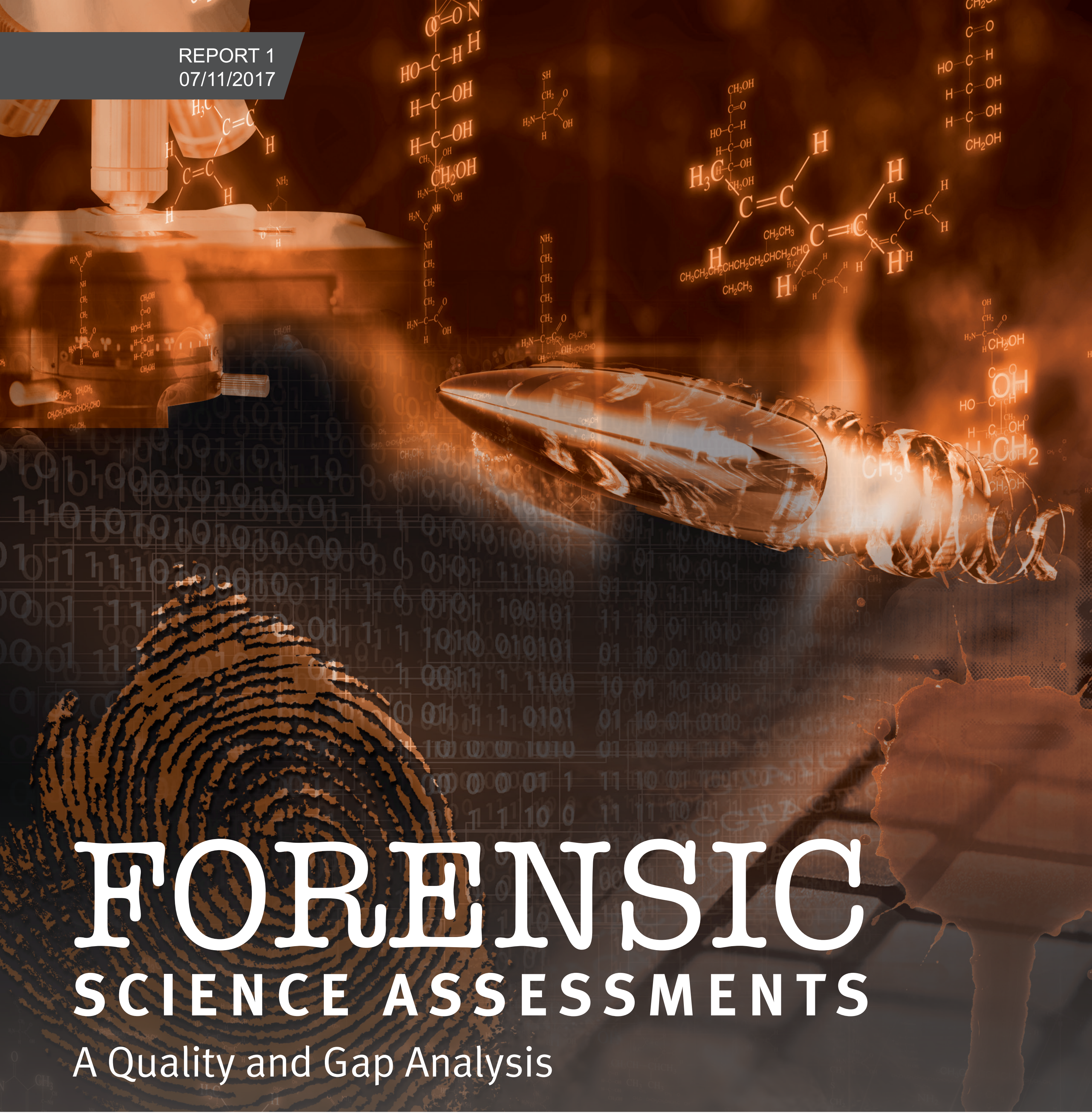

REPORT 1
07/11/2017

# FORENSIC SCIENCE ASSESSMENTS

## A Quality and Gap Analysis

## Fire Investigation

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# Forensic Science Assessments: A Quality and Gap Analysis

## Fire Investigation

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## PREFACE

Valid and reliable forensic science is an essential tool for apprehending suspected criminals during investigations and helping to determine guilt or innocence at trial. Nevertheless, there have long been assertions that many of the forensic sciences are neither valid nor reliable. In fact, in some cases, reports and testimony based on substandard science have contributed to the convictions of individuals later proved innocent through DNA testing.

The following report addresses fire investigations, setting forth what is known about fire science and what remains unknown. The Conclusions and Recommendations section draws on the technical sections that begin on Page 6, and is a distillation of that information. Each conclusion is accompanied by a page number(s), referring to the location in the technical section where support for it can be found. Fire investigation is a two-part process. The first is the fire scene investigation and the second part is the analysis of the fire debris collected at the fire scene. The organization of this report reflects these two elements of an investigation. Both the Conclusions and Recommendations section and the technical sections are organized on this basis. The Methods (Appendix A) section describes the methods that were used to prepare this report. This is followed by a Primer (Appendix B), which concisely describes some basic facts about fire science and the investigation of fires.

While this report presents a scientific assessment of the status of fire investigation, it is up to the legal community—lawyers and judges—to determine how to use the information in legal proceedings.

## INTRODUCTION

In its 1993 opinion in *Daubert v. Merrell Dow Pharmaceuticals*, the Supreme Court set forth standards for the admission of scientific evidence in litigation. The Court ruled that, under Rule 702 of the Federal Rules of Evidence, a "trial judge must ensure that any and all scientific testimony or evidence admitted is not only relevant but reliable" (*Daubert v. Merrell Dow, 1993*). In short, federal judges have an obligation to be "gatekeepers," separating good science from dubious science. Although attorneys representing defendants in civil cases have taken advantage of the door the Court has opened for them, often challenging the admission of plaintiffs' evidence for failing to meet these new standards, by and large attorneys representing criminal defendants have made relatively few challenges to the state's evidence (NAS Report, 2009 at p. 3-17). Thus, evidence that might be "dubious" has continued to carry weight in criminal trials.

Congress was aware of the criticisms of forensic science and, in 2005, under the Science, State, Justice, Commerce, and Related Agencies Appropriation Act of 2006, authorized the National Academy of Sciences/National Research Council (NAS) to report on the status of forensic science (H.R. Rep. No. 109‐272, 2005). In 2009, the NAS issued its report, "Strengthening Forensic Science in the United States: A Path Forward" (hereafter referred to as the "NAS

Report”). The report’s most significant conclusion is that much of forensic science as currently practiced has “little systematic research to validate the discipline’s basic premises and techniques” (NAS Report, 2009).

Furthermore, the NAS Report also emphasizes that most forensic sciences depend on human judgment and interpretation and, therefore, cognitive factors are at play and must be accounted for. As the report notes, it is especially problematic that “forensic science experts are vulnerable to cognitive and contextual bias.”

The NAS Report provided a good start on improving forensic science and, coming from such a prestigious organization, has been widely quoted and influential. Nevertheless, in its overall critique of forensic science, it did not point to specific areas where practices are supported by sound research and those where they are not. While the NAS Report called for research from the “scientific community,” it did not provide a research agenda to aid that community, including funding agencies.

Also in 2009, the National Science and Technology Council’s Committee on Science established a Subcommittee on Forensic Science (SoFS). SoFS members were told to focus on “developing practical and timely approaches to enhancing the validity and reliability…in forensic science….” (Charter of the Subcommittee, 2009). Further, the reauthorization of the SoFS charter “encouraged” it to “create a prioritized forensic science research agenda through a comprehensive gap analysis or other appropriate means….” (Charter of the Subcommittee, 2012). SoFS appointed five Interagency Working Groups (IWGs), one of which, the Research, Development, Testing, and Evaluation (RDTE) IWG, was tasked with fulfilling the charter’s mandate. The RDTE IWG soon realized that it was not possible to undertake a gap analysis unless they had a better grasp of the extant literature. Members drew up a set of questions for ten forensic fields: (1) bite marks, (2) bloodstain patterns, (3) digital evidence, (4) fiber evidence, (5) fire investigation, (6) firearms and tool marks, (7) footwear and tire tracks, (8) hair evidence, (9) latent fingerprints, and (10) paints and coatings. The answers to these questions were deemed critical in determining whether the scientific foundation for a particular discipline was valid and reliable. The questions, in turn, were submitted to groups of practitioners in the field who submitted articles they deemed “foundational” to the field and believed constituted a sound scientific basis for addressing the questions. The final product was, thus, a series of questions or propositions and articles, or other scientific sources, purported to address the question. The result of this effort, while not a gap analysis, was an important step on the way to that goal, providing future investigators with an annotated bibliography for each of the ten fields.

In May 2014, the NSTC’s SoFS issued a report – “Strengthening Forensic Science” – based on the conclusions reached by each of the five IWGs that together constituted the SoFS. The report stated that the RDTE IWG had “pursued the identification of foundational research that can be mapped to specific principles across the various disciplines of forensic science” (NSTC, 2014).

Coincident with the SoFS' activities, Congress took note of the problems with current forensic practice. Specifically, then-Senator Jay Rockefeller, Chair of the US Senate Committee on Commerce, Science, and Transportation, held three hearings on forensics (December 2011 (U.S. Senate Committee, 2011), May 2012 (U.S. Senate Committee, 2012), and June 2013 (U.S. Senate Committee, 2013)). At the first hearing, the Senator commented that most Americans think that forensic science is "nearly infallible, always conclusive." He went on to say "the reality is far from this depiction." Senator Rockefeller introduced the Forensic Science and Standards Act of 2012 that recommended the federal government establish a "national research agenda to improve, expand, and coordinate Federal research in the forensic sciences." There was no companion bill from the House, and the bill never became law (Library of Congress, 2012). In 2011, Senator Patrick Leahy introduced the Criminal Justice and Forensic Science Reform Act, which called for the establishment of "oversight and advisory offices and committees" that would be facilitated by the Department of Justice and the National Institute of Standards and Technology and would "ensure that basic research is conducted to establish the validity and reliability of key forensic science disciplines."

The federal government did, however, signal its continuing interest in forensic science by establishing the National Commission on Forensic Science (the Commission), a joint effort of the Department of Justice and the National Institute of Standards and Technology (NIST) in April 2013 (Charter of the NCFS, 2014). The Commission's responsibilities include the "identif[ication] and assess[ment of] the current and future needs of the forensic sciences to strengthen their disciplines…." At the Commission's first meeting in February 2014, John Holdren, then-Assistant to the President for Science and Technology and Director of the White House Office of Science and Technology Policy, noted that the Commission's recommendations will "help ensure that the forensic sciences are supported by the most rigorous standards available – a foundational requirement in a nation built on the credo of 'justice for all'" (Department of Justice, 2014). And then-Under Secretary of Commerce for Standards and Technology Patrick Gallagher said the Commission's purpose is to "help ensure that forensic science is supported by the strongest possible science-based evidence gathering, analysis and measurement" (AAFS, 2013).

In addition to the Commission, the 2009 NAS Report also prompted the redesign of the standards-making processes in the forensic science community. A memorandum of understanding between the Department of Justice and NIST resulted in the formation of a Forensic Science Standards Board with oversight of an Organization for Scientific Area Committees (OSAC) and 25 subcommittees dealing with various forensic science disciplines. Included among these subcommittees is one dealing with fire and explosion scenes, and one dealing with fire debris analysis. This report will be among those considered by the OSAC subcommittees.

## *AAAS Project*

This evaluation is intended to point out where forensic practice is well founded in science and where it is not, and to produce a research agenda to serve as the basis for arriving at forensic methods that will inspire greater confidence in the criminal justice system. This type of thorough analysis has been long needed, and many in the public and private spheres have urged its implementation.

This report addresses the reliability and validity of fire investigations, one of the forensic areas the SoFS IWG identified as needing an up-to-date evaluation. To oversee this effort, AAAS appointed a distinguished Project Advisory Committee to advise on all aspects of the project. The Advisory Committee members included a law enforcement official, a social scientist, a cognitive psychologist, a law professor, a judge, a biomedical researcher, a forensic scientist, and a statistician. Because AAAS intended to analyze more than one forensic discipline, the Advisory Committee was asked to help choose which field to tackle first. The Advisory Committee based their selection(s) on two factors: (1) how often it is used in criminal investigations, and (2) the degree of current controversy and the extent to which the field's legitimacy is being challenged.

In its report, the NAS noted that because most forensic science was developed in crime labs, not academic laboratories, and its practitioners had little training in research and statistical methods, the forensic fields had "never been exposed to stringent scientific testing." Similarly, Senator Rockefeller, quoting a witness who testified at one of his hearings, lamented that most forensic fields lack a "culture of science." Based on these descriptions of the practice of forensics, staff decided to include scientists and engineers trained in research methods and embedded in a "culture of science" in the fire investigation Working Group. These individuals were identified by staff and vetted by the Advisory Committee. A forensic practitioner was also included in the Working Group to assure forensic practitioners that they had a voice at the table and to help staff, and other Working Group members, if necessary, to understand the forensic practice and to write a primer. The fire investigation Working Group included an academic fire engineer, an analytical chemist, and a psychologist who studies decision-making, in addition to a forensic practitioner (see Appendices D and E).

Working Group members were sent the annotated bibliography developed in the SoFS process, updated by AAAS staff (see Appendix C). These bibliographies were not intended to limit the Working Groups in the sources they could rely on, although the bibliographies can serve as a good starting place for the evaluation.

AAAS supported the Working Group, but the authors of this report are the Working Group members themselves. This report consists of two main sections, fire scene investigation and fire debris analysis, and is organized around questions the Working Group decided were key to the evaluation of this particular field.

## *Project Findings and Outcomes*

The recommendations emerging from this report promise to be influential in the advance of fire and fire debris analysis. The report offers an agenda encouraging the injection of rigorous scientific methods and standards into efforts to better understand the strengths and weaknesses of the current scientific bases of fire investigation. The report can be used by funders, public and private, to develop “calls for proposals” that will generate investigator-initiated research into questions touching, directly or indirectly, on fire investigation. This research ideally will come from a broader range of disciplines and institutions than have traditionally been engaged in the study of fires. For example, this and other forensic studies can benefit from contributions by physicists, psychologists, statisticians, and chemists. We also hope that this and future reports, and the increase in funding it may encourage, will lead to more collaborative research by teams of forensic and academic scientists and engineers.

This report should also help other key actors in the criminal justice system—law enforcement, attorneys, and judges—better understand the limits of the current scientific underpinnings of fire analysis. For instance, as judges gain a better understanding of the current state of knowledge regarding fires they will be better able to fulfill their gatekeeping responsibilities, thus bringing a “culture of science” into legal decision-making.

## *Fire Science*

Fire investigation has been the target of well-founded skepticism as relatively newer investigative assumptions and practices are replacing those that historically were accepted “wisdom” in the field. However, not everyone is ready to abandon the standards they have relied on for their entire careers. “Police and fire investigators across the country were often slow to accept advances in fire science that called into question what had long been considered unmistakable evidence of arson” and in “many jurisdictions, those [new] rules were slow to take hold, as veteran investigators clung to what are now considered disproven theories.” In fact, some investigators have been “openly hostile to the updated science” (Mills, 2015).

