"CLEAN BURN" FIRE PATTERNS – A NEW PERSPECTIVE FOR INTERPRETATION

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

ABSTRACT

In the process of determining the location of a fire's origin in a building, investigators often rely upon their interpretation of burn patterns created during the fire. During a series of recent fire tests designed to further understand burn pattern development during ventilation-controlled, post-flashover fires, unexpected findings emerged related to patterns commonly known as "clean-burn". Experienced investigators who examined the compartments after each fire noted variances in clean-burn pattern generation despite each of the fires having been initiated in the same manner and at the same locations. If analyzed solely based upon current knowledge of clean burn pattern development, these burn patterns could have led to widely varying conclusions.

Most of the present-day definitions in fire investigation literature associated with the term "clean burn", relate to oxidative combustion of soot deposited on various surfaces. According to NFPA 921, "clean burn" is defined as, "… a phenomenon that appears on noncombustible surfaces when the soot and smoke condensate that would normally be found adhering to the surface is burned off. This produces a clean area adjacent to areas darkened by products of combustion…"

In three, single-room compartment fire tests conducted in 2008 at the U.S. Bureau of ATF's Fire Research Laboratory in Maryland, each fire was started in the same manner and location. The main variable in each of the tests was the length of time the fires burned under ventilation-controlled conditions. While some similarities in the ensuing burn patterns were identified, there were also variances, particularly in clean burn indicators. Analysis of video recordings made during the tests, suggest that the clean burn patterns might not have been generated via the mechanism suggested by common definitions like that referenced above from NFPA 921. Further in two tests where clean burn patterns were expected, they were not seen. The anticipated pattern areas were instead covered over with soot deposits.

Persistence of clean burn patterns is examined. The author's initial hypothesis is that the mechanism for clean-burn pattern development may be different than the popular notion of combustion of previously deposited soot. The patterns may be due in part to high thermal gradients on surfaces preventing localized deposition from occurring. A better understanding of such mechanisms may improve the interpretation of such patterns, particularly in relation to identifying aspects related to the timing of their creation.

A review of the literature related to the deposition of soot on wall surfaces is conducted to identify thoughts on potential variables and mechanisms at play. Additionally, clean-burn pattern development will be discussed in relation to ventilation flows.

BURN PATTERN RECOGNITION AND INTERPRETATION

"Fire investigation" is defined by the U.S. National Fire Protection Association (NFPA) in document NFPA 921 as "the process of determining the origin, cause and development of a fire or explosion."[1] Elsewhere it is defined as simply, "the analysis of fire related incidents."[2] The method by which an investigator analyzes information and determines a fire's origin and cause as well as how it developed involves, among other things, examination of fire-damaged areas known in the profession as "fire patterns" or "burn patterns". For years, many efforts have been made amongst fire investigation professionals to categorize and explain the variety of patterns that might be encountered at a fire scene.

Many prominent references used by fire investigators and fire investigation trainers throughout the world dedicate significant attention to defining fire patterns and attempting to explain the mechanisms responsible for their creation. The 2008 edition of <u>NFPA 921, Guide for Fire & Explosion Investigations</u> devotes an entire chapter to fire patterns and their interpretation. Other texts while not necessarily setting aside entire chapters strictly for this purpose still often have lengthy discussions of the topic.

One the patterns described in fire investigation literature is that of clean burn. An early mention of the topic was included in the 1985 text, <u>Fires and Explosions – Determining Cause and Origin</u> by John and Patrick Kennedy. An section in the book states, *"Clean Burn Patterns – This effect is most often seen on metal, concrete, brick, masonry or plaster in which the temperature of the heat source is sufficient to burn up any soot material which may have been adhering to the surface. Generally, clean burn patterns do not occur at temperatures below 1200 ºF. These clean burn patterns can be utilized for flame spread travel analysis, as they do produce Lines of Heat/Temperature Demarcation. They are especially prevalent in structures with concrete or cinder block walls that have experienced total burn out, thus producing a high ventilation effect. However one must be careful not to rely too heavily on the clean burn patterns as they are greatly affected by ventilation, and heat shadowing is common with them."*[3]

