 2005 fire investigation seminar in Las Vegas. There, the author and three others from the U.S. Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) designed and presented training on fire dynamics. Before the seminar's start, two identical, 12' x 14', single-room compartments were burned. Identical fires were set in each cell but in different locations. Each fire burned a total of seven minutes and reached flashover in three-and-a-half minutes. Fifty-three fire investigators/students then participated in an exercise like one offered at ATF's "Advanced Origin and Cause" course at the Federal Law Enforcement Training Center (FLETC) in Glynco, Georgia.

The fifty-three students did not see the fires burn. Each student was asked to walk through the first burn cell and identify the quadrant in which they thought the fire started. Just three of fifty-three students correctly identified the quadrant of fire origin; a success rate of 5.7 percent. The group then repeated the exercise in the other burn cell. Again, only three students (a different three than in the first cell) correctly identified the quadrant of origin. Even though students only briefly examined the scenes, the exercise demonstrated the significance most placed on the area of most severe damage.

A review of the FLETC exercises showed similar results. At the start of each of those classes, students examined what was described as a "complex fire scene". Like the 2005 Las Vegas exercise, the FLETC assignments were intended to assess students' familiarity with ventilation-controlled burning. The FLETC fire scene included a bedroom, living room/kitchen area, and a hallway connecting the two. Students were asked to locate the fire's origin and justify their conclusions. Anecdotal reports of thirteen years of results showed that on average, fewer than 10 percent of students correctly identified the area of fire origin.

POST-FLASHOVER FIRE BEHAVIOR

To many, it seems logical that the most damage in a fire would be where it burned longest. For ventilation-limited fires, however, this is not necessarily true. Much of our understanding of compartment fire behavior is based upon what we see. Few investigators though have ever observed ventilation-limited burning occurring inside a compartment. Instead, most observations of such burning are made from the exterior where, flames extend through room openings such as windows and doors. Because walls block interior views, it is usually not possible to watch the fire burning inside.

In most flashover training demonstrations, investigators watch compartment fires grow in compartments with entire walls missing. “Front” walls are intentionally removed or left out during construction to allow for better visibility. As the demonstration fires reach flashover, flames extend throughout the compartment. While such demonstrations can be illustrative, they give an erroneous impression of post-flashover burning in a normal room.

In both pre- and post-flashover fires, flaming occurs only in gaseous fuel and air. In fuel-limited fires, there is plenty of air available to burn all the fuel gas. At flashover, radiation from the upper smoke layer causes so much fuel gas to be released that the compartment becomes fuel-rich. When that occurs, there is no longer enough air inside to burn all the gaseous fuel. This is the onset of ventilation-limited burning.

At about the time of flashover, compartment fires become ventilation-limited. Unlike with flashover demonstrations, areas of active burning are not uniform as one might suspect. The most energetic burning occurs near the available oxygen. There, higher temperatures lead to high heat fluxes or intensities, which in turn cause the greatest amount of damage. The high temperature also causes the turbulence to increase throughout the room.

Consider how air and smoke flow in and out of a fully involved compartment through an opening in a wall such as a window or doorway. The mass of smoke and hot gas flowing out of the burning compartment is automatically replaced by the same mass of inflowing air. Because of its buoyancy, hot smoke flows out the top of openings while cooler air enters through the bottom. In a fully involved or post-flashover compartment fire with one open doorway, the smoke layer generally fills the upper 2/3 to 3/4 of the opening. The inflowing air enters through a smaller portion of the opening than that through which smoke exits. Accordingly, the air flows at a higher velocity than the smoke. Higher velocity results in high momentum, which carries the air well into the room before the oxygen is consumed by combustion.

In areas remote from inflowing air paths, oxygen concentrations readily fall to near zero percent under post-flashover conditions. There, since oxygen does not get replenished, virtually no combustion occurs despite high concentrations of unburned fuel gases. The fuel gas does not remain motionless however. The intense turbulence moves the fuel gas around the space until it encounters enough oxygen to burn. Some of the fuel flows out of the compartment before reaching oxygen and igniting. This outward flow of hot, fuel-rich gas leads to the flames burning at the room openings.