As advances in fire science are being made, investigators and attorneys are revisiting old cases. What they are finding is chilling. John Lentini (one of the authors of this report) estimates that “a couple hundred” people are wrongly imprisoned because of methods used in fire investigation that have not been empirically validated. According to the National Registry of Exonerations, 63 individuals convicted of arson have already been exonerated since 1991 (http://www.exonerationregistry.org/). Michael Keller, an electrical engineer at a research facility supported by the Bureau of Alcohol, Tobacco, Firearms and Explosives, has investigated three potential capital cases in which the fires were eventually found to be accidental (Bui, 2015). We will never know for sure how many people have been wrongfully convicted based on the aforementioned methods and practices. Likewise, we will never know how many criminal arsonists have not been indicted because of inadequate forensic tools. This report sets forth an evaluation of research on fire scene investigation and fire debris analysis, and we hope, will be read by judges, lawyers for the prosecution and defense, law enforcement officers, laboratory scientists, policymakers, funding agencies, and fire investigation practitioners. It also points to future directions that much-needed research should take.

# CONCLUSIONS & RECOMMENDATIONS
## *FIRE SCENE INVESTIGATION*

The conclusions presented in this section of the report are drawn from the two technical sections that follow (fire scene investigation and fire debris analysis). Recommendations are tied to the conclusions. As with the technical sections that follow, the Conclusions and Recommendations are divided between fire scene investigation and fire debris analysis. Each conclusion is accompanied by page numbers to guide the reader to the location in the technical section that supports it. The 25 recommendations can be the basis for further research by fire scientists, as well as scientists from other disciplines in academia.

## Origin and Cause Determination

### Conclusions

- Fire has been extensively studied, but the complex chemical and physical processes involved are still not fully understood. While much is known about the behavior of fires in building enclosures, using that knowledge to determine where a particular fire started and what caused it remains very challenging. An incorrect determination of a fire's origin generally leads to an incorrect determination of its cause (pp. 13, 18).
- Determining the origin of a pre-flashover fire is generally a straightforward exercise based on burn pattern analysis. However, determining the origin of post-flashover fires is more difficult because post-flashover fires may create new ventilation-generated burn patterns while obscuring pre-existing burn patterns. Moreover, the longer a fire burns in a fully involved condition, the more difficult is the determination of the correct area of origin (pp. 13, 17, 19).
- The speed with which a fire spreads in residences with contemporary furnishings cannot generally be used alone to classify a fire as accidental or incendiary because fires involving modern upholstered furnishings tend to burn faster than those used in older furnishings, regardless of the cause of the fire (p. 19).
- Computer-based deterministic fire models can be used as one means of testing different hypotheses regarding the origin and development of a fire, but such models cannot generally be used alone to determine the cause of a fire. Uncertainties exist concerning these models when they are applied to fire cause determination (p. 23).

### Recommendations

**1.** To improve the analysis of a fire's origin and cause, tests should be run in both reduced and full scale, using multiple compartments and multiple openings, fully documenting the aftermath; with the burning of different materials under a range of realistic fire conditions; and by lighting fires in identically constructed compartments. These tests should be scientifically instrumented so that information, such as temperature at various layers of the room and radiant heat fluxes are measured. A major consideration in deciding to conduct this research is the high cost of burning compartment test rooms. However, by using reduced scale testing, the cost can be lowered and may provide the same critical values related to heat as a full-scale test.

**2.** When a physical fire test is conducted, the fire scenario being tested should also be simulated with a deterministic fire model to evaluate the accuracy of the model and to better understand uncertainties associated with the model. Based on the data obtained through such comparisons, the computer-based deterministic fire models can be continually refined to produce more accurate results, and over time may find an expanded role as a useful tool in actual investigations.

## Locating Ignitable Liquid Residues in Fire Debris

### Conclusions

- A well-trained canine detection team is the current "gold standard" for locating samples at the fire scene that may test positive for ignitable liquid residues (ILRs) in the fire debris analysis laboratory. Canines are advantageous because they provide immediate feedback and are mobile, allowing them to search a large space in a very short time. However, canine alerts should not be relied upon unless confirmed by laboratory analysis (pp. 18, 30).
- Many substances are produced during a fire, but investigators are currently in a position to look only for evidence of ignitable liquids, for which there is currently validated instrumentation. Other chemical markers are of little value, because there is no way to determine *when* they may have been created during a fire (p. 23).

### Recommendations

**3.** Testimony that relies on canine alerts only, without supporting laboratory results, should not be used in court proceedings.

**4.** New technologies, as well as additional training aids and research on new methods need to be developed for measuring canine performance that could enhance their effectiveness.

**5**. Comparative research assessing the effectiveness of technologically more innovative field tools against the effectiveness of canine use should be a research priority.

## Reliability and Validity

### Conclusion

- Little is known about the consistency and accuracy of conclusions among experienced investigators when presented with the same data (p. 25).

### Recommendations

**6.** The reliability of conclusions when fire investigators are presented with similar data of fire origin and cause should be studied. This will allow the calculation of both error rates and the reliability of investigators' conclusions. This exercise should be repeated over several fire scenarios to help determine what types of fire scenes elicit few disagreements and what types elicit many. These tests of reliability will provide feedback on decision points that cause divergent findings among investigators.

**7.** Not only should the reliability of investigators' conclusions or diagnoses be established, but research should also be done on the validity of those conclusions or diagnoses. The use of "test fires" (described in recommendation #1) will help to establish a "ground truth" against which the validity of investigators' conclusions can be assessed. Such tests will also create crucial knowledge about which cues or diagnostics are genuinely associated with various fire characteristics.

**8.** The data generated by the research on reliability and validity should be incorporated into a database that could be used to develop standards for identifying the origin and cause of fires and serve as a resource for the education and training of fire investigators.

## Cognitive Bias

### Conclusions

- Interpretation of the evidence regarding origin and cause is often subjective and depends to a significant degree on human cognitive factors (p. 13).
- Evidence from other domains, as well as within forensic science, suggests that there are practical ways to mitigate and minimize bias (such as, Linear Sequential Unmasking). The aim of such procedures is to maximize the independence of mind of forensic examiners to be as bias free as possible in both the identification of relevant evidence and the conclusion about what the evidence shows about a fire's origin and cause. In this context, the distinction between bias and relevance should be noted. For example, eyewitness testimony although potentially biasing, can also be relevant in some instances. One of the recommendations from the OSAC (Organization of Scientific Area Committees) Fire and Explosion Investigation Subcommittee suggests research in this area (p. 26).

### Recommendations

**9**. Given what is known about the role of cognitive bias in interpretation and decision making, the work by fire scene investigators should be separated from other components of the fire investigation. Those who gather and prepare evidence should focus on scientific analysis and be as neutral as possible in deciding what evidence to collect and how to interpret it. This would help to minimize bias that might affect fire scene investigation. In some jurisdictions, this will be cost prohibitive, but in those jurisdictions where this is not the case, this recommendation should be followed.

**10**. Case management interventions should be adopted that shield fire scene investigators from information irrelevant, but potentially biasing, for assessing the scientific evidence critical to determining fire origin and cause (see the National Commission on Forensic Science document "Ensuring That Forensic Science Is Based Upon Task-Relevant Information").

**11**. There should be policies and procedures that clarify what is or is not relevant for fire investigators to know at each stage of an investigation, in order to reduce the possibility of bias.

**12**. Forensic laboratories and fire scene investigators' professional societies should adopt policies and procedures to help implement the recommended changes in case management. Policies and procedures should reflect what is best for helping fire investigators reach accurate scientific conclusions without regard for the convenience of the labs or others associated with the investigation, such as law enforcement.

**13**. In general scientific practices, bias is often handled by "blinded procedures," whereby researchers are unaware of information irrelevant to their task. This should be the gold standard for fire scene investigation as well. The literature on this topic discussed in the technical report includes specific suggestions for accomplishing this challenging task in the context of forensic science.

**14**. The implementation of the recommendations for minimizing the influence of cognitive bias should be accompanied by monitoring and evaluation to assess their impact and, where appropriate, lead to modifications.

## Education, Certification, and Experience

### Conclusions

- There are insufficient educational and proficiency testing requirements for fire scene investigators (p. 22).
- There is currently no scientific basis for concluding that the accuracy of *certified* fire investigators, in particular, is better than the accuracy of non-certified fire investigators (p. 22).

### Recommendations

**15.** Education and training for fire investigators should cover the issues of human cognition and cognitive bias, as well as what has been discovered in the reliability and validity testing discussed in recommendations #6 and #7. The training could be done through live training simulations as well as online with photographs and videos or other depictions of test fires in which the origin and cause are known with certainty. Testing materials could employ the same technique with new fire depictions not used in the training materials.

**16**. The effects of education, training, and certification on fire investigators' ability to determine fire origin and cause should be further studied.

# CONCLUSIONS & RECOMMENDATIONS
## *FIRE DEBRIS ANALYSIS*

## From Fire Scene to Laboratory
### Conclusion

- Although the science of fire debris analysis (analytical chemistry) is more mature and reliable than the science of fire scene investigation, there is still room for improvement in the knowledge base and in the practice of fire debris analysis (p. 28).

### Recommendation

**1.** Enhanced field tools should be explored to optimize sample identification and sample collection at the fire scene. Such tools include field-based mass spectrometers, field-based ignitable liquid residue (ILR) analysis that allows for rapid feedback to investigators, and more sensitive and specific electronic “noses” that can also detect the broad spectrum of potential ILRs. For example, research using sampling approaches providing enrichment such as Solid Phase Microextraction (SPME), membrane extraction with sorbent interface and Needle Traps with portable mass spectrometers to detect and locate ILRs, may improve the effectiveness of the current use of hydrocarbon detectors.

## Applying Analytical Methods in the Laboratory
### Conclusion

- Several ASTM (American Society for Testing and Materials) standard test methods (E1386, E1388, E1412, E1413, E1618, E2154) currently exist for the detection, extraction, analysis and interpretation of ILRs from debris, and these methods are generally, but not uniformly, used by the forensic science community. Such standardization of analytical methods is a positive step in improving the testing and evaluation of fire scene debris. Yet, it must be acknowledged that each case is different, and may require different extraction or analytical methods, necessitating some flexibility in deciding what standard method(s) to apply (p. 32).

### Recommendations

**2**. Although research to improve ASTM standard test methods for extraction, separation, and analysis of ILRs would be useful, it is important to stress that the basic science is sufficiently developed and mature, and there is no reason for operational laboratories not to use these methods. Hence, all fire debris analysis laboratories and forensic practitioners should be made aware of these methods, should have access to them, and should be expected to follow them.

**3**. Additional research to determine the performance of the ASTM methods under various real-world case scenarios is needed. For example, a useful study would involve testing fire debris analysts by using blind samples containing known amounts of ILRs in the presence of background, combustion and pyrolysis products as well as samples containing only background, combustion and pyrolysis products.

**4.** Error rates in fire debris analysis should be quantified to lead to a more quantitative assessment of the extent of false positive or false negative determinations of ILRs. Interlaboratory studies testing the performance of the existing standard methods and standard practices can provide useful data on the overall performance of the discipline, including the error rates for specific scenarios normally encountered in cases.

## Challenges in Analyzing ILRs

### Conclusions

- The changing nature of available fuels and consumer products requires the continual monitoring of possible sources of ILRs. Studies have shown the risk of confusing combustion and pyrolysis products with ILRs. Additionally, some man-made products emit volatile organic compounds (VOCs) that also resemble ILR signatures (background products). An error in confusing background, combustion and/or pyrolysis products with an ILR would have serious and detrimental effects on the overall process of fire investigation (pp. 33-34).
- The difficulty of the task of data interpretation in fire debris analysis cannot be overstated. Essentially, forensic scientists are asked to classify any of the potential flammable liquids into a limited number of chemical categories. Although the existing standard is more than adequate for the vast majority of forensic casework, it is imperfect (p. 35).
- There is a risk of missing ILR signatures due to advanced weathering and/or microbial degradation as time goes by. The degree to which false negatives—that is, the number of cases where the examiner does not find any ILRs even though they are present—can be attributed to weathering and/or microbial degradation effects is not known. A wide variety of situations and the number of variables affect both weathering and microbial degradation (p. 34).
- There is debate in the fire debris analytical community on whether to limit the sensitivity of the methods used, with the justification that this approach reduces the risk of confusing ILRs with background products or with combustion/pyrolysis products (pp. 34-35).

### Recommendations

**5.** Studies are needed on the differentiation of intentionally added ILRs from pyrolysis/combustion products and from products innocently present in materials at the fire scene. Comparison samples should be analyzed whenever possible.

**6.** Additional work on the classification of ILRs is needed, particularly with regard to whether the existing classification scheme should be modified to accommodate new products on the market (e.g., more environmentally friendly fuels such as biodiesel and plant-based lamp oils).

**7**. Experiments that explore the effects of weathering on different types of ILRs should be conducted. Such experiments could include subjecting ILRs in fire debris to the heat of a fire or to dousing with water.

**8**. The impacts of potential microbial degradation on fire debris should be studied. To date, a great amount of work has been performed on this phenomenon with respect to soil. There may be other substrates and situations in which these effects may be encountered.

**9**. The on-going debate on the use of more sensitive methods under certain conditions should be addressed in order to assess the actual effects of more sensitivity when examining ILRs. Research on the performance of highly sensitive methods, such as SPME, will answer some of the questions, such as whether “too much sensitivity” should be considered an undesirable technical feature of a method. Studies to determine the frequency of false positives and false negatives given some determination (absolute concentration) criteria will help to answer this question. Research to determine the background levels of ILRs present in substrates encountered in a wide variety of settings may lead to the determination that a low concentration of ILRs in substrates is encountered so frequently that it would be conservative to set a threshold on sensitivity. This would minimize or eliminate false positive determinations based on “too much sensitivity.”

## A. FIRE SCENE INVESTIGATION

In 2015, over 1.3 million fires were reported in the United States, resulting in over 18,000 civilian casualties and $14.3 billion in property damage (NFPA, 2017). This included vehicle fires, outside/unclassified fires and home/structure fires. The latter caused over 70% of both civilian fire deaths and injuries, and were the result of either cooking or heating equipment, electrical distribution/lighting, arson or smoking materials (NFPA, 2017). The Certified Fire Investigators (CFIs) of the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF), which support fire and arson investigations throughout the United States, conducted 2,451 arson investigations in 2016 (ATF, 2017).

Fire has been extensively studied, but the complex chemical and physical processes involved in fire have defied complete scientific understanding. While much is known about the behavior of fires in building enclosures, using that knowledge to determine where a particular fire started and what caused it can be very challenging and is based on subjective judgments and interpretations. Outdoor fires behave differently from indoor fires, and small fires behave differently from large fires. If a fire goes out or is extinguished before it becomes “fully involved,” then determining where and how it started is a straightforward exercise (Carman, 2008; Lentini, 2013). For these fires that are not fully involved, little or no expertise is required to identify the origin because the fire patterns provide a clear indication of where the fire started.

Fires in buildings are known as *enclosure fires* because of the effects that room boundaries and vents have on fire development. Enclosure fires can generally progress through four stages (Mowrer, 2008), identified as:

- The fire plume/ceiling jet stage
- The enclosure smoke-filling stage
- The pre-flashover vented stage
- The post-flashover vented stage

During the fire plume/ceiling jet stage, buoyant gases rise from a localized fire in a coherent plume, as shown in Figure 1. As the plume rises to the ceiling, fresh air is entrained into the plume. This air entrainment dilutes the smoke and decreases the plume temperature as it rises. Once the plume impinges on the ceiling, the buoyant gases move laterally across the ceiling and are deflected down from the ceiling and form a layer of smoke known as a ceiling jet. The ceiling jet spreads beneath the ceiling until it is confined by the walls of the enclosure. As the ceiling jet spreads beneath the ceiling, it loses heat to the ceiling, causing the temperature of the gases in the ceiling jet to decrease with radial distance from the fire plume.