A discussion of clean burn was included in the first edition of NFPA 921 in 1992. It continued to appear through the most recent edition published in 2008. The latest entry states in section 6.2.11, *"Clean burn is a phenomenon that appears on noncombustible surfaces when the soot and smoke condensate that would normally be found adhering to the surface is burned off. This produces a clean area adjacent to areas darkened by products of combustion… Clean burn is produced most commonly by direct flame contact or intense radiated heat. Smoke deposits on surfaces are subject to oxidation. The dark char of the paper surface of gypsum wallboard, soot deposits and paint can be oxidized by continued flame exposure. The carbon will be oxidized to gases and disappear from the surface.*[4]

The fourth and later editions of <u>Kirk's Fire Investigation</u> also mention clean burn. The sixth edition states, *"When a noncombustible surface is exposed to soot and pyrolysis products, they condense on it. If that surface is heated sufficiently, those materials can be burned off, leaving a 'clean burn.' The temperatures needed to accomplish (this) are flame temperatures (>500 ºC [1000 ºF). Therefore, a clean burn indicates direct flame contact of some duration. This may be from flames from a fuel package playing on the surface or from incursion of fresh air into an under ventilated post-flashover room…"*[5]

<u>Forensic Fire Reconstruction</u> states, *"When a solid surface is exposed to a fire environment, products of combustion – water vapor, soot, and pyrolysis products – will condense on it. The cooler the surface, the faster products will condense (giving rise to the shadowy outlines of studs, nail heads, and other hidden features of a wall structure that cause a temperature differential). When a sooted surface is exposed to direct flame, it can reach high enough temperatures that the accumulated products can burn away, leaving behind a clean surface.*

This pattern can be used to identify areas of direct contact between a surface and the flaming portion of the plume. Surfaces not in contact with the flame will rarely reach sufficiently high temperatures to allow the complete combustion of condensed or pyrolysates. An unpublished study by Ingolf Kotthoff indicates that for a clean burn to occur, the material must reach approximately 700°C (l300°F). A clean burn can also result where charred organic materials are burned away leaving a bare noncombustible substrate exposed."[6]

These definitions seem to all have an element of timing inherent to them in that in each, there is an implication that soot or combustion products of some sort are first deposited on a non-combustible surface and then later burned away. The result as suggested in the name, is an area that appears to have burned clean, surrounded by darker regions of a surface still covered with soot or smoke residue. Investigators interpreting these patterns may try to use this implied timing factor to deduce the direction of fire progression, duration of fire exposure and possibly the location of burning fuel packages. Some may tend to attribute severe damage to a longer period of burning, and thus associate the patterns with fire origin.

Recent fire tests have provided results suggesting that the phenomenon responsible for clean burn may actually be somewhat different than the process often described as causing it. Understanding these potential differences may reduce the chance that investigators might interpret such patterns incorrectly.

FIRE TESTS

In July 2008, a series of three compartment fire tests were conducted at the Fire Research Laboratory (FRL) of the U.S. Bureau of Alcohol, Tobacco, Firearms and Explosives in Ammendale, Maryland. The tests were designed to identify factors at play in creating burn patterns under differing times of ventilation-controlled exposures. A summary report was written that presented findings related to that topic.[7]

Engineers and technicians at the FRL assisted in designing and building cubicles for three test burns to follow on from two Las Vegas fires tests conducted in 2005. New furnishings fore each cell were purchased. They were identical with the exception of the fabric color on one of three upholstered chairs. Cell measurements were approximately 14 feet by 12 feet with 8 feet high ceilings and each was built with an open doorway in the front wall fitted with a hinged, inward-swinging, hollow-core door. Every cell was furnished with a dressed queen-sized mattress and box springs, two foam pads under the sheets, two polyester pillows, wooden headboard, footboard and bed frame, an upholstered wing back chair, wooden chest of drawers, wooden dresser with attached mirror, wooden nightstand, lamp, and small plastic trashcan with 10 sheets of crumpled newsprint. Cells were also carpeted with wall-to-wall, carpeting over carpet pad. Electricity was supplied. The Las Vegas tests involved the same sized cells with somewhat similar furnishings. In each of the FRL tests, an upholstered chair replaced a wicker chair used in Las Vegas, a chest of drawers took the place of a second nightstand, and no table/TV combination was present in the corner opposite the doorway. The upholstered chair was needed to increase the fuel load since the 2008 mattresses burned less vigorously (due to newer flammability standards) and would not drive the cells to flashover.