An important aspect of post-flashover burning is that of "heat flux". Heat flux is defined as the amount of heat energy passing through a given area in a certain amount of time. Typical units of measurement are given in kilowatts per square meter. 1 kW/m^2 is the same as 1 kilojoule of energy (similar to a BTU) passing through a 1 square meter area every second.

Every investigator should be familiar with the following heat flux values:

Thermal radiation from the sun at noon on a hot day	1 kW/m^2
Heat flux on a residential room floor at the onset of flashover	20 kW/m^2
Maximum heat flux measured in post-flashover fire tests.	> 200 kW/m^2

Post-flashover levels have been measured at more than 200 kW/m^2, more than ten times the 20 kW/m^2 value associated with the onset of flashover. Although heat fluxes are highest during post-flashover burning, levels are not equal throughout a room. The highest levels occur near ventilation flows.

As mentioned, heat flux has an element of time associated with it. At the onset of flashover, heat flux in a residential compartment results in about 20 kilojoules (kJ) of energy passing through every square meter of surface each second. As flux levels rise, the rate of energy exposure increases. The higher the cumulative exposure, the greater the resulting damage.

The damage caused in 1 second of 200 kW/m^2 post-flashover burning require 10 seconds of burning in 20 kW/m^2 flux conditions. In other words, post-flashover burning can generate damage ten times faster than a fire at the onset of flashover. Similarly, the 20 kW/m^2 heat flux at the onset of flashover is far greater than that present at ignition and during early burning. The result is that damage is generated far more quickly in post-flashover burning than early in a fire.

USEFUL RULES OF THUMB

A general rule of thumb in fire investigation is that burn damage created during pre-flashover, fuel-limited burning will typically occur near burning solid or liquid fuels. Once a fuel package ignites and fuel is released, the gases will burn near the source of the fuel since oxygen is plentiful. As the gas burns, the heat is released and causes nearby damage.

In a post-flashover, ventilation-limited fire however, things change. Fuels located in a part of a room devoid of oxygen (and thus unable to burn) will release gases. With insufficient oxygen however, these gases cannot burn as they are given off. Instead, they are swirled away by turbulence. They may travel a considerable distance before they encounter enough oxygen to burn. As a result, the heat is released where the oxygen is plentiful, not where the fuel originated. The two locations could be far apart.

The following photographs show the rear walls of three different burn cells. Identical fires were set in each towards the left side of the photographs. The damage in the first fire, shown in Figure 1, was worst near the origin. That fire only burned in pre-flashover conditions. The compartments shown in Figures 2 and 3 each burned two minutes post-flashover. Damage in those two fires was more severe than that in the first fire. The most badly damaged area in each was located several feet away from the origin, closer to the inflowing air.

Fig. 1 - Cell 1 – This fire was extinguished at flashover. The origin is at the left side of this photograph. The patterns on the wall and ceiling above the nightstand were created late in the fire when turbulence moved the fuel gas from the oxygen deficient area in the left corner to where it could burn. The white wall area at the lower right is unburned.

Fig. 2 - Cell 2 – This fire also set to the left of this photograph burned two minutes post-flashover. This pattern could be interpreted as a classic “V” pattern, pointing downward towards the origin. It was generated wholly from fuel rich gases migrating from the left and burning from the top downward as they encountered fresh oxygen. It does not mark the origin.

Fig. 3 Cell 3 - This fire was also set to the left of this photograph and, like Cell 2, burned for two minutes post-flashover. The ventilation flow was affected primarily by the room’s physical layout. The flow resulted in the recurring, post-flashover “V” shaped burn patterns in Cells 2 and 3. These patterns marked the most severely damaged areas in each cell. The apex of each “V” is several feet away from the fire’s origin.