The duration of the fire plume/ceiling jet stage of fire depends primarily on the size of the enclosure. In residential scale rooms, this stage of a fire will typically last for only seconds; in large enclosures, such as “big box” stores or warehouses, this stage can last for tens of minutes.

The fire patterns generated during this stage of a fire can provide a clear indication of the location of a fire. Fires located near the walls of a room will leave distinguishable fire patterns associated with the fire plume on the walls and fires located anywhere else in a room will leave distinguishable fire patterns on the ceiling (NFPA 921 at 6.3.7.5, p. 71).

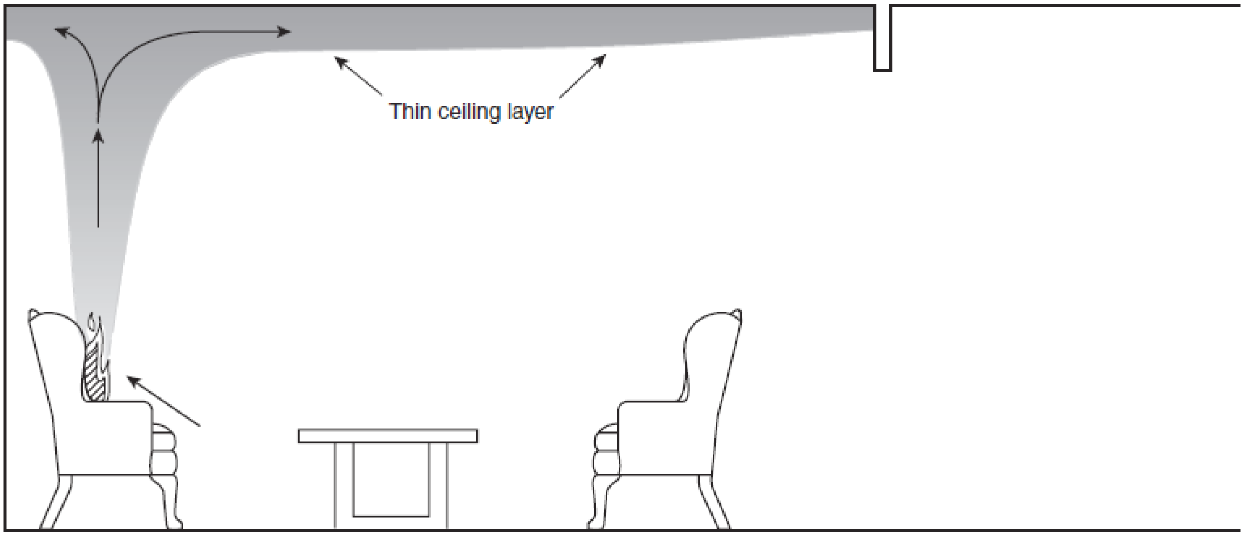

**Figure 1. The fire plume/ceiling jet stage of an enclosure fire.**
(Figure 5.10.2.1 from NFPA 921- Reproduced with permission from NFPA 921-2017, *Guide for Fire and Explosion Investigations*, Copyright© 2016, National Fire Protection Association.)

Once the ceiling jet reaches the walls of the enclosure, the second stage begins. During this enclosure smoke-filling stage, the smoke layer that has formed beneath the ceiling continues to descend from the ceiling as a result of the smoke being injected into the hot gas layer via the fire plume, as shown in Figure 2. The duration of the enclosure smoke-filling period depends on the size of the room and the presence of ventilation openings in the enclosure boundaries. In residential-scale rooms with open doors to adjacent spaces, the enclosure smoke-filling stage is insignificant because smoke begins to flow through such openings during the fire plume/ceiling jet phase. In very large spaces with no vents, the enclosure smoke-filling stage can last tens of minutes.

Fire patterns generated during the enclosure smoke-filling stage include evidence of smoke stains on enclosure walls. These stains can be used to determine how far the smoke layer descended within the fire enclosure. A fire in a small fully enclosed room may consume the available oxygen within the room and the fire may suppress itself due to oxygen depletion within the room. Without the introduction of additional oxygen, such a fire may continue to burn at a reduced rate or it may extinguish. The fire patterns generated during this stage will generally complement those generated during the fire plume/ceiling jet stage rather than obscure these previously generated patterns.

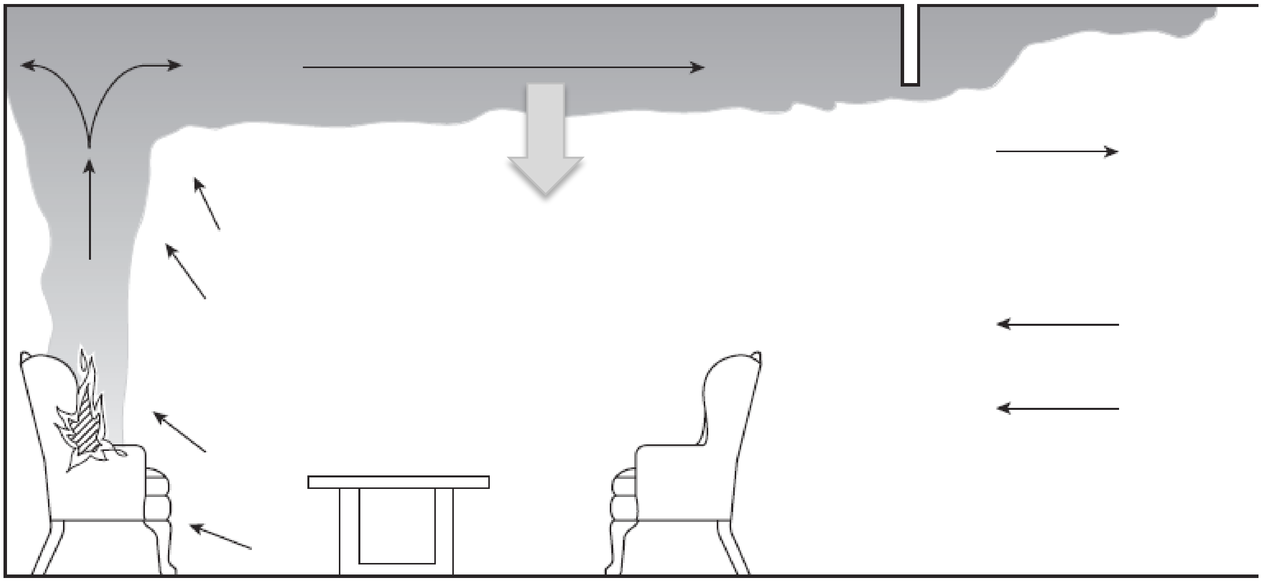

**Figure 2. The enclosure smoke filling stage of an enclosure fire.**
(Adapted from Figure 5.10.2.3 of NFPA 921- Reproduced with permission from NFPA 921-2017, *Guide for Fire and Explosion Investigations*, Copyright© 2016, National Fire Protection Association.)

The third stage of enclosure fire development, the pre-flashover vented stage, starts when smoke leaves the fire enclosure through ventilation pathways, which are typically open doors or windows. During this stage, a quasi-steady balance develops between the rate of air flow into the room, the rate of smoke flow into the smoke layer via the plume and the rate of smoke flow from the enclosure via the wall or ceiling vents, as shown in Figure 3. The smoke layer equilibrates when this balance between inflow and outflow occurs. Stains on enclosure walls are a distinguishing fire pattern for this stage of fire development (Karlsson and Quintiere, 1999).

The fourth stage of enclosure fire development is the post-flashover vented stage. NFPA 921 defines flashover as a “transition phase in the development of a compartment fire in which surfaces exposed to thermal radiation reach ignition temperature more or less simultaneously and fire spreads rapidly throughout the space, resulting in full room involvement or total involvement of the compartment or enclosed space.” NFPA 921 also suggests that flashover represents the transition from “a fire in a room” to “a room on fire.” Figure 4 represents the transition through flashover to a fully involved enclosure fire.

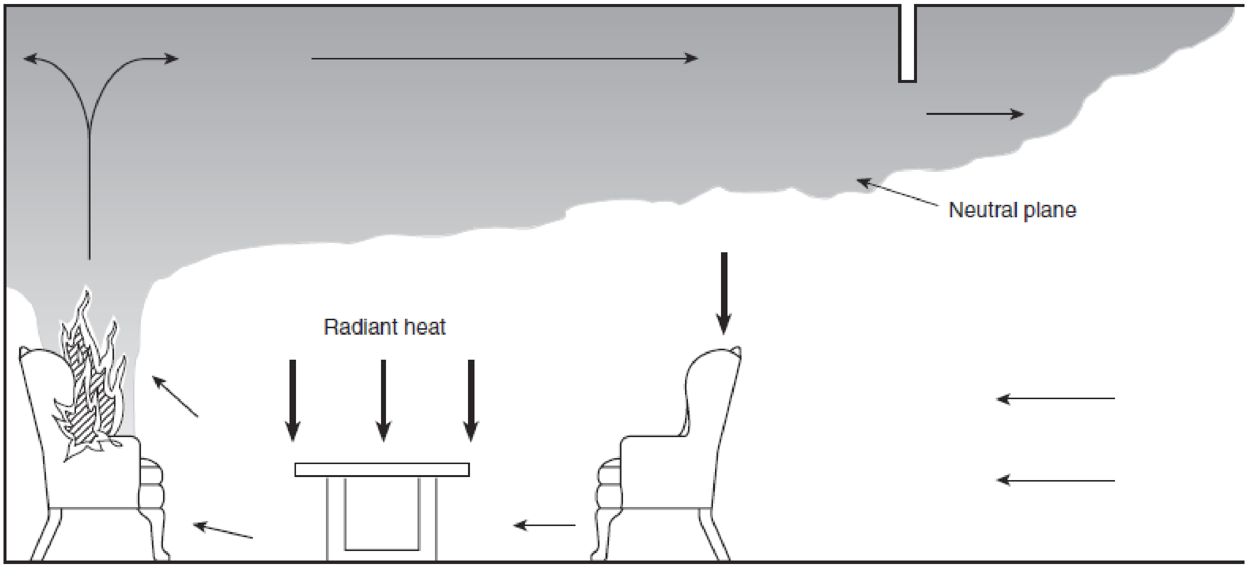

**Figure 3. The pre-flashover vented stage of an enclosure fire.**
(Figure 5.10.2.4 from NFPA 921- Reproduced with permission from NFPA 921-2017, *Guide for Fire and Explosion Investigations*, Copyright© 2016, National Fire Protection Association.)

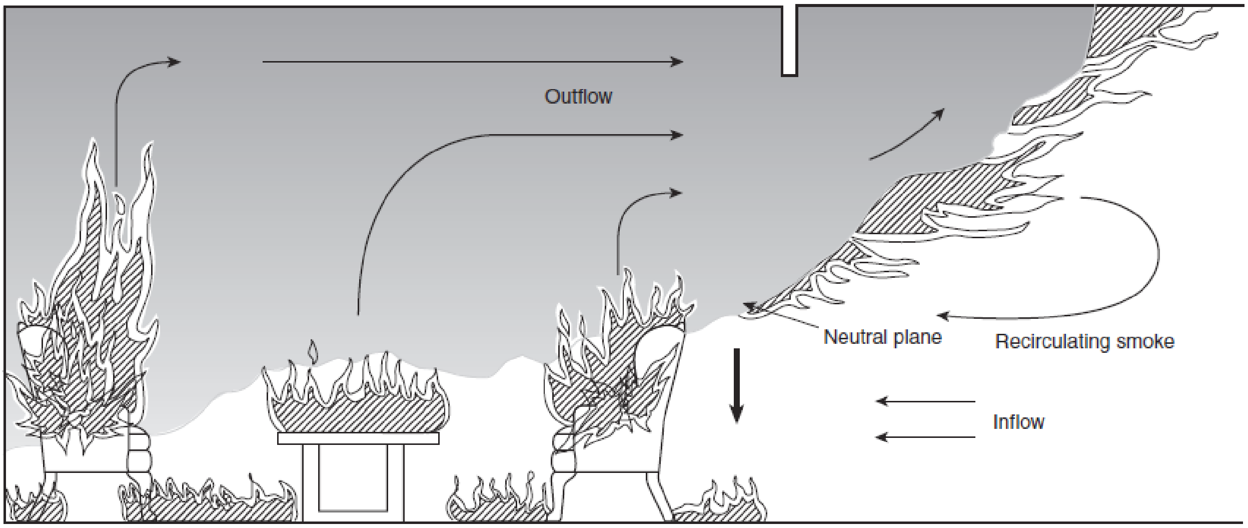

**Figure 4. Flashover conditions in a compartment fire.**
(Figure 5.10.2.6 from NFPA 921- Reproduced with permission from NFPA 921-2017, *Guide for Fire and Explosion Investigations*, Copyright© 2016, National Fire Protection Association.)

Flashover conditions have been characterized experimentally in room fire tests involving relatively small enclosures with floor areas in the order of 100 square feet and heights of approximately 8 to 10 feet (Poulsen et al., 2013). Flashover has been observed to occur when the smoke layer temperature reaches approximately 500 to 600°C, which is associated with a heat flux at floor level of approximately 20 kW/m$^2$. In comparison, intense direct sunlight produces a heat flux of approximately 1 kW/m$^2$. Under this imposed heat flux, exposed combustible surfaces begin to ignite almost simultaneously, which is why this transition is called *flashover* (NFPA 921-17 at Table 5.5.4.2, p. 28).

Once flashover occurs, fully developed fire conditions ensue with smoke layer temperatures that can exceed 1,000°C and heat fluxes at floor level that have been measured to be as high as 170 kW/m$^2$. Flames can fill virtually the entire volume of the room (hence, the “room on fire” description) and extend through vents to other enclosures or up the building façade. The rate of heat release within the fire enclosure typically becomes “ventilation limited” once all the exposed combustible surfaces ignite, with the burning rate within the enclosure regulated by the airflow rate through vents into the enclosure. The airflow rate may not be sufficient to combust within the enclosure all the fuel being released from the surfaces (hence, the term *ventilation limited*), with the excess fuel vapors burning outside the enclosure where they come in contact with additional air (Drysdale, 2016).

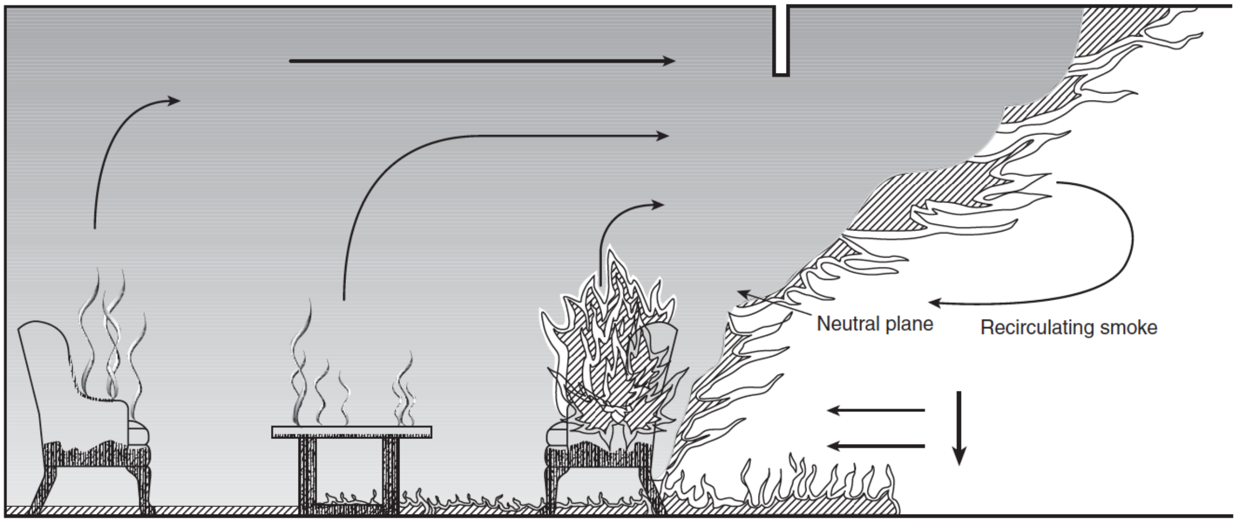

**Figure 5. Post-flashover or full-room involvement in a compartment fire.**
Although pyrolysis can continue throughout the compartment, flaming combustion will only occur where there is sufficient oxygen present. Depending on the momentum of the entraining air, flaming combustion may occur within the ventilation stream at various depths into the compartment.
(Figure 5.10.2.7 from NFPA 921- Reproduced with permission from NFPA 921-2017, *Guide for Fire and Explosion Investigations*, Copyright© 2016, National Fire Protection Association.)