In addition, more instrumentation was used in the FRL tests than had been used in Las Vegas when only 2 thermocouple trees were employed. Included were four thermocouple trees, three total heat flux (THF) gauges, one radiant heat flux (RHF) gauge, four gas sensors measuring oxygen, carbon dioxide and carbon monoxide, two interior and two exterior video cameras, smoke and carbon monoxide detectors and three gas velocity probes at the doorway. Numerous photos were also taken both pre- and post-fire to document the scenes.

Calorimetry data was not monitored during the tests. A diagram of the cells is shown in Figure 1.

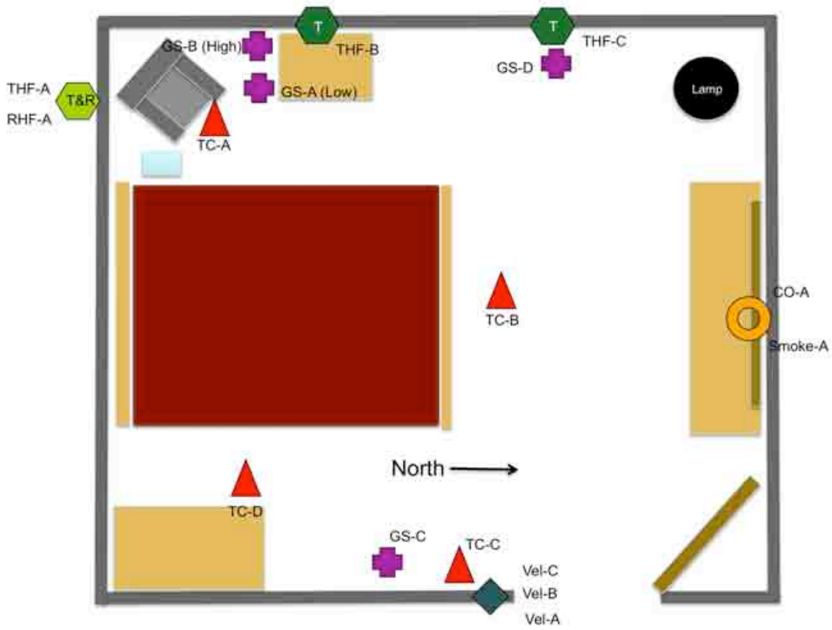

Figure 1. Layout of FRL burn cells
showing instrumentation

The FRL test plan called for each fire to transition through flashover and into ventilation-controlled burning. The only planned variable in each test would be the length of time the cell was allowed to burn fully involved, under ventilation-controlled conditions. The location and method of ignition in each test would be similar to the first Las Vegas test. An open flame from a butane lighter was used to light newspaper in a trashcan between the bed and wingback chair. As with any fire test, accurately determining the onset of flashover is challenging, as several methods exist to identify it. [8,9] For the FRL tests, when upper layer temperatures reached 600 °C, flashover was said to have occurred even though other factors commonly associated the phenomenon may not yet have been attained. To ensure equal datum points for measuring times of ventilation-controlled (VC) burning, the onset of steady flame extension out of the doorway was used as a starting point. The first fire was to be extinguished ten seconds after the onset of steady flame extension (VC + 10 seconds), and the second and third cells after two and four minutes respectively (VC + 2 minutes and VC + 4 minutes).

After unforeseen events occurred during test 2 (the door closed three different times on its own), it was decided that the third test should repeat the burn time of VC + 2 minutes. This decision was made even though the total time the door was closed was only 15 seconds and the final opening occurred 20 seconds before steady flame extension (VC – 20 seconds) started. Prior to the start of test 3, the door was secured open and the test run without any difficulties.

The three FRL tests were designed to allow researchers to better understand the extent and location of fire damage created during the post-flashover / ventilation-controlled burning period. In the two Las Vegas tests, the fires were started in different locations. One of those locations, a trashcan between the bed and a chair, was chosen for use in all the FRL tests.