INVESTIGATING PRE- VS. POST-FLASHOVER FIRES

Section 6.4.1.1 of NFPA 921 states, "Movement patterns are produced by the growth, spread, and flow of products of combustion away from an initial heat source. If accurately identified and analyzed, these patterns can be traced back to the origin of the heat source that produced them." The investigative techniques used to locate the origins of pre-flashover fires do not always apply directly to post-flashover scenes. Burn damage created in post-flashover conditions can seem confusing to investigators using these simpler analyses.

Areas of pre- and post-flashover damage created during the same fire can be far removed from each other and show no apparent connection. The post-flashover damage can be far more severe and appear indicative of longer burning. Investigators unfamiliar with post-flashover burning behavior might conclude that separate fires were set independently of the others. Such analyses can mistakenly lead to incorrect origin determinations and cause classifications.

DIFFERENTIATING PRE- VS. POST-FLASHOVER DAMAGE

Identifying an area of origin in a post-flashover fire based only upon the location of most severe damage is risky. The investigator must instead, first determine whether the damage was created as a result of pre-flashover, fuel-limited burning or post-flashover, ventilation-limited fire. Failure to do so and to disregard damage created in post-flashover burning can result in incorrect origin determinations.

To illustrate this point, consider the following example of a fire that burns a total of 400 seconds, 200 pre-flashover and 200 post-flashover. Assume the fire burns near the origin referred to as "Point A" with a localized, pre-flashover peak heat flux of 40 kW/m^2. Since during the pre-flashover period, there is likely enough oxygen for this fuel-limited fire, assume the area near the origin is exposed to this flux for the 200 seconds. By multiplying the heat flux by the time of exposure, one can estimate the total, pre-flashover energy exposure near "Point A" at about 8,000 kJ per square meter.

Now assume the same fire reaches flashover and burns post-flashover with heat fluxes near 200 kW/m^2 near "Point B" for the remaining 200 seconds. Assume "Point B" is located well away from the origin. Using the same technique, the post-flashover energy exposure at "Point B" would be calculated to be 40,000 kJ per square meter, five times that created near "Point A" during pre-flashover burning. Because "Point B" is distant from "Point A", separate and distinct burn patterns would likely result.

During the last 200 seconds after flashover, fuels near "Point A" may continue to burn. The rate of post-flashover burning at "Point A" will depend on whether there is ventilation there. If there is no oxygen at "Point A", the fire at "Point B" will burn more aggressively. The result is that the total damage at "Point A" may still be less than that at "Point B" even though "Point A" burned twice as long.

Because post-flashover patterns like that at "Point B" can be more severe than those generated pre-flashover, an investigator using the technique of moving from areas of least damage to more damage would move away from the actual origin rather than towards it. Such a process would lead to an incorrect origin determination.

Although interpreting pre- vs. post-flashover fire damage can be complex, there are useful techniques to help with the process. Fire investigators must first identify which burn patterns were likely caused in whole or part later in the fire by ventilation-limited burning.

Consider the following example. Assume there are two prominent burn patterns at the fire scene depicted below in Figure 4. One pattern marked "X" is shown on the diagram at the "B" wall to the left. Another, larger, more extensive area of burn damage marked "Y" is on the adjacent "C" wall. The investigation reveals that a doorway located in the "A" wall was open during the fire. Firefighters observed flames blowing out that door when they arrived.