The intense fire conditions that occur during fully developed fires can obscure fire patterns generated during the three previous stages of fire development. The level of this obscuration depends on the duration of the post-flashover burning. Of equal or even greater significance, post-flashover fires can generate different types of ventilation-generated fire patterns that have been misinterpreted as being related to accelerated fires in the past. Figure 5 represents the post-flashover stage.

Once a fully involved fire becomes ventilation limited, the actual combustion zone can separate from the fuel surface(s) and move toward the ventilation openings, where the unburned fuel vapors mix with the incoming air and burn. This can result in more substantial damage patterns remote from the area of origin of a fire, which can lead to inaccurate origin and cause determinations (Carman, 2008). To accurately determine the origin of a fully involved fire, a fire investigator needs to understand these processes. This is why enclosure fires that develop into fully involved fires require a higher level of expertise.

In a 2007 unpublished study conducted by the ATF, only 13 of 53 investigators were able to correctly identify the quadrant of origin in a fire that burned for 180 seconds beyond flashover; this is no better than random chance (Heenan, 2010). This study's conclusion should warrant further consideration because an incorrect origin determination almost inevitably leads to an incorrect cause determination. The results also suggest that fire investigators who rely solely on fire pattern analysis are likely to make errors in both origin and cause determination.

Fire patterns can provide important evidence, but fire investigators also need to consider other factors. As noted above, knowledge of fire dynamics is important if the fire investigator is to account for the spread of the fire. The observations of eyewitnesses can provide crucial data in finding the fire's origin. Arc mapping, an examination of the damage to a structure's electrical system, is another source of data (NFPA 921-17 at 18.4.5, p. 211).

If the use of a liquid accelerant is suspected, samples are collected for laboratory analysis. Combustible gas detectors may aid in this search, but a well-trained canine detection team is the current "gold standard" for locating samples that have a higher likelihood of testing positive in the fire debris analysis laboratory (Kurz et al., 1994; NFPA 921-17 at 17.5.4.7, p. 197; Ottley, 2010; Tindall and Lothridge, 1995). As useful as canines can be in locating ignitable liquid residues, their alerts must be followed up with actual laboratory analysis (described in the next section). In fact, the Canine Accelerant Detection Association (CADA) issued a statement in 2012, saying they "[do] not support, nor do we recommend, Accelerant Detection Canine Handlers testifying in criminal or civil court to the presence of an ignitable liquid without having received confirmation through laboratory analysis." CADA is the oldest national organization dedicated solely to the use of accelerant detection canines, and they urge all ADC Canine Handlers, and all prosecutors and attorneys to follow the National Fire Protection Association 921, Guide for Fire and Explosion Investigations which states, "any canine alert not confirmed by laboratory analysis should not be considered validated (CADA, 2012)."

As a forensic science discipline, fire investigation is hampered by the amount of widespread, persistent and problematic literature affecting the beliefs and the behavior of its practitioners (Lentini, 2006). As long ago as 1977, Boudreau, Kwan and Faragher, working on an Aerospace Corporation grant from the Law Enforcement Assistance Administration (LEAA), conducted a "Survey and Assessment" of arson and arson investigation techniques. In that assessment, the authors listed seven "burn indicators," but stated, "Although burn indicators are widely used to establish the causes of fires, they have received little or no scientific testing." They recommended "that a program of carefully planned scientific experiments be conducted to establish the reliability of currently used burn indicators," and "a handbook based on the results of the testing program should be prepared for field use by arson investigators" (Boudreau et al., 1977).

Three years later, this "Fire Investigation Handbook" was published by the United States National Bureau of Standards (NBS). Unfortunately, the "scientific studies" recommended in the 1977 survey had not been conducted. The NBS editors, Brannigan, Bright, and Jason, were advised by two members of the National Fire Academy staff, and in Chapter 1 they repeated most of the myths that have been used to incorrectly determine that a fire burned faster or hotter than normal. The text refers to "hot" fires and a "rapid buildup of heat," which was generally interpreted by many investigators as indicative of the use of liquid accelerants through the 1980s (Brannigan et al., 1980). Lentini (2006) explored the development, publication and eventual debunking of this myth and a number of other arson myths.

Over the past three decades, much has been learned about fire behavior and investigation, but the distribution of the knowledge among field investigators, has not been uniform (Tinsley and Gorbett, 2012). The most important knowledge, which was often used to distinguish between arson and accidental fires in the past, can be briefly summarized as follows:

- The evidence left behind by fully involved accidental fires is often indistinguishable from evidence left by fully involved incendiary fires (Putorti, 1997). Artifacts once thought to indicate incendiarism but now known to be of little value in classifying the cause of fires include: downward burning; charring of floors and baseboards; charring on the undersides of surfaces; large shiny char blisters; irregular fire patterns; melted metals; crazed glass; and spalled concrete (Lentini, 2006)**.**

- Modern furnishings, particularly upholstered furniture made with polyurethane or polyester fiberfill cushions, can burn so quickly as to cause a room to become fully engulfed in flames in less than five minutes. This is in contrast to "legacy" furnishings made with cotton and wood, which burn with much lower intensity (UL, 2015). Because of this, the speed with which a fire spreads in modern residences is not ordinarily a data point that can be used alone to classify a fire as accidental or incendiary.

- The behavior of fires under differing ventilation conditions, unless well understood, can lead to erroneous determinations of whether a fire is accidental or incendiary (Carman, 2013). The ventilation (oxygen) available to a fire is largely responsible for the behavior of a ventilation-limited fire, including its temperature. In ventilation-limited fires, the amount and flow path of available oxygen determines how severely a fire will burn at a particular location. In ventilation-limited fires, fuel vapors move away from the fuel source and burn near ventilation openings where they mix with the incoming oxygen. This will cause ventilation-generated burn patterns, remote from the area of origin, that need to be taken into account during an investigation (Carman, 2008).

- For post-flashover fires, it is generally more difficult for fire investigators to correctly determine the area(s) of origin based only on interpreting fire patterns, and the level of difficulty increases the longer a fire burns in a fully involved condition. Research conducted since 2005 reveals that in some cases, the ability of a fire investigator to determine the correct area of origin in a fully involved room by only interpreting fire patterns may be no better than random chance (Carman, 2008; Cox, 2013; Heenan, 2010; Tinsley and Gorbett 2012). Tinsley and Gorbett's 2012 study showed 22-26% erroneous conclusions when 587 self-selected investigators, working independently, viewed photos and data from a fire that burned for only one minute beyond flashover. These results were similar to the 31% erroneous conclusions found in a 70-second – beyond-flashover study conducted in 2007 (Heenan, 2010). Similar experiments occur to this day at the Federal Law Enforcement Training Center in Glynnco, Georgia, with similar dismal, yet unpublished results.

## The Working Group identified the following questions where gaps in knowledge exist and where additional research in investigative methodologies would benefit the field of fire investigation.

### 1. How do post-flashover fire conditions influence the reliability of origin and cause determination?

#### a) Can you determine the point of origin for a fire that burned for 5 or 10 minutes after the room became fully involved?

Based on the limited literature on this topic, it appears that more than a few minutes after a room has become fully involved, the point of origin of a fire cannot be reliably determined using only fire patterns, unless unequivocal evidence of causation (e.g., a malfunctioning appliance, evidence of incendiarism) is found (Cox, 2013). Additional fire testing is needed in this area.

In order to get the most value from such research, the tests need to be run with multiple compartments and multiple openings to more realistically represent actual residences, and the aftermath needs to be recorded in detail. The ability of fire investigators to determine the point of origin by reading fire patterns can be more carefully examined if such data are available. Lighting multiple identical fires in identically constructed compartments would also contribute to the knowledge about the reproducibility of fire behavior. As a means of pursuing such research, ATF recently built six burn cells at their training facility at the National Center for Explosives Training and Research. Four of these burn cells can be made into multi-room, single-story configurations. The other two are two-story burn cells that can be formed into varying multi-room configurations. In addition, the heights of the ceilings and locations of the stairwells can be adjusted. This new construction, with the ability to create multiple permutations of potential fire sites, will likely reduce the cost of testing. The ATF facility is just one of several in the country. Other full-scale experiment facilities include the Underwriters Laboratories (UL) Fire Safety Research Institute and Eastern Kentucky University's seven-room test burn facility at the Ashland, Inc. Fire and Test Safety Laboratory.

#### b) How can you identify when a room has become fully involved?

This is a fairly straightforward exercise, as described earlier on pages 16-17. In rooms with combustible wall surfaces, or baseboards at the bottom of gypsum drywall, the presence of charring of the base of the wall and the presence of charring of the floor allows one to state that a room has become fully involved. The ignition of chair backs and combustibles located on tables provides another clue. Further research in this area would add little new information; however, it could be included as part of the research described under **a)**.

**c) Is there a point in time after a room becomes fully involved when it becomes impossible to determine the point of origin?**

For a given room, there is a point when one can no longer reliably determine the point of origin by reading fire patterns alone. In the real world, however, it is nonetheless worthwhile for fire investigators to examine every potential ignition source in the room of origin. It might be possible to find evidence of a malfunction of an appliance or a component of the electrical system.

It is certainly possible to find evidence of incendiary activity, e.g., ignitable liquids foreign to the scene or incendiary devices, if it exists.

**2. Does training and experience influence the accuracy of the determination?**

**a) Is there research that shows a correlation between education and accuracy?**

There is very little research on this question, and what there is, fails to show a correlation, if any, between education and accuracy (Cook, 2015; Tinsley and Gorbett, 2012).

People tend to believe that certification by the National Association of Fire Investigators and International Association of Arson Investigators, for example, is better than no certification, but there is no scientific basis for this belief in the field of fire investigation (Cook, 2015). The research described under Recommendation #6, where numerous artifacts and fire patterns from numerous fire scenes are shown to both certified and uncertified fire investigators, could help resolve this issue.

**b) Are there sufficient educational requirements for fire investigators? Are there sufficient proficiency testing requirements?**

No. There is very little proficiency testing, and currently, NFPA 1033 calls for knowledge of sixteen subject areas to a level beyond a high school education (NFPA 1033 at 1.3.7, p. 6). Yet, there has been no systematic research to determine whether these subject areas are *the* content areas that would tend to affect performance, or research that demonstrates whether knowledge in one or more of these subjects is likely to improve performance.

**3. What chemical markers would aid in the determination of origin and cause?**

The only chemical markers currently available are findings of petroleum products and other ignitable liquids in cases of incendiary fires.

**a) Do we have the technology to analyze those markers?**

Yes. See the discussions under fire debris analysis. The technology currently available allows the detection of 0.1 µL of ignitable liquids in a kilogram of debris.

**b) Do we have validated instrumentation to detect different chemical markers?**

There are so many substances produced during a fire that we are only in a position to look for evidence of ignitable liquids, or other materials used to initiate or spread a fire, such as matches, candles or residues of road flares or pyrophoric substances. Other chemical markers are of little value, because there is no way to determine *when* they were created. For example, burning vinyl produces aromatic compounds that are indistinguishable from the aromatic compounds found in petroleum products, other than by the fact that the relative concentrations of the compounds in vinyl pyrolysis residue are different. For the detection of ignitable liquids, the instrumentation is validated.

**c) Can we use current advanced deterministic fire models (e.g., CFAST, FDS) to improve post-fire analysis?**

Yes, current advanced deterministic fire models can be used to improve post-fire analysis. As noted in NFPA 921, the use of computer fire models can be very helpful in analyzing the effects of building design on the development, spread, and ultimate damage from a fire (NFPA 921 at 7.2.5, p. 77). NFPA 921 also notes that fire models can be used to test origin hypotheses. "The models use incident-specific data to predict the fire environment given a proposed hypothesis. The results can be compared to physical and eyewitness evidence to test the origin hypothesis. Models can address issues related to fire development, spread, and occupant exposure" (NFPA 921 at 18.6.2.2, p. 198).

There are more than a dozen computer-based deterministic fire models. The most commonly used one is Fire Dynamics Simulator (FDS) a field model that has its own graphical output program called Smokeview. Both programs are available for no cost from NIST. The website is here: https://www.nist.gov/publications/fire-dynamics-simulator-technical-reference-guide-sixth-edition.

For an overview of other models that were in existence in 1997, see here: http://fire.nist.gov/bfrlpubs/fire97/PDF/f97043.pdf. These models are costly.

In addition to field models, there are also zone models, which divide the room into two compartments, and offering a lower level, as opposed to the field models which can divide a room into as many cubes as the modeler wants to use, keeping in mind that more cubes means more computing time.

NFPA 921 recognizes that fire models have inherent limitations and assumptions that should be considered when used in support of fire investigations. Consequently, NFPA 921 notes that "Care must be taken to assure that the model is being used with due regard for limitations, assumptions, and validation. While computational models can be used to test hypotheses, models should not be used as the sole basis of a fire origin and cause determination" (NFPA 921-17 at 22.4.1.3, p. 228).

**4. Do we know what information/factors are needed to determine the origin and cause of a fire?**

Yes, but the fact remains that the evidence is often confusing, contradictory, or insufficient. When a compartment has burned for three minutes or more beyond flashover, the only reliable origin determination is “the fire began in this room.” There is no peer-reviewed literature that supports the proposition that under these circumstances, the origin can be reliably narrowed to an area smaller than the whole room. The fire investigator must then evaluate every potential ignition source and every potential first fuel in the room. It may thus be possible to find a malfunctioning appliance, or an incendiary device, or evidence of an introduced ignitable liquid, and reach a correct determination of the origin and cause.

**To what extent is the information we have now sufficient?**

Determining the origin of a fire before it goes to flashover is usually a straightforward exercise. Such fires require little or no expertise.

For fires that continue beyond flashover, further research is needed under realistic conditions. There are times when it is possible to understand the ventilation, and there are times when fire patterns created by the original fire remain even after a few minutes of post flashover burning. The key is recognizing which fire patterns were created first. When available, the most useful information can come from eyewitnesses or security cameras, not from fire patterns in compartments that burned for more than a few minutes beyond flashover (Carman, 2008, 2009; Cox, 2013; Tinsley and Gorbett, 2012). The reason this information can be useful is because there is insufficient knowledge to validate conclusions from fires that go beyond flashover (see **1c**).

**5. How does the stage of fire development affect the information that can be inferred from a fire scene investigation?**

In compartment fires that burn beyond flashover, more research is needed to more fully understand what can be inferred from post fire artifacts.