Each of the Las Vegas tests burned for 7 minutes, 3.5 minutes to flashover and 3.5 minutes post-flashover. In the test started between the bed and chair, a surviving clean burn pattern was found on the wall at the head of the bed generally between the bed and chair. In planning the FRL tests, it was anticipated that similar burn patterns might result.

After the FRL tests were completed, burn damage was documented and examined. After the first test fire (Cell 1), an area of clean burn was observed on the wall near the area of origin (left wall facing the door from outside). Approximately 45 inches above the floor was an irregularly shaped clean burn pattern that measured about 20 inches wide and 12 inches high. This area was contiguous to and above the top of the plastic trashcan that had been between the bed and upholstered chair. Arrows in Figures 2 and 3 point to the pattern.

Fig 2 - Cell 1 showing clean burn

Fig 3 – Closer view of Cell 1 clean burn

Examination of interior and exterior video revealed this pattern was consistent with an area of early flame contact with the wall. Figures 4 and 5 are still-photos captured from video 28 seconds after ignition in Test 1. In the video, no noticeable smoke or soot deposits are seen on the wall adjacent to the flames.

Fig 4 – Test 1 at 28 seconds after ignition (video shot through exterior viewing port)

Fig 5 – Test 1 at 28 seconds after ignition (video shot from inside the cell)

The three cells were examined in the order they were burned. Since each of the fires was started in the same fashion, investigators expected to find similar fire patterns near the origins. It was thought that the extent of damage might differ due to longer burn times in Tests 2 and 3. The findings were surprising. Neither Cells 2 nor 3 had any clean burn patterns near the origin as seen in Figures 6 and 7. This was despite video showing similar early flame contact with the nearby walls in each of those tests like occurred in Test 1. Photos of the flames impacting the walls are shown in Figures 8 through 11.

Fig 6 - Wall behind origin, Cell 2

Fig 7 - Wall behind origin, Cell 3

Fig 8 - Test 2 shortly after ignition

Fig 9 - Test 2 at same time as Fig 8

Fig 10 - Test 3 shortly after ignition

Fig 11 – Test 3 at same time as Fig 10

Although there was no similar clean burn areas on the left-side walls of Cells 2 or 3, depth-of-calcination measurements taken in all three cells near the origin showed similar, localized damage in the same general areas. In each case, areas of deeper calcination were generally consistent with the location of initial flame impact seen in the videos. In Cells 2 and 3, calcination damage was somewhat more severe that in Cell 1, possibly due to the longer burning times of the adjacent chairs. Damage on the wall between the chair and the bed was greatest from about 2 to 4 feet off the floor and then lessened moving further upwards.

POSSIBLE MECHANISMS OF CLEAN-BURN PATTERN CREATION

To better understand how clean burn patterns might be created, one should be familiar with the variety of factors involved. In most any fire with a visible flame, the luminosity of the flame is due to soot particles radiating visible light as well as infrared heat energy. Soot consists of small, carbon-based particles formed during incomplete combustion in the fuel-rich areas of diffusion flames. Flames that contain relatively large amounts of soot generally radiate more energy.

Certain combustibles tend to produce copious amounts of soot and smoke. Organic compounds containing stable, six-carbon rings are notorious smoke generators. Such rings tend to be more difficult to pyrolyze or decompose than simpler, straight chain organic molecules. The stable, ringed compounds fall into a class of organics known as "aromatics" and include such products as styrene, toluene, benzene and many others. Common building materials rich with such chemical structures include roofing felt, polystyrene insulation, and various plastics. Fuel gases from such materials tend to burn less completely and thus emit greater amounts of sooty smoke.

Smoke production is also greatly dependant upon a fire's ventilation. Poorly ventilated fires generate more smoke than well-ventilated blazes. In clean, nearly smoke-free atmospheres, surrounding air is quickly entrained into the flames before they cool via radiation. When oxygen reaches hot fuel molecules, more complete oxidation and less smoke generally results. In fires with inadequate ventilation, soot-rich fuels can cool before encountering enough oxygen to burn. This leads to increased smoke production.

In well-ventilated fires, flame temperatures are generally higher than they would be in vitiated conditions. With sootier, under-ventilated fires, greater radiant losses result in lower flame temperatures. Fires are classified as ventilation-controlled when there is not enough oxygen to burn all of the available fuel gases. Under such conditions, soot production will be greater than with well-ventilated, fuel-controlled fires.