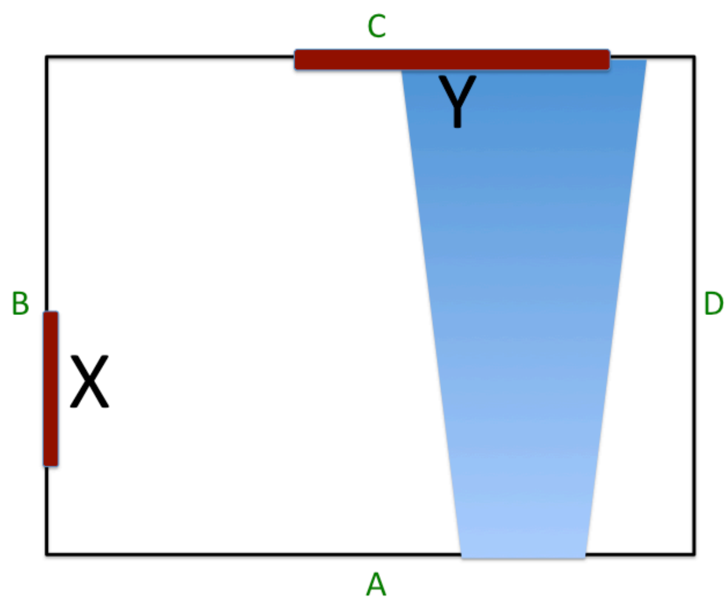

Fig 4. Example Post-Flashover Investigative Diagram

An investigator following the scientific method might generate at least three hypotheses as to fire origin; one that the fire started at position "X" and spread to "Y"; another that it started at "Y" and spread to "X"; and lastly that there were multiple origins at both "X" and "Y". Heat sources and fuels each with the potential to have caused the fire are located near both "X" and "Y".

Since flames were observed extending through the "A" door, the investigator should first consider that the fire may have burned post-flashover. Next, if flashover was determined to have occurred, he or she must identify ventilation paths through which air would have entered the fully involved compartment. If any hypothesized areas of origin lies along those paths, then the investigator must conclude whether damage at those points was possibly caused by ventilation enhanced, post-flashover burning.

In this example, "Y" is clearly located in a likely ventilation path (shown in blue and extending through the door on the "A" side). In order to conclude "Y" was an origin, that hypothesis must be tested. To identify "Y" as an origin based on the amount of damage there, post-flashover burning at "Y" must be eliminated as having caused that damage. Such burning at "Y" likely occurred post-flashover, "Y" cannot yet be identified as the origin based simply upon the extent of its damage.

The burn pattern at "X" is not on or near the expected post-flashover airflow path (through the "A" door). Because oxygen levels in that area were likely very low during post-flashover burning, it might be concluded that the damage at "X" may have been created during pre-flashover burning. Based on this, the investigator must consider that the damage at "X" may have occurred early during the pre-flashover fire.

EVALUATING EXPERT OPINIONS FOR POST-FLASHOVER FIRES

Establishing post-flashover ventilation flows after a fire can be challenging but useful methods are available. Computational fluid dynamics-based computer models are one type of tool that can be used. They can also help understand the impact of fires burning in different locations. Models will not by themselves, identify a fire's origin but they can test various experts' hypotheses as to fire development.

The following figures show examples of CFD model outputs. Figures 5 and 6 depict oxygen concentrations at different times for the first of the Las Vegas burn cell fires. The top-down view shows the open doorway at the bottom. The origin is near the top left. Figure 5 displays oxygen levels near the floor about 10 seconds before flashover. Areas in red indicate adequate oxygen levels in the still fuel-limited fire. Figure 6 shows the same view seconds after flashover. Blue areas indicate an absence of oxygen where burning can no longer occur. The red area in Figure 6 marks inflowing air where sufficient oxygen could support post-flashover burning. The highest heat fluxes would be expected to occur in those areas.

Figures 7 and 8 show heat fluxes at the walls during the pre- and post-flashover phases. In this view, the fire's origin is on the floor next to the bed at the top right of the graphic. The open door is shown near the bottom left. Figure 7 represents the heat flux shortly after ignition as hot gases from the fire rise in a plume, impact the ceiling and spread outward. Figure 8 shows how during flashover, the highest heat flux levels shift away from the origin to areas with adequate oxygen. The color bars at the right of each diagram represent heat flux intensities with red being the highest at more than 150 kW/m^2.

Figures 9 and 10 show how the post-flashover heat flux viewed from a particular perspective (changeable by the user) can be compared with a post-fire photograph of the same area. The area shown is directly across the room from the open doorway. Air flowing in at the bottom promoted energetic, ventilation-limited burning along its path.

Investigators and attorneys alike can use such data to evaluate hypotheses as to how and when damage was created. Attorneys should consider using fire modeling before litigation to examine various hypotheses for fully involved, post-flashover fires. Origin determinations for fully involved fires that were based chiefly on the locations of the most severe burn patterns should never be accepted without scrutiny.