**6.** I**s there a good estimate of the uncertainty in burn pattern analysis associated with the burning of different materials under a range of realistic fire conditions?**

Much more research is needed on this topic. In one example, using gypsum wallboard surfaces, Madrzykowski and Fleishchmann (2010) show the uncertainty regarding burn patterns for simple fuels, natural gas, gasoline, and polyurethane foam under controlled conditions. They measured the following data from 32 experiments with three different fuels. Not surprisingly, they found greater uncertainty in pattern height, width and area with more complicated fuels. They also reported a measurement uncertainty for the NIST oxygen consumption calorimeter, which measures heat release, rate at 11%.

**Fuel Comparison Fire Pattern Dimensions with 95% Confidence Limits (Madrzykowski and Fleishchmann, 2010)**

| **Fuel (number of experiments)** | **Height (m)** | **Width (m)** | **Height @ Max Width (m)** | **Area ($m^2$)** |
|---|---|---|---|---|
| Natural Gas (10) | 0.74 ± 16% | 0.24 ± 25% | 0.41 ± 17% | 0.15 ± 33% |
| Gasoline (12) | 0.83 ± 18% | 0.28 ± 32% | 0.44 ± 41% | 0.17 ± 25% |
| Polyurethane Foam (10) | 0.24 ± 50% | 0.28 ± 29% | 0.04 ± 60% | 0.05 ± 57% |

## 7. Is there a need for additional research and peer-reviewed literature that measures the consistency of conclusions among experienced investigators and the factors that mediate it when presented with the same data?

Yes.

Much more research is needed to measure the consistency of conclusions, which is termed *reliability* in the testing literature. Fire investigation is not alone in this regard. All pattern evidence techniques require this kind of research (this type of research has already begun in fingerprint analysis (Dror et al., 2011; Ulery et al., 2012) and DNA (Dror and Hampikian, 2011)). It is not clear that in the end fire pattern analysis will be found to be sufficiently consistent, but research should be conducted to make this determination. There have been a few compilations of known inaccuracies in fire cause investigation (Bieber, 2014; Cook, 2015), but no quantitative studies.

## 8. Is there a need to incorporate more exercises with known ground truth for fire scene investigators?

Yes.

*Validity* represents the relation between the estimate and the ground truth, and it is constrained mathematically by reliability, as described above. Thus, the first and easiest order of business is to assess the reliability of multiple investigators' "diagnoses." If reliability is poor, we can be absolutely sure that the validity of their conclusions is also poor.

There are no easy answers in determining ground truth in fire scene investigations because unfortunately much of the evidence can be lost in the fire. However, reasonable substitutes can be made available. Many municipalities are in the process of razing buildings. In those jurisdictions that permit it, these structures could be used to create controlled test fires under a wide variety of conditions, such as in known but variable locations within a home, fires initiated using various accelerants of known amounts, and variable ventilation conditions. In this manner, ground truth can be established and a great deal of information regarding the processes and patterns can be generated. Because the test fires are set in a specific location in a test home with or without the use of a specific accelerant, these exercises can be used to test the ability of fire investigators to produce accurate determinations. These exercises can also be meticulously documented before, during, and after the burn in order to produce extensive sets of virtual scenes that can be useful for training and research purposes.

Another valuable benefit of test fires is that it would be possible to ascertain exactly which cues are truly associated with various fire characteristics and which are not. Lentini (2006) points out that the fire investigation community has persisted in using non-diagnostic cues for a substantial period of time. Carman (2008, 2009, 2010) has found unacceptably low levels of accuracy in investigators' ability to specify in which quadrant of a room a fire started. Which cues are valid and which are not? If investigators can learn to attend to the valid cues and ignore the invalid ones, the validity and reliability of their conclusions would rise.

### 9. Is there scientific research that supports the idea that masking from irrelevant cognitive information would improve the performance of fire investigation teams, and can we generalize what we have learned about cognitive bias from other disciplines?

Research on performance of forensic examiners has enabled the quantification of their reliability and susceptibility to bias (Dror and Rosenthal, 2008). Such findings are based on the more objective forensic domains and, therefore, it is reasonable to conclude that it also affects fire investigators to at least the same degree. Many fire investigators receive little or no cognitive education as part of the basic training or subsequent professional development.

This research, among other studies, has demonstrated the biasing impact of irrelevant cognitive information. In other words, fire scene investigators should work without any presuppositions. For this reason, it is advisable to keep the scientific fire scene investigators separate from the law enforcement case management team (NCFS, 2015). This is to keep the former as neutral as possible in order to reduce cognitive contamination of conclusions. The Working Group acknowledges in its recommendation related to this matter that in some jurisdictions this will be cost prohibitive.

Evidence from other domains, as well as within forensic science, suggests that there are practical ways to mitigate and minimize bias, such as Linear Sequential Unmasking (LSU). This procedure "not only requires examiners to first examine the trace evidence in isolation from the reference material, but also provides a balanced restriction on the changes that are permitted post-exposure to the reference material" (Dror et al., 2015). The aim of such procedures is to maximize the independence of mind of the forensic examiner so that it is bias-free as much as possible in both the identification of relevant evidence and their conclusion about what the evidence shows about a fire's origin and cause. One of the recommendations from the OSAC Subcommittee on Fire and Explosion Investigation suggests research in this area (OSAC, 2016). Although some fields have resisted using sequential unmasking as a tool to eliminate bias, research has shown that telling people to be unbiased is not an effective strategy (e.g., Fischhoff, 1975; Thompson et al., 2011; Thornton, 2010).

### 10. What new data would be of value within the field of fire scene investigation?

The series of live fire experiments previously suggested, documented in detail (e.g., with sketches, diagrams, photographs, detailed notes, video, and sensor data), and shown to hundreds of fire investigators would allow for a scientific determination of reliability and validity. Another valuable source of instruction would be created by the fires intentionally set by authorities in various cities, done in order to demolish condemned buildings. Such fires would provide data in order to determine a) which cues are valid indicators of various conclusions, and b) whether multiple investigators come to the same conclusion, thereby comprising an excellent test of inter-rater reliability.

#### What available databases would be useful in assessing fire pattern determination?

There has been comment since at least 1977 of the need for a comprehensive database of fire burn patterns, but such a database has not yet been compiled (Boudreau et al., 1977). Data are scattered in the scientific literature, with limited efforts to compile such data for practical field use. For example, the University of Maryland Department of Fire Protection Engineering developed a burning item database (http://www.firebid.umd.edu/) with NIJ support, but this database addresses the heat release rates of various items and not the fire patterns generated by the burning items. Now, almost 40 years since the need for a comprehensive database of fire burn patterns was first identified, this need still exists and has not been addressed.

Some of the data that would be of value within the field of fire investigation includes:

- A comprehensive and consolidated database of the fire properties of common building materials and furnishings, including thermal properties and heat release rate characteristics;
- A comprehensive and consolidated database of the heat release rate characteristics of typical residential and commercial furnishings;
- A comprehensive database of photographs of burn patterns generated on different building materials as a function of known heating conditions (i.e., heat flux history);
- A comprehensive database of photographs of ventilation-induced burn patterns along with a detailed description of the conditions under which the patterns were generated.

Any future efforts to establish such a database must ensure that data are valid and reliable.

## B. FIRE DEBRIS ANALYSIS

Forensic science laboratories that conduct fire debris analysis often focus on the analysis of ignitable liquid residues (ILRs). This process aims to identify any potential accelerant in a sample collected from a fire scene that is suspected of being deliberately set. While solids (paper) and gases may be used to accelerate a fire, ILR analysis is always restricted to liquids (typically mixtures of ignitable compounds) and their residues.

Laboratory scientists depend on the proper recognition of samples that may contain ILRs at the scene of a suspect fire, adequate packaging, secure transmittal, and an assured chain of custody. After the collection of the evidence, the laboratory process involves sample preparation (usually an extraction of the liquid-residue mixture), a separation technique (usually gas chromatography), and compound identification (typically mass spectrometry but other methods of compound identification may be used, such as FTIR) followed by the interpretation of the data collected from the analysis (DeHaan and Icove, 2012; Lentini, 2013). A thorough introduction of forensic fire debris analysis can be found in a chapter within a recently published forensic chemistry textbook (Newman, 2016). This chapter details the critical steps undertaken at the forensic laboratory after sample collection at the scene, and includes acceptance of the evidence into the laboratory, sample selection, packaging requirements, the advantages and disadvantages of several extraction methods, analytical methods and instrumentation, with a focus on the recommended ASTM methods and, finally, the interpretation of the findings, including how the matrix can contribute to the chemical signatures found (Newman, 2016). Although far less frequently, laboratories will attempt to identify other materials as well. Some examples of items of interest might include road flare residue, matches, butane lighters, smokeless powder (intact and residual), black powder/black powder substitutes (intact and residual), wax from possible candles, and hypergolic mixture residues, amongst other things.

Although the science of fire debris analysis (analytical chemistry) is more mature and reliable than the fire investigation science presented in the previous section, there is still room for improvement in the knowledge base and in the practice of fire debris analysis. The ultimate goal of a fire debris examiner is to determine whether an ignitable liquid residue is present in the debris submitted to the laboratory by the fire investigators and, if so, what is the chemical nature of the ILR found. This examination requires a broad knowledge of not only the potential universe of thousands of formulations of ignitable liquid products, but also of other contributing chemical mixtures that may be "innocently" present in the fire debris and may be confused with an ignitable liquid product, leading to an erroneous determination of "presence of an ignitable liquid residue." These "innocent" chemical mixtures could be derived from combustion products and pyrolysis products generated from the burning of materials during the fire. They also could be derived from interfering products naturally present in the materials or "innocently" added to materials prior to the fire. These "innocent" products are not indicative of an intentionally set fire.

Many different commercial products can be used to initiate and/or accelerate a fire, with gasoline being one of the most commonly encountered by fire debris analysts. Nevertheless, analytical scientists must be familiar with the wide variety and changing nature of these products if they are to be effective in identifying them in the course of their work. Similarly, the scientists must be familiar with the chemical nature of substrates that contain the same or similar chemical characteristics as ILRs but are not ILRs and should not be characterized as such. The scientists must be familiar with combustion and pyrolysis chemistry and the generation of combustion/pyrolysis products during a fire and be able to differentiate combustion/pyrolysis products from ILRs, a difficult feat at times that is not easily mastered.

The scientists must be fully aware of the advantages, limitations, and performance of the analytical methods used in fire debris analysis, including extraction (recovery) methods, separation science (chromatography), and compound detection/identification (usually, mass spectrometry). There are many good textbooks that outline the specific scientific topics described above; the reader is referred to these texts and also to the relevant NFPA 921 section on fire debris analysis (Almirall and Furton, 2004b; Stauffer, Dolan and Newman, 2008). A more recent and comprehensive treatise on the subject of fire debris analysis by Hendriske, Grutters and Schafer (2016) expands on the use of ASTM E1618 by discussing, in great detail, “the characteristics of, and variation in, chemical composition of different classes of ILRs as defined by ASTM E1618-14 as well as the effects that have an impact on their compositions.” This guideline text may be used during laboratory validations and as complementary information to the E1618:2014 standard method.

Finally, the scientific discipline of fire debris analysis is in need of wholesale validation studies to determine the performance of the scientists within the field, in addition to the external proficiency tests that are already being performed. Proficiency tests are high-stakes evaluations of individuals and their laboratories in the determination of ILRs similar in nature to very routine casework and are, therefore, only a snapshot of performance of the field at a relatively low level of difficulty. A low-stakes evaluation of the field should be attempted. This should include the performance of the ASTM E1618:2014 method itself, which would provide a wider view of error rates for the field varying the level of difficulty of analysis and complexity of samples analyzed. Anonymous interlaboratory trials would provide the scientists and their laboratory leadership with a better estimate of performance for a wider set of casework situations.

## The Working Group identified the following questions where gaps in knowledge exist and where additional research would benefit the overall analysis of ILRs.

### 1. Are the current analytical methods for the examination of fire debris adequate in the determination of ignitable liquid residues?

One area that requires additional research relates to the steps taken *before* the samples reach the laboratory. The Working Group identified proper sample identification and sample collection at the fire scene as areas where additional research and technology would be beneficial. After all, the laboratory analysis is irrelevant if the sample containing the ILR is incorrectly identified or collected.

In addition to properly trained investigators familiar with NFPA 921 protocols, properly trained and maintained “Ignitable Liquid Detection” canines have been shown to be effective when attempting to determine the best locations to sample for ILRs at a fire scene. Electronic “noses” (hydrocarbon detectors) are also available, but the current electronic instruments do not perform as well as properly trained canines (Gialamas, 1996; Harper, Almirall and Furton, 2005; Lentini, 2013; NFPA 921 2020 edition Task Group).

Since more powerful and specific portable instrumentation is continually entering the market, there should be some effort concentrated on the evaluation of such tools for use with respect to analysis at the fire scene. Some such tools that should be explored include field-based mass spectrometers, portable gas chromatographs, field ILR analysis that allows for rapid feedback to investigators, and more sensitive and specific electronic “noses” that can detect the broad spectrum of potential ILRs. Research using sampling approaches providing enrichment such as SPME and Needle Traps with portable mass spectrometers to detect and locate ILRs, will improve the effectiveness of the current use of hydrocarbon detectors (Lord et al., 2010). Canines are advantageous because they provide instantaneous feedback and are mobile, allowing them to search a large space in a very short time. Additional training aids and methods of measuring canine performance would also enhance their effectiveness and this field of research should be further developed (SWGDOG Approved Guidelines: http://swgdog.fiu.edu/approved-guidelines/). The research and technology section of the SWGDOG guidelines identifies the following research needs to improve the use of canines:

1. Identification and quantification of target odorants**:** Research to evaluate canines’ ability to discern, under a variety of environmental conditions, target materials from extraneous materials with similar physicochemical properties.
2. Research on olfaction: Focused on laboratory research, either chemical or behavioral. For example, the question regarding the limitation of tracking would be better considered under “dog performance” and not under olfaction.
3. Research on Learning: Experimentation on training methodologies, types of reinforcement, the relationship between training and operations performance and questions on generalization and concept formation.

4. Dog Performance: Determination of the performance envelope of the dogs so that there is a correct understanding of their capabilities and limitations. Only when we know how the dogs are presently working will we be able to determine the effectiveness of new manipulations. Basically, the goal would be to obtain a clear understanding of how the current working dogs actually work and what variables affect their probability of detection.
5. Selection, development, and early canine experience**.** This is a somewhat related collection of topics. The overall goal would be to determine how to optimize the development of detector dogs.
6. Veterinary issues related to canine performance.
7. Human scent chemistry and science.
8. Investigation of the use of technology in combination with canine olfaction that may improve location/detection of ILRs such as the use of GPS and video cameras mounted on canines.
9. Handler selection and training.
10. Optimal deployment considerations such as behavioral analysis, concealment techniques, and trends.