NFPA 921 states, "*When flames touch walls and ceilings, particulates and aerosols will commonly be deposited. Some deposits can collect on surfaces by settling and deposition.*" It further says, *"Smoke deposits can collect on cooler surfaces or a building or its contents, often on upper parts of walls in rooms adjacent to the fire. Smoke condensates can be wet and sticky, thin or thick, or dried and resinous. Smoke, especially from smoldering fires, tends to condense on walls, windows, and other cooler surfaces."*[4]

Several mechanisms can be involved in causing soot and aerosols to adhere to surfaces. These include diffusion, deposition, electrical migration, London-van der Waals forces and thermophoresis.[10] The last, thermophoresis, means "being carried by heat".[11] It occurs when small particles are driven in a temperature gradient from high- to low-temperature regions. Many fire investigation references describe the adherence of smoke and soot to walls as "condensation" since warmer particles tend to coalesce or condense on cooler surfaces. As cooler surfaces absorb the energy of hot fuel gases and aerosols, combustion products tend to adhere to the surfaces.

When a fire compartment surface is cooler than nearby smoke, then thermophoresis will move minute soot particulates from the hotter fire environment towards the lower-temperature zone. For vertical walls, soot particles can adsorb against the surface. Gravity may cause airborne particles to settle loosely onto the tops of horizontal surfaces. Buoyant forces coupled with thermophoresis can lead to soot adhering to the undersides of horizontal surfaces.

Most fire investigation references mentioning clean burn patterns describe them occurring when previously deposited soot is burned away. These patterns may also occur somewhat differently. Early in a fire, as flames initially play against surfaces like walls, the heat transfer can result in steep thermal gradients between the areas directly impacted by flame and those nearby outside the flames. The hotter areas can exhibit a thermophoresis-type effect forcing small soot particles away. In such situations, the "particles are bombarded by higher-energy molecules on their 'hot' side and thus driven towards the lower temperature zone(s)", thus away from the hot wall.[11] This would tend to minimize soot deposition on these hotter surfaces.

REVIEW OF FIRE TEST RESULTS

Such wall heating prior to soot adsorption may have been responsible for causing the clean burn pattern near the area of origin in Test 1. Early on in the fire, flames from the trashcan impacted a relatively small area of the left wall causing a likely steep temperature gradient in the gypsum wallboard. The resulting thermophoresis would have tended to repel soot particles from the hotter surface.

In Tests 2 and 3, the fires burned under ventilation-controlled conditions about two minutes longer than happened in Test 1. In that extra time, temperatures throughout the hot gas layer remained high causing the walls to heat more evenly. Even-heating would tend to dissipate thermal gradients across the wall faces. With lower gradients, soot would not tend to be repelled from localized areas. Also, the extra two minutes of ventilation-controlled burning in Tests 2 and 3 would have fostered higher soot production than in Test 1 (which mostly burned in the fuel-controlled stage).

More even, longer-term wall heating in Tests 2 and 3 (and presumably lower thermophoretic forces away from them) coupled with a higher concentration of soot in the room likely enabled formation of a soot layer over any clean-burn areas that may have begun to form near the origin as in Test 1. While the possible interim creation of such clean-burn patterns in Tests 2 and 3 cannot be confirmed, similar, localized calcination damage was found after all three tests. This suggests the early conditions in each fire may have been similar and conducive to forming comparable clean-burn patterns.

Figure 12 shows a clean burn pattern found near the fire origin in one of the Las Vegas fire tests. That fire burned for 3-1/2 minutes post-flashover. Some might argue this shows that extended burning will not eliminate clean burn patterns since the Las Vegas fire burned longer than either FRL Test 2 or 3. A major difference in the tests is that in the Las Vegas, there was less soot-producing fuel near the clean burn pattern. The wicker chair used in Las Vegas had a small, upholstered cushion shown in Figure 13. In each of the FRL tests, the wicker chair was replaced with a larger, upholstered chair. Those chairs had much more polyurethane foam that would have continued to pyrolyze and release soot into the room after the wicker chair would have mostly burned away. This extra foam could have produced the nearby soot layer coating the wall adjacent to the fires' origins.