Fig. 5 - Oxygen concentration seconds before flashover

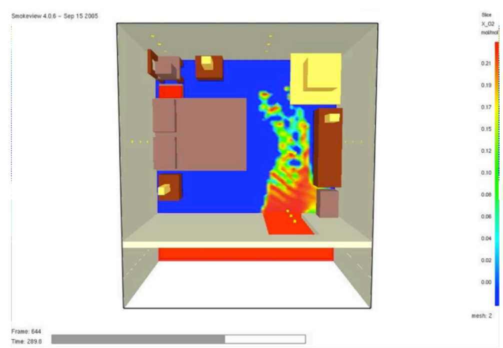

Fig. 6 - Oxygen concentration shortly after flashover

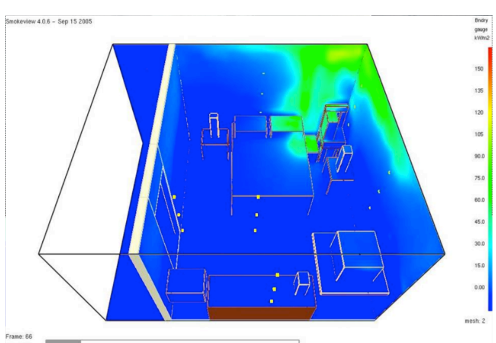

Fig. 7 - Estimated heat flux shortly after ignition

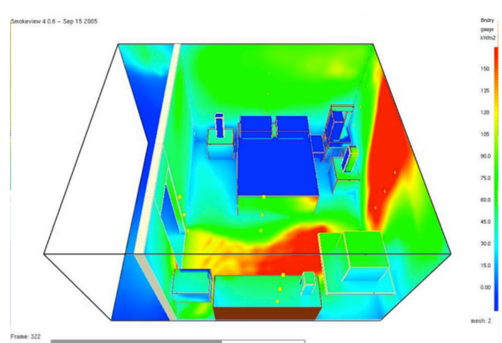

Fig. 8 - Estimated post-flashover heat flux

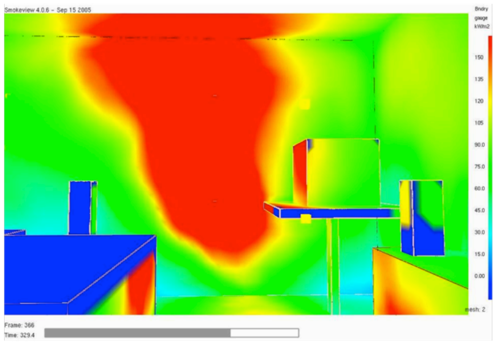

Fig . 9 – Calculated heat flux as viewed from the doorway

Fig. 10 - Photograph of actual burn as viewed from the doorway

CONCLUSIONS

Post-flashover, ventilation-limited fires can be challenging for even the most experienced fire investigators. Steps that have proven effective in investigating pre-flashover fires may not be adequate in post-flashover investigations. Computer fire modeling can prove extremely useful in discerning between pre- and post-flashover burn patterns and evaluating hypotheses as to origin and cause.

New evidence illustrating the role ventilation plays in fully involved fires should encourage litigators to question those opposing experts' conclusions based on "old-school" assumptions. Post-flashover origin determinations reached by identifying the area of most severe burning should receive particularly close scrutiny.

ADDITIONAL READING

Carman, Steven W., "Improving the Understanding of Post-flashover Fire Behavior," Proceedings of the International Symposium on Fire Investigation Science and Technology, 2008, Sarasota, FL

Carman, Steven W., "Progressive Burn Pattern Development in Post-flashover Fires", Proceedings of Fire and Materials, 2009, Interscience Communications, London, UK.

Carman, Steven W., "Science Trumps Art in Fire Investigation", Texas Bar Journal, July 2011, Vol. 74, No. 7, pp. 586-591