### 2. Is there enough research to validate current sample preparation prior to determination?

The literature for the laboratory analysis of ILRs is very mature, spanning more than four decades with in-step development of the corresponding analytical chemistry (Chrostowski and Holmes, 1979; DeHaan and Icove, 2012; Dietz, 1991; Juhala, 1982; Lentini, 2013; Smith, 1982). While there have been many new developments in the field of sample preparation (e.g., Solid Phase Microextraction (SPME) PLOT cryoadsorption (Bruno, 2009) and Capillary Microextraction of Volatiles (Fan and Almirall, 2013; Tarifa and Almirall, 2015)), and other techniques that are shown to improve sensitivity of the extraction, the practice of sample preparation has remained relatively unchanged over the past two decades or so (Almirall, Bruna, and Furton, 1996; Furton, Almirall and Bruna, 1995; Furton, Bruna and Almirall 1996 ; Pérès, Viallon and Berdagué, 2001; Ren and Bertsch,1999; Stauffer and Lentini, 2003). Additional research focused on the extraction steps would improve the body of knowledge in this area and perhaps, improve the selectivity and sensitivity of the current methods of extraction. For example, there have been some anomalous observations made with respect to preferential adsorption of certain compounds onto carbon strips. There may be some competitive effects between the charring on debris and the strips themselves. Additionally, different compounds of the same class and in the same range may also have different adsorption rates and retentions on carbon strips. Finally, competitive adsorption between ILR compounds and pyrolysis/combustion products may affect patterns that are observed. New bulk adsorption media have been investigated for targeted purposes (Rodgers, St. Pierre and Hall, 2014; St. Pierre, Desiderio and Hall, 2014).

The advantages of the SPME technology include solvent-free processes, efficient transfer of collected volatiles, and the field portable capability, in addition to improved sensitivity in some cases. The disadvantages of SPME stem from the equilibrium nature of the technique resulting from fractionation of the chemical profile extracted (Ren and Bertsch, 1999). The combination of SPME with portable Gas Chromatography/Mass Spectrometry has the potential to become a more reliable approach of identifying “hot spots,” when sampling in combination with the use of canines in the field. This is an area that is full of research potential.

Despite the potential of these new technologies, many practitioners argue that more sensitivity, under any circumstance, is not required or advisable. And most forensic laboratory protocols call for some form of adsorption procedure, such as dynamic headspace extraction, using sorbent tubes or, more commonly, static headspace extraction using an activated charcoal strip (ACS). Because of sample dilution, these solvent-based approaches are less sensitive in comparison to SPME. Research in the performance of highly sensitive methods such as SPME would answer some of the prevailing questions regarding “too much sensitivity” as a negative technical quality.

Several ASTM standard test methods (E1386, E1388, E1412, E1413, E2154) currently exist for the extraction of ILRs from debris, and these methods are generally (but not uniformly) used by the forensic science community. The fire debris analysis community is in agreement that the standardization of analytical methods would be a positive step in improving the practice, but it must be recognized that every case is different and may require different extraction or analysis methods. Some flexibility in method selection is also required. Static headspace and dynamic headspace extraction have been shown to perform very well for the extraction of less than 0.1uL of ILRs, and several ASTM standard test methods may provide even better sensitivity (ASTM E1386-10; ASTM E1388-12; ASTM E1412; ASTM E1412-1; ASTM E1618-14; Cacho et al., 2014; Dietz, 1991; Newman, Dietz and Lothridge, 1996; Nichols et al., 2014; Phelps, Chasteen and Render, 1994).

Additional research in extraction methods could improve these standard methods. For example, the phenomenon of displacement has been reported as problematic for some situations by Newman, Dietz and Lothridge (1996). A better understanding of the fundamental analytical chemistry that supports extraction and pre-concentration is needed (i.e., quantification strategies) (Salgueiro, Borges and Bettencourt da Silva, 2012). Also, the current standard methods and practice do not include quantitative analysis or even semi-quantitative analysis of the extracted materials. Additional research may reveal new methods to assess the ILR composition beyond the current qualitative analysis. Nevertheless, the Working Group believes the ASTM standard test methods for extraction, separation, and analysis of ILRs are sufficiently developed and mature and there is no reason for operational laboratories *not* to use these methods. All forensic practitioners should be made aware of these methods, should have access to them, and should be required to follow them if their analyses are to be admitted by courts.

### 3. Does the current scientific literature support the use of gas chromatography/mass spectrometry as the principal instrumental method for determination?

Separation science (GC), detection, and compound identification using mass spectrometry have also evolved over the past two decades. The current industry standard for operational laboratories is capillary column GC coupled with mass spectrometry detection. The current literature supports the incorporation of GC-MS (instead of GC-FID, for example) into the routine analytical scheme of the fire debris analysis laboratory. Ionization modes other than electron impact (EI) such as chemical ionization (CI) should also be further explored. Improvements in separation tools (such as 2-dimensional GC) are weighed against the cost and complexity of these instruments, but there is some literature that has shown the benefits of 2-D GC (Frysinger and Gaines, 2002). Similarly, isotope ratio mass spectrometry (IRMS) has been applied to ILR compound identification to enhance the analysis of ILRs (Benson et al., 2006). Portable GC instrumentation should also be investigated for on-site screening and identification of "hot spots" (Casamento et al., 2005).

#### a) Can improvement in the language of the existing ASTM Test Methods result in better classification of ILRs?

The ASTM E1618 Test Method for Analysis of ILRs has been developed over the past 15-20 years but there has never been a comprehensive, wholesale validation of the method conducted by the fire debris analysis community. Inter-laboratory trials designed with varying degrees of difficulty may provide important information regarding the gaps in knowledge in the application of the current classification scheme. The classification scheme has improved over time, but there is still room for improvement regarding how classifications of the ILRs can be declared, given a chemical profile. Additional work in the classification of ILRs is needed, and improvement in the language of the data interpretation is also needed. The evolving field of fire debris analysis and the changing nature of available fuels (e.g. more environmentally friendly fuels such as biodiesel and plant-based lamp oils) and consumer products necessitates the continual monitoring of possible sources of ILRs and, more importantly, how these new products can be classified under the existing classification scheme or whether the scheme should be revised. For example, a recent publication (Peschier et al., 2017) describes the use of Alkylate components for classifying gasoline in fire debris samples. There is also a major effort underway as part of the Organization of Scientific Area Committees (OSAC) to restructure the existing classification ASTM standard method (E1618-14) and dividing this single standard into several standards in order to improve the classification scheme (see the Fire Debris and Explosives Subcommittee of the OSAC position statement: https://www.nist.gov/sites/default/files/documents/2017/05/19/osac_fde_subcommittee_-_e1618_position_statement.pdf).

**b) Can additional research in the chemical characterization of background, combustion, and pyrolysis products improve the classification of ILRs and avoid confusion between ILRs and these products?**

Several studies have shown the risk of confusing combustion and pyrolysis products with ILRs **(**Keto and Wineman, 1991; Keto, 1995; Lentini, 1998; Smith, 1982; Wineman and Keto, 1994). Additionally, some man-made products emit volatile organic compounds (VOCs) that also resemble ILR signatures. Additional research in the differentiation of intentionally added ILRs from pyrolysis/combustion products and from products innocently present in materials (background VOC products) should be undertaken (Almirall and Furton, 2004; Lentini, Dolan and Cherry, 2000). Additional research is also needed for determining the performance of the ASTM methods when comparing blind samples containing known amounts of ILRs in the presence of background, combustion and pyrolysis products with samples containing only background, combustion and pyrolysis products.

**c) What can further research in weathering effects on ILRs reveal to forensic scientists working to identify ILRs in fire debris?**

Much work has been published on the effect of (thermal) weathering on ILR profiles (Birks et al. 2017; Sinkov, Sandercock and Harynuk, 2014; Vergeer et al., 2014). There is a risk of missing an ILR signature due to advanced weathering (Stauffer, Dolan and Newman, 2008). Additional research is necessary to explore the effects of weathering on different types of ILRs. Experiments that simulate a wide variety of weathering situations, such as ILRs in fire debris subjected to the heat of a fire or ILRs subjected to dousing with water from extinguishing efforts would shed some light on the magnitude of weathering effects on ILRs in debris. In addition, chemical and biological weathering of samples can also play a significant role in the loss of chemical data. Research that explores chemical reactivity after collection from contact with the container is needed (heating of PVC will release HCl which may result in acid-catalyzed reactions with the ILRs, for example). Biological degradation is typically associated with soil samples and additional research into the magnitude of biodegradation of ILRs in soil is also needed. There are various other conditions, parameters and sample types that might exhibit sample degradation.

**d) Is there a need to improve the sensitivity of the extraction and analysis of ILRs, or should we limit the sensitivity of analytical protocols to avoid confusing ILRs with background products and combustion/pyrolysis products?**

There is debate among the fire debris analytical community on whether to limit the sensitivity of the methods used, with the justification that this approach reduces the risk of confusing ILRs with background products or with combustion/pyrolysis products. Not everyone agrees on this approach and further research is needed to address this question. A research project devoted to determining the background levels of ILRs in substrates normally encountered could help to establish sensitivity thresholds of ILRs in common materials. For example, gasoline is so prevalent that if one was to try and detect gasoline at extremely low levels, it may be commonly found on many substrates, materials and surfaces. Additional survey research in this area is needed.

**e) Is there sufficient research that supports the interpretation criteria currently used in fire debris analysis?**

The difficulty of the task of data interpretation cannot be overstated. Essentially, forensic scientists are asked to classify any of the potential flammable liquids into a limited number of chemical categories (Frysinger and Gaines, 2002; Lentini, 2013). ASTM E1618 attempts to address this enormous challenge, and although this existing standard is more than adequate for the vast majority of forensic casework, it is imperfect. The forensic science community should strive to continually improve the interpretation of chemical data derived from GC-MS analysis of fire debris.

One area of particular importance is the unambiguous determination of background products, combustion products, and pyrolysis products that are normally present at the scene of a fire (Almirall and Furton, 2004; Li, Liang and Shen, 2013). An error in confusing background, combustion and/or pyrolysis products with an ILR would have serious and detrimental effects on the overall process of fire investigation. Much more work is needed in the chemical analysis of fire debris in order to avoid a false positive determination of ILRs in fire debris. New research is also needed to address error rates, which do not currently exist for the field of fire debris analysis.

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ASTM E 1388-12, Standard Practice for Sampling of Headspace Vapors from Fire Debris Samples.

ASTM E 1412-12, Standard Practice for Separation of Ignitable Liquid Residues from Fire Debris Samples by Passive Headspace Concentration with Activated Charcoal.

ASTM E 1413-13 Standard Practice for Separation of Ignitable Liquid Residues from Fire Debris Samples by Dynamic Headspace Concentration.

ASTM E 1618-14, Standard Test Method for Ignitable Liquid Residues in Extracts from Fire Debris Samples by Gas Chromatography-Mass Spectrometry.

ASTM E 2154 - 15a Standard Practice for Separation and Concentration of Ignitable Liquid Residues from Fire Debris Samples by Passive Headspace Concentration with Solid Phase Microextraction (SPME).

## APPENDICES

A. Methods

B. Primer

C. Bibliography and Questions

D. Working Group Roster

E. Working Group Bios

F. Project Advisory Committee and Staff

## A. METHODS

The methodology required flexibility to accommodate the nature of the diverse subject matter and the styles of the Working Group (WG) members. The components used in preparing this report are described below.

The first task of this fire investigation study was to update the bibliography compiled by the White House Subcommittee on Forensic Science (SoFS). Two online university libraries were initially used for the search. The first was Boston University Medical Center's Alumni Medical Library, using the Google Scholar search engine. The second was The George Washington University's Gelman Library, using the *ArticlesPlus* search engine. A time range was implemented (January 2012- June 2015) for both search engines to limit the results to those published since the release of the original bibliographies. Key terms entered into both search engines included "fire investigation", "arson investigation", "fire debris", "forensic fire investigation", "forensic fire debris analysis", "forensic fires" and "fire scene investigation". Relevant articles were reviewed by project staff and combined with the original bibliography to create an updated bibliography with a complete citation and abstract for each article.

The articles that could not be located were included in the updated bibliography, with a note stating that a PDF copy was not available. The articles published since 2012 were marked by a single asterisk (*) and numbered along with the articles from the SoFS bibliography. Any questions associated with the SoFS bibliography that addressed issues determined by staff to be outside the scope of project goals were not included in the updated bibliography. Similarly, some case studies were not included, because these articles would provide little rigorous scientific information.

A draft primer was prepared by project staff to familiarize the non-forensic scientists in the Group with the field of fire investigation. The updated bibliography, primer, subsequently reviewed by the forensic scientist on the WG, and other documents assembled by project staff were sent to the WG members. Articles or reports recommended by the WG were added to the bibliography and marked with a double asterisk (**), but without a number.

To make the WG's tasks less onerous, staff decided that rather than dividing the sources and assigning particular articles or other references to each member, the WG members themselves would select the sources they felt most qualified to review. Experts in statistics, human factors or cognitive psychology were to select a sample of the references and evaluate them on the basis of their area of expertise. While this process would likely mean that not all articles would be reviewed, the WG would cover a representative sample of the articles and address each of the SoFS-created questions. WG members were instructed to evaluate each article or other source and decide whether it was responsive to the question with which it was paired and whether it was "good science." If they determined that the article was not sound science, they were to state a reason(s), for example, "inadequate statistics," "no control group."

To further ease the burden on the WG members, staff developed an assessment tool with five overarching questions to be answered for each article including, for example, “What are the weaknesses/strengths of the article/report?” “Did the article/report answer the specific question under which it was listed?” Additionally, staff developed assessment guidelines to provide further assistance to WG members as they reviewed articles and other sources. Both documents were vetted by the Advisory Committee. WG members were instructed to complete one form for each source they read. However, the WG proposed a more meaningful and efficient approach to evaluating the literature and the status of the science.

The chair of the fire investigation WG met with a staff member prior to the in-person meeting held at AAAS headquarters on July 20, 2015 to discuss the most useful methodology for moving forward with the assessment. At the July 20 meeting, members of the WG developed their own set of questions that needed to be addressed in order to provide a useful evaluation of fire investigation science, both at the scene of the fire and the analysis of debris. Members of the WG identified the questions that each would address. They could use the bibliography and were free to include other sources they deemed relevant. Because they chose which sources best answered their questions, not all of the articles in the bibliography are referenced in the report.

The resulting report constitutes a review of the forensic discipline of fire investigation, rather than a review of each article in the expanded bibliography. The audience for this report reaches well beyond the forensic community. As set forth in our proposal, the audience for the report includes members of both the defense and prosecutorial bars, judges, policy makers (such as members of Congress and members of the Executive branch), and funders. Because of this broad constituency for the report, the approach used by the WG has distinct advantages over a review of a majority, if not all, of the bibliographic sources. This constituency will not find it useful to learn, for example, that article #15 meets the requirements of a “good” scientific study, but article #43 has an inadequate sample size, article #53 used the wrong statistic, etc. The methodology used provides a useful guide to answer the questions-What do we know about fire investigation? What don’t we know? What are the gaps? What research or other activities should be pursued to improve fire investigations?

Finally, drafts of the report were sent to the Advisory Committee and two fire investigation practitioners for their review, and their remarks contributed to the preparation of this final report.

## B. FIRE INVESTIGATION— A PRIMER

Fire investigation includes two basic types of analysis -- fire scene investigation and fire debris analysis. The former occurs primarily at the scene, while the latter occurs primarily in the laboratory for the purpose of detecting and identifying ignitable liquid residues (ILRs). Fire debris analysis is based on established scientific principles and has been one of the most fully standardized forensic fields for the past 20 years (Lentini, 2009). Nevertheless, there are instances where additional research would help to improve its analytical capabilities.

Fire scene investigation is much more challenging than fire debris analysis for a number of reasons, including the extensive destruction of evidence caused by the fire and firefighting activities, the complex behavior of fire, and the generally inadequate understanding of fire chemistry and physics by many investigators. Many of the evaluations and determinations are based on subjective determinations and judgments and, hence, depend on human cognitive factors. Depending on the extent of damage, one of the most difficult tasks is determining the fire's point of origin. "The origin of a fire is one of the most important hypotheses that an investigator develops and tests during the investigation. Generally, if the origin cannot be determined, the cause cannot be determined, and generally, if the correct origin is not identified, the subsequent cause determination will also be incorrect" (NFPA 921 at 18.1, p. 186).