Fig 12 - Las Vegas clean burn

Fig 13 – Las Vegas cell before fire

There were also other large clean burn patterns in each of the three FRL cells. Two of the patterns, one each in Cell 2 and Cell 3 were amazingly similar in size and location. The onset of the damage in those patterns was recorded on video. Burning of already-deposited soot did not seem to occur. Videos shot from the right wall towards the origin clearly showed flames on the rear wall (opposite the door) appearing to originate in the hot gas layer. At the time, the rear wall near where the flames were burning appeared mostly soot-free.

Fig 14 - Test 2 at 3 min 54 sec

Fig 15 - Test 2 rear wall (arrow shows the orientation of video images in Figs 14 and 16)

The white, V-shaped areas across the rear walls of Cells 2 and 3 (Figures 15 and 17) were adjacent to the flames visible at the right of Figures 14 and 16. While the resulting fire damage was severe, it was unrelated to the location of the fires' origins. Ventilation-fed flames in the hot gas layer caused the damage. Depth-of-calcination measurements in the clean burned areas were the deepest in the cells. While some might interpret the patterns as typical V-patterns created by upward plume movement, this was not the case. The burning away of soot deposits off the wall also did not appear to be involved. Instead, likely high thermal gradients on the walls (caused by flame impingement) may have resisted soot from ever being deposited there.

Fig 16 - Test 3, 2 min 48 sec

Fig 17 - Test 3 Rear Wall

A significant finding in these tests was that the rear-wall clean burn patterns were not caused by fuels burning at their bases. Though appearing similar to V-patterns, plumes rising from the bottom of the Vs and intersecting the walls did not cause them. Instead, hot clouds of fuel-rich gases originating elsewhere in the cells had actually created the V shapes by burning from the top downward.

FIRE MODELING

FDS fire modeling of the FRL tests was performed. A complete review of the results will not be included here for sake of brevity. In summary, the model results supported the conclusions that the rear wall clean-burn patterns in Tests 2 and 3 were created as a result of localized, high heat fluxes. The similarity in location and size of the patterns in both Cells 2 and 3 is believed dependant mostly on compartment geometry and ventilation flows. Calculated oxygen concentrations near clean burned areas were higher than near the more uniformly sooted areas. These results were in part supported by actual oxygen measurements made during the tests in various parts of the compartments.

CLOSING THOUGHTS

It should be noted the findings arising from these tests may be limited in their reach and might not apply to all fire scenarios. They are offered to add to the existing theories on the creating of clean burn patterns while simultaneously pointing out potential limitations in them. This work is insufficient to suggest an all-encompassing characterization of the clean burn phenomenon. The most important lesson from the results may be to affirm the need to understand the timing of clean burn pattern generation in relation to soot deposition.

Investigators using clean burn patterns to propose specific timing scenarios and perhaps direction of fire movement would be advised to carefully consider their data. Those associating these patterns with longest burn duration ought to be particularly cautious. Even when certain clean burn damage is the most severe in a compartment, it is imperative to consider if it occurred early, near the origin of a fire or later, distant from the origin as a result of ventilation-fed, energetic flames.

In well-ventilated areas, clean burn patterns may occur differently than from the popular concept of flames removing existing soot deposits. These test results suggest flames may instead cause high thermal gradients on soot-free surfaces. Those "hot spots" then could further resist soot condensation. Nearby, soot might still adhere to cooler surfaces.

In fully involved, ventilation-controlled compartment fires, temperatures throughout much of the compartments are sufficient to burn soot. In such cases, the localized oxygen concentration would be the controlling factor in developing clean burn patterns. In areas mostly devoid of oxygen, surviving soot deposits might be typical. Where oxygen is plentiful, clean burn patterns in the soot layers are more likely to occur.

In recent months, proposals have been made in the U.S. to conduct further research into the science affecting clean burn pattern production. With funding, researchers may someday provide quantifiable results on this topic and investigators might no longer have to rely on anecdotal evidence to support their interpretations.

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ABOUT THE AUTHOR

Steven W. Carman, IAAI-CFI, 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. 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 "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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