Fire origin and cause determination involves the evaluation of several variables, including witness statements, fire patterns, arc mapping and fire dynamics. Analyzing these variables and documenting the relevant evidence is essential to understanding what the fire did and why. It is also important for fire investigators to document any actions taken by firefighters that may have altered the scene and/or evidence, so that it can be taken into account when conducting the investigation.

Investigators must understand the relationship between the elements that constitute the fire tetrahedron: heat, fuel, oxygen and the chemical reaction among the three. Although fire investigations are complex because of the different variables that must be considered, fires generally follow predictable behaviors. Initially, flames and smoke tend to flow up and outwards in a three-dimensional buoyant plume rising from the fire. In confined spaces, these hot gases rise to the ceiling and then expand downward to form a smoke layer, charring or discoloring anything in this hot upper layer of the room. Patterns on surfaces in the fire enclosure will demonstrate how far the hot gases extended down from the ceiling. These behaviors leave behind patterns of damage that, if interpreted correctly, allow fire investigators to determine how the fire progressed through the structure, the fuels involved, and the point of origin.

Fire patterns can manifest themselves as V-patterns, caused by the intersection of a plume by a vertical surface. Some of the most common fire patterns include char patterns, damage patterns, and smoke and soot patterns. Char patterns typically result from direct flame involvement and may indicate the relative duration of burning, as well as the directionality of the flame movement. Damage patterns on objects, when unmoved, such as melted light bulbs, will also indicate the directionality of the heat source. Smoke and soot patterns may help the investigator determine how the fire developed.

Yet, except in the simplest cases, burn patterns can be confusing and misleading because the point of origin will not necessarily be located where charring is deepest or heat damage is most severe. This is particularly true for enclosure fires that grow to the point of flashover and become fully involved. Flashover is a transitional phase during which all exposed combustible surfaces in a room ignite almost simultaneously due to intense radiant heating from the hot gas layer in the room; flashover occurs when the temperature of the hot gas layer reaches 500-600°C. Once flashover occurs, enclosure fires typically become “fully involved,” which means the room is filled with fire, and “ventilation-limited,” which means the rate of burning within the room becomes limited by the rate of air flow into the enclosure through ventilation pathways rather than by the rate of fuel released by burning surfaces.

In a fully involved[1] enclosure fire, the most intense burning occurs where fuel vapors come in contact with oxygen entering the fire enclosure, and that may not be where the fire started. Such ventilation-generated burn patterns have been interpreted incorrectly in the past and are the subject of ongoing interest and research in the fire investigation community. Such misinterpretations have included inaccurate findings regarding the use of ignitable liquids and multiple fire origins, leading to incorrect determinations of incendiary fires.

It is the goal of current research in burn patterns, fire dynamics, and fire modeling to better characterize the patterns that can be expected under specific circumstances. However, duplication of all circumstances from the research setting to actual fire scenes is unlikely so investigators will never have complete data to test their hypotheses as to a fire’s origin. Burn patterns provide only a portion of the data that must be identified and analyzed, and frequently they are not sufficient in and of themselves to determine the origin or cause of the fire.

Before making any conclusive determinations with respect to the burn patterns, some factors that should be considered by knowledgeable fire investigators have been noted to include “prevailing drafts and winds; secondary fires due to collapsing floors and roofs; the physical arrangement of the burning structure; stairways and elevator shafts; holes in the floor, wall, or roof; and the effects of the firefighter in suppressing the fire ….”(Saferstein, 2011)**.** After all the parameters are considered and current understanding of their effects are applied, the investigator may be able to use them to form a hypothesis as to the area of origin, the spread of the fire, the time for development, and the heat generated during the fire.

At this time, forensic fire debris analysis in the laboratory focuses on the presence and identity of ignitable liquids, a process based on established scientific principles. The validity and reliability of fire debris analysis is well established due to several organized efforts within the

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[1] When all exposed fuel sources are involved in combustion.

discipline including (but not limited to) the Technical/Scientific Working Group for Fire and Explosion Analysis (swgfex.org), and the Criminalistics Subcommittee of the American Society for Testing and Materials (ASTM) E30 Committee on Forensic Sciences. The T/SWGFEX was established in 1996 to assist fire and explosives forensic examiners by developing guidelines, creating and maintaining databases and providing much-needed training and professional development to scientists. The members of E30, a broader and larger group, collaborate on the development of consensus analytical standards for the terminology, extraction, analysis, and interpretation of ignitable liquid residues extracted from fire debris samples in the laboratory. The chemical analysis and interpretation of forensic evidence from fire debris has benefitted from a coordinated volunteer effort to develop and continuously improve analytical standards. Advancements in analytical methodology have driven the improvements in these standards (e.g., adoption of gas chromatography coupled to mass spectrometry (GC-MS) as opposed to gas chromatography (GC) alone). Despite the overall validity and reliability of fire debris analysis, there is still work to be done. The changing nature of ignitable liquids, such as gasoline composition and our understanding of ignitable liquid residues (ILRs), necessitates the continued refinement of these analytical standards.

# C. BIBLIOGRAPHY

## PREFACE TO THE ANNOTATED BIBLIOGRAPHY ON "BURN PATTERN" QUESTIONS

The Technical/Scientific Working Group for Fire and Explosions (T/SWGFEX) would like to extend its appreciation to the Research Development Testing & Evaluation Interagency Working Group (RDT&E IWG) for allowing it to participate in their research into the use of burn patterns in the investigation of fires. Before we can provide the annotated bibliography for the questions posed to us, T/SWGFEX would like to clarify its position on the use of burn patterns in the examination of a fire scene.

At this time, "Burn Pattern Analysis" is a misnomer. The examination of the burn patterns following a fire is not a forensic examination and "burn pattern analysis" is not a forensic discipline. "Burn pattern analysis" has not risen to the level where it can be used exclusively as the only determinant of a fire investigation. T/SWGFEX supports the position that burn patterns provide the investigator with information as to "Where the fire's destruction did and did not take place constitutes the fire pattern." [1]

Due to the large number of variables and unknowns which have not yet been conclusively established by scientific research, "burn pattern analysis" cannot be considered as rising to the level where it is a recognized forensic discipline. Existing and planned research is seeking to address and collect data on the many variables that affect the production and appearance of burn patterns within a scene. What has been determined so far is that many of the variables are interconnected and slight variations will change the resulting burn patterns.

> "However, many factors can contribute to the deviation of a fire from normal behavior. Prevailing drafts and winds; secondary fires due to collapsing floors and roofs; the physical arrangement of the burning structure; stairways and elevator shafts; holes in the floor, wall, or roof; and the effects of the firefighter in suppressing the fire are all factors that the knowledgeable fire investigator must consider before determining conclusive findings."[2]

Since this was written, many more parameters that affect the production of burn patterns have been identified. Burn patterns provide data to the fire investigator in order to apply the scientific method to their investigation. The authoritative reference used by competent fire investigators is the National Fire Protection Association 921 "Guide for Fire and Explosion Investigations". In section 6.3.1 the reference offers this disclaimer:

> "The circumstances of every fire are different from every other fire because of the differences in the structures, fuel loads, ignition factors, airflow, ventilation, and many other variables. This discussion, therefore, cannot cover every possible variation in fire patterns and how they come about. The basic principles are covered here, and the investigator should apply them to the particular fire incident under investigation."[3]

It is the goal of current research in burn patterns, fire dynamics, and fire modeling to better characterize the patterns that can be expected to develop under specific circumstances. However duplication of all circumstances from the research setting to actual fire scenes is highly unlikely and the investigator will be left with applying the best data they can obtain to test their hypothesis as to a fire's origin. Burn patterns provide only a portion of the data that must be identified and analyzed by the investigator and are not sufficient in and of themselves to conclude the origin or cause of the fire. After all parameters are considered and current understanding of their effects are applied, the investigator may be able to use them to build their hypothesis as to area of origin, the directionality of the fire, the time for fire development, and the heat generated during the fire. There may be other aspects of the fire suggested by the patterns that are not listed here.

At this time the most commonly used "forensic" discipline intimately connected to fire investigations is the analysis of fire debris for the presence and identity of ignitable liquids. It is based on established scientific principles and is not under scrutiny as a result of the National Academy of Science's 2009 report, "Strengthening Forensic Science: A Path Forward."[4]

1. Kirk's Fire Investigation, 7th edition, DeHaan, J. & Icove, D, Pearson Education, 2012, p258
2. Criminalistics, 10th edition, Saferstein, R., Prentice Hall, 2011, p 362
3. NFPA 921 Guide for Fire and Explosion Investigations, 2011 edition, National Fire Protection Association, Technical Committee on Fire investigations, 2011. Section 6.3.1 p 52.
4. "Strengthening Forensic Science: A Path Forward", a report from the National Academy of Science, 2009

# Annotated Bibliography from IWG Questions + Recent Publications (indicated by *)/Late additions (indicated by **)

Most of the publications and websites listed below each question apply to all of the questions. These publications are accepted references by the majority of fire investigators throughout the United States. It is important to remember that pattern analysis is not a forensic science, although in interpreting fire patterns the fire investigator must rely on forensic science such as fire dynamics.

Some annotations are provided for groups of references.

**NFPA 1033: Standard for Professional Qualifications for Fire Investigator, 2009 Edition, NFPA, 2011, 16 pages, Copyright, National Fire Protection Association**

The entire Standard provides guidelines for the Fire Investigator in interpretation of the information (including burn patterns) to determine a fire's cause: Sections 4.2.4, 4.6.5 and 4.7.1.

**NFPA 921: Guide for Fire & Explosion Investigations, 2008 Edition**

Section 17.4 through Section 17.8, refers to analyzing the data with discussions regarding fire pattern analysis. The entire chapter 1, NFPA 921, Chapter 8 also applies.

## I. What literature exists that describes how basic science in the physics and chemistry of fires is translated into the practice of burn pattern analysis for practitioners?

****Carman S.W. (2013). The Impact of Ventilation in Fire Investigation. *Fire Science and Litigation Seminar*, pp. 37-52.**

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 casual 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.

****Cox A. (2013). Origin Matrix Analysis: A Systematic Methodology for the Assessment and Interpretation of Compartment Fire Damage. *Fire & Arson Investigation*, July 2013, pp. 37-47.**

Fire investigators routinely assess and interpret fire scene patterns and damages in an effort to develop hypotheses, and eventually draw conclusions about where a fire may have started and how that fire spread throughout a structure. In the case of pre-flashover fires, there is rarely disparity among fire investigators about the general area in which a fire originated. However, despite significant advances in the science of fire investigation, it is still a relatively common occurrence that two qualified fire investigators look at the same post-flashover fire scene evidence and reach different conclusions regarding area of origin, and then ultimately cause. The fact that different investigators can review the same fire scene damages, yet reach different interpretations about how those damages were generated, has been, and continues to be the premier problem in the evolution of fire investigation as a more reproducible scientific process. It is recognized that no system will ever completely eliminate all disputes among investigators, as an essential feature of origin and cause opinions is that they rely upon individual interpretation of data. Nevertheless, investigations that employ approaches based upon a solid scientific foundation are more likely to yield substantially similar conclusions, rather than vastly differing opinions. A major road block in quality, scientific-based fire investigations may be a generalized lack of understanding of the fundamental principles governing fire damage development among many practicing fire investigators. Investigators must have a clear understanding not just of the fire-related physics and material properties that are responsible for creating fire damages, but they must also be able to justifiably interpret those damages in a meaningful and technically accurate way. A number of resources, including texts like NFPA 921 *Guide for Fire and Explosion Investigations,* organizations like the International Association of Arson Investigators (IAAI), and educational institutions like the National Fire Academy (NFA), attempt to address the issue of fire scene damage assessment and interpretation with some effectiveness, but the issue is by no means resolved. The purpose of this paper is to outline a practical and logical thought process to assist fire investigators in more accurately and consistently identifying correct areas of origin. Before outlining this framework, a brief review of some fundamental fire science and damage dynamics principles is required.

**1. DeHaan J. and Icove D.J . (2012). *Forensic Fire Scene Reconstruction*, 3rd edition. Upper Saddle River, NJ: Prentice Hall, 432 pages, ISBN: 978-0-1326-0577-9 [hereinafter Icove]**

Pages 1 – 54 describe a systematic approach to reconstructing fire scenes in which investigators rely on the combined principles of fire protection engineering along with forensic and behavioral science. Using this approach the investigator can more accurately document a structural fire origin, intensity, growth, direction of travel, and duration, as well as the behavior of the occupants.

**2. DeHaan J. and Icove D.J. (2012). *Kirk's Fire Investigation*, 7th edition. Upper Saddle River, NJ: Brady / Pearson Education, 800 pages, ISBN: 978-0-1350-8263-8, BK6007 [hereinafter Kirk]**

Chapters 3 through 7, Pages 32 – 323, provide an understanding of the basic fundamentals of fire behavior, material characteristics, properties, combustion and the processes of heat transfer, heat release rate, fire propagation, and the assessment that must be applied to give the fire investigator an understanding of how they affect fire growth and patterns.

**3. Karlsson B. and Quintiere J. (2000). *Enclosure Fire Dynamics*. Boca Raton, FL: CRC Press, 336 pages, ISBN: 978-0-8493-1300-4**

This is a comprehensive discussion of scientific factors affecting the development and progression of a fire in an enclosed space.

****Lentini J.J. (1992). Behavior of Glass at Elevated Temperatures. *Journal of Forensic Sciences*, Vol. 37, No. 5, pp. 1358-1362.**

The author conducted a series of tests to examine the usefulness of crazed glass as an indicator of abnormal fire behavior. Despite widely held beliefs and widely published statements that crazing of glass is a result of exposure to rapidly increasing temperature, the test results show that glass will not craze, except when its temperature is rapidly decreased. A finding of crazed glass in a fire scene has no special meaning regarding the temperatures to which the glass was exposed.

***4. Lentini J. (2013). *Scientific Protocols for Fire Investigation*, 2nd edition. Boca Raton, FL: CRC Press, 624 pages, ISBN 978-1-4398-7598-8 [hereinafter Lentini, Scientific Protocols].**

Scientific Protocols for Fire Investigation provides comprehensive coverage from historical, developmental, current, and practical perspectives. The author, uniquely qualified with years of experience in both on-site investigations and lab analyses, provides a resource that is unparalleled in depth and focus. The book is distinctive in that it not only discusses the appropriate techniques for fire scene investigation and the chemical analysis of fire debris, but it also focuses on the history of fire investigation and how the profession has evolved. Specific topics of interest include: an interpretation of GC-MS data from ignitable liquid residues. An explanation of fire analysis as it relates to chemistry, physics, and fluid dynamics. A critical assessment of common fire investigation errors with a discussion of how these errors affect real cases. A systematic examination of fire investigation mythology - how the myths originated and how they continue to be promulgated The presentation of landmark legal cases that affect the protocol of fire investigations The development of new tools used in investigations Professional interaction - how to deal with clients, expert witnesses, lawyers, and the courts A thorough and accessible book, Scientific Protocols for Fire Investigation provides not only the practical information necessary to conduct an effective inquiry but also with insight into the science, history, and theory behind what makes fire investigation a multi-faceted profession.

### 5. NFPA 921: Guide for Fire and Explosion Investigations 2014 edition. (12/2013), NFPA, 394 pages, ISBN: 978-1-4559-0850-9 (Print), ISBN: 978-1-4559-0862-2 (PDF) [hereinafter NFPA 921]

Chapters 4 through 6, pages 19-74 provide a detailed overview of basic methodology, basic fire science and fire patterns, the fire effects, the pattern itself, and their analysis. It details information and guidelines to assist the fire investigator in evaluating fire patterns accurately.

### *6. Shintani Y., et al. (2014). Simple Method to Predict Downward Heat Flux from Flame to Floor. *Fire Science and Technology*, Vol. 33, No. 1, pp. 17-34.

This work presents a simple model to predict the radiation heat flux from a flame to a floor surrounding it. This heat flux was measured both in an unconfined space (open air) and under a ceiling. Flame lengths, flame temperatures, and ceiling surface temperatures, all of which are necessary to predict radiation heat flux, were also measured. Flame shapes were modeled by two cylinders and two disks representing the impinging flame's continuous and intermittent flame regions. The emissivity of the cylinders was calculated from the heat balance at the flame surface, and the radiation heat flux to the floor was predicted well by the model.

## II. How long a fire has burned has a big effect on the information that can be inferred from a fire scene. What literature exists that shows how burn time affects the ability to determine source and/or origin?

### 7. Carman S. "Progressive Burn Pattern Development in Post-Flashover Fires", available at: http://carmanfireinvestigations.com/dl/%28Carman&Associates%29%20-%20Progressive%20Burn%20Pattern%20Development%20in%20Post-Flashover%20Fires.pdf

In 2005, fire investigators from the U.S. Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) designed and presented a seminar on fire dynamics. Two identical, one-room burn cells with standard-sized doorways were each burned for seven minutes. Later, fifty-three experienced fire investigators from the public and private sectors (who had not observed the fires) were asked to briefly examine the cells and identify in which quadrant they thought each fire had started. 5.7% of the students correctly selected the quadrant of origin in each cell.

A subsequent review of experienced investigators' responses to similar, post-flashover exercises at the Federal Law Enforcement Training Center in Georgia revealed that since the early-1990s, about 8-10% of students correctly located the origins of similar fires. Those who were mistaken typically reported they were misled by burn patterns generated in fully involved, ventilation-controlled conditions. In 2008, three follow-up tests fires were designed and conducted in single-room cells (similar to those from 2005) at the ATF Fire Research Laboratory in Ammendale, Maryland. The tests were used to evaluate burn pattern development in fully involved, ventilation-controlled fires with similar physical layouts, furnishings and ignition scenarios. The principle variable between the tests was time of exposure to full fire involvement. Analyses of heat flux, temperature and gas concentration data as well as examination of burn patterns were conducted to better understand the various mechanisms involved.

Information from the tests was also used as the basis of a new Internet-based training module on Post- Flashover Fires at the training site, *CFITrainer.net.*

****Carman S. (2008). Improving the Understanding of Post-Flashover Fire Behavior. *Proceedings of the International Symposium on Fire Investigation Science and Technology*. Sarasota, FL.**

Fire investigators are regularly called upon to interpret burn patterns and to determine where fires originate. Patterns created by pre-flashover fires are often easily deciphered by investigators seeking the fire origins. The severe burn damage found in fully-involved fires can be far more daunting to interpret, making origin determination extremely difficult.

At a 2005 fire training conference, fire investigators from the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) designed and presented a seminar on Fire Dynamics. Two, identical, one-room burn cells with standard-sized doorways were each burned for seven minutes. Hours later, fifty-three fire investigator-students (who had not observed the fires) were asked to briefly examine the cells and decide in which quadrant of each cell they thought the fires had started. 5.7% of the students correctly identified the quadrant of origin in each cell. A review was undertaken of investigators' responses in similar, postflashover exercises at the Federal Law Enforcement Training Center in Georgia. Though written records of those responses are not kept, anecdotal reports by long-time instructors indicate that since the class' inception in the early-1990s, about 8-10% of students correctly identified the fire's origin. Those who identified an incorrect origin typically reported they were misled during their analyses by extensive, postflashover-generated burn patterns.

This paper offers a new and proven approach for enhancing investigators' understanding of post-flashover fire behavior through use of standard fire dynamics instruction combined with the graphic output of the computer programs, Fire Dynamics Simulator and Smokeview. Such training offers students a visual introduction to the nuances of ventilation-limited burning. It also introduces the use of computer models in hypothesis-testing as part of an investigative methodology.

### 8. Icove

Pages 55 – 99 describes fire dynamics knowledge as it applies to fire scene reconstruction and analysis. It is is based on the combined disciplines of thermodynamics, chemistry, heat transfer, and fluid mechanics. The growth and development of fires are influenced by a number of variables, such as available fuel load, ventilation, and physical configuration of the room. To estimate accurately a fire's origin, intensity, growth, direction of travel, and duration, investigators must rely on and understand the principles of fire dynamics.

### 9. Kirk

Pages 279-282, discuss char depth and char appearance, and what variables affect them. It also discusses how heat penetration is not linear with burn time and the variables that affect heat penetration.

### 10. NFPA 921

Chapter 6, section 6.2.4, pages 43 – 44 provides a detailed overview of char and the rate of wood charring and the variables that affect it.

Chapter 5, pages 20 – 42 provides a guideline of fire science principles. The investigator is made aware of all the factors that that have an effect on a burn time line, such as the properties of the material burning, the geometry of the enclosure, the ventilation, and several other characteristics.

## III. What is the literature that describes the key investigative issues that must be considered when performing burn pattern analysis and arson investigation at the crime scene?

### **Carman S. (2008). Improving the Understanding of Post-Flashover Fire Behavior. *Proceedings of the International Symposium on Fire Investigation Science and Technology*. Sarasota, FL.

Fire investigators are regularly called upon to interpret burn patterns and to determine where fires originate. Patterns created by pre-flashover fires are often easily deciphered by investigators seeking the fire origins. The severe burn damage found in fully-involved fires can be far more daunting to interpret, making origin determination extremely difficult.

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### 11. Icove

Pages 101 – 165 describes the underpinnings of how fire patterns are used by investigators in assessing fire damage and determining a fire's origin. Fire patterns are often the only remaining visible evidence after a fire is extinguished. The ability to document and interpret fire pattern damage accurately is a skill of paramount importance to investigators when they are reconstructing fire scenes.

### 12. Kirk

Pages 249-323, provide details of how fire patterns are generated, and what variables occur that can change their direction. On page 321, Analysis and Hypothesis testing is discussed. It emphasizes that the investigator continually observes the totality of indicators and uses the scientific method.

### **Lentini J.J., Smith D.M. and Henderson R.W. (1992). The Oakland Experience. *Fire Technology*, Vol. 28, No. 3, pp. 1-8.

The authors examined the remains of fifty structures destroyed in the October, 1991 fire in the hills east of Oakland, California. Traditional indicators of "abnormal fire behavior" were examined in each of the structures, including apparently melted steel items, melted copper and melted, as well as crazed, glass. These indicators were found to have no probative value as to the presence of liquid accelerants, abnormally heavy fuel loads or abnormally high temperatures.

### *13. Lentini Scientific Protocols

Chapter 3- Fire Dynamics and Fire Pattern Development, pages 76-109 describe methods for determining the significance of fire patterns, whether they are caused by fire plumes or increased access to oxygen in an otherwise oxygen-deficient compartment.

### *14. Li Y.Y., Liang D. and Shen H. (2013). An Analysis of Background Interference on Fire Debris. *Procedia Engineering*, Vol. 52, pp. 664-670.

In this study, the controlled burn experiments of carpets with and without gasoline in this study and commonly encountered substrates produced complex chromatograms producing peaks that were identified by mass spectrometry and comparison with reference standards and each other. The result shows that many of the compounds frequently encountered as a result of either combustion products or pyrolysis products of carpets are detected in fresh gasoline as well. These compounds are background interferences that detect whether the gasoline exists in carpet combustion products or not.

### 15. NFPA 921

Chapter 6, section 6.4, page 63, discusses the process of identifying and interpreting fire patterns. It also states reference to the fire dynamics that is discussed in section 5.10 Compartment Fire Development, pages 38 – 43. This section discusses the rate and pattern of a fire development and its dependences the complex relationships between the burning fuel and the surrounding environment.

Chapters 18 and 19, pages 186-203 provides methodology and guidelines for determining origin and cause. The investigator is basically instructed to be aware of the totality of information and data involved in performing an analysis of the fire scene.

### *16. Tinsley A.T., Burdette E.G. and Icove D.J. (2014). Structural Deformations as an Indicator of Fire Origin. *Journal of Performance of Constructed Facilities*, Vol. 28, No. 3, pp. 440-449.

Current methodologies of fire origin investigation have yet to include the structural deformations witnessed in steel buildings as a viable indicator of the area of fire origin. In this paper, the validity of using such a technique for fire investigation has been assessed. A series of full scale burn tests were conducted to validate the proposed methodology. While it did not turn out that the greatest magnitude of deflection was always indicative of the precise area of origin, the tests have shown that the deflections can be used as important indicators of the area of origin.

### **Tinsley A.T. and Gorbett G.E. (2012). Fire Investigation Origin Determination Survey. International Symposium on Fire Investigation Science and Technology, ISFI 2012, pp. 53-68.

The fire investigation industry is considered to be lagging behind the rest of the forensic science fields in its assessment of the performance of methodological approaches and conclusions drawn by practitioners within the field. Despite the best efforts of certifying bodies and industry members, there are still many unknowns within the profession. As such, the researchers have collected a large survey of demographics to formulate a picture of our industry with regards to experience, age, employment, training, and opinions regarding methodology within the industry. In addition to these demographics, the researchers collected data regarding area of origin determination both with and without measurable data (depth of char, calcination) to evaluate its effectiveness when applied without an on-site scene examination. This permitted the comparison of the demographics and accuracy in determining the most important hypothesis in fire investigations, the area of origin. It is shown that 73.8% of the participants without measurable data and 77.7% with measurable data accurately determined the area of origin.

Thus, the total percentage of participants choosing the correct area increased 3.9% with the inclusion of measurable data as part of the given. Additional selected outcomes from this research are presented within this paper.

## IV. What is the literature that describes how fire modeling and fire simulation is used in fire investigations?

### 17. Anderson G. W. (1997). Burning Rate Model for Charring Materials. NIST GCR 97-725; p. 93.

A one-dimensional model has been developed to describe the processes involved in the transient pyrolysis of a semi-infinite charring material subjected to a constant radiant heat flux. Material properties are assumed constant with respect to temperature and time. The model tracks the char layer growth, thermal penetration depth, surface temperature and mass loss rate. A review of the physical phenomena involved in charring pyrolysis is presented and the relevant phenomena included in the model; the integral method is described, and an example for constant surface heat flux is solved. The derivation of the model divides the material into three regions: char layer, vaporization plane, and virgin material and the equations of conservation of mass and energy are applied to each region using the integral approximation with polynomial temperature profiles. The resulting coupled, nonlinear, autonomous system of three different equations and one algebraic equation is suitably nondimensionalized and solved using Mathematics (tm) software. The results generated by the model are compared to existing models and, a method by which effective properties for use in the model might be deduced from experimental data is suggested.

### 18. Bryner N. P., Johnsson E. L. and Pitts W. M. (1994). Carbon Monoxide Production in Compartment Fires: Full-Scale Enclosure Burns. NISTIR 5499; September 1994. National Institute of Standards and Technology. Annual Conference on Fire Research: Book of Abstracts. October 17-20, 1994, Gaithersburg, MD, 53-54 pp, 1994.

Recent studies attribute a large percentage of fire injuries and deaths to the generation of carbon monoxide (CO) and indicate that in roughly two-thirds of the fire deaths the fire victims have fatal or incapacitating levels of carboxyhemoglobin in their blood. A series of natural-gas fires within reduced- and full-scale rooms have been designed to improve the understanding of and to develop a predictive capability for CO formation in compartment fires. The findings will be used in realistic fire models and in the development of strategies for reducing the number of deaths attributed to carbon monoxide.

### 19. Bundy M., et al. (2007). Measurements of Heat and Combustion Products in Reduced-Scale Ventilation-Limited Compartment Fires. NIST Technical Note 1483; NIST TN 1483; 154 p.

A series of new reduced-scale compartment fire experiments were conducted that included local measurements of temperature and species composition. The measurements are unique to the compartment fire literature. By design, the experiments provided a comprehensive and quantitative assessment of major and minor carbonaceous gaseous species and soot at two locations in the upper layer of fire in a 2/5 scale International Organization for Standards (ISO) 9705 room. The enclosure defined in the international standard ISO 9705 "Full-scale room test for surface products" is an important structure in which to conduct fire research. Many dozens of research projects and journal articles have focused on this enclosure and the standard describing its use. It is a common reference point for studies of many fire-related phenomena as well as fire modeling efforts. While some previous studies have considered the mixture fraction to analyze experimental compartment fire data, few have considered minor hydrocarbon species and none have considered soot. In tandem, accurate measurements of temperature at these same locations allowed analysis of thermal effects on species concentrations. A wide range of fuel types were considered, including aliphatic hydrocarbons (natural gas and heptane), aromatic hydrocarbons (toluene and polystyrene) and alcohols (methanol and ethanol). Field models, such as the National Institute of

Standards and Technology (NIST) Fire Dynamics Simulator (FDS), are widely used by fire protection engineers to predict fire growth and smoke transport for practical engineering applications. Field models numerically solve the conservation equations of mass, momentum and energy that govern low-speed, thermally-driven flows with an emphasis on smoke and heat transport from fires. All field models have strengths and weaknesses. Among the various assumptions used in the development of previous versions of FDS, all chemical species were tied to the mixture fraction state relations. A single mixture fraction variable cannot be used for the prediction of carbon monoxide and soot, and the yield of these species was prescribed in FDS 4, rather than predicted. In fact, the yield of these species is usually not constant, but a complex function of their time-temperature history. In practice, an engineer using FDS 4 would choose combustion product yields directly from literature values for well-ventilated burning, using data from a bench-scale apparatus. Using this approach, the carbon monoxide (CO) volume fraction for pool fire burning in an under-ventilated compartment can be underestimated by as much as a factor of ten. A new version of FDS (version 5) is currently being tested which implements a predictive model of CO production. The experimental results provided in this report are the first step of a long-term NIST project to generate the data necessary to test our understanding of fire phenomena in enclosures and to guide the development and validation of field models by providing high quality experimental data. The experimental plan was designed in cooperation with developers of the NIST FDS model to assure that the measurements would be of maximum value. Advanced development of FDS and other field models is extremely important, since it will lead to improved accuracy in the prediction of underventilated burning, typical of fire conditions that occur in structures. Improving models for under-ventilated burning will foster improved prediction of important life safety and fire dynamic phenomena, including fire spread, backdraft, flashover, and egress (involving the presence of toxic gases and smoke), which are critically important for application of fire models for fire safety. In summary, the main objective of this project is to provide an improved understanding of the physics, chemistry, and structure of underventilated compartment fires, and to provide experimental measurements to guide the development of fire chemistry sub-models.

### *20. Chi J.H. (2012). Metallographic Analysis and Fire Dynamics Simulation Is Used for Electrical Fire Scene Reconstruction. *Journal of Forensic Sciences*, Vol. 57, No. 1, pp. 246-49.

This study demonstrated the use of metallographic analysis and NIST's Fire Dynamics Simulator (FDS) program to identify the cause of an actual electrical fire. A severely carbonized steel plate and a cable with a bead were found inside a damaged switchboard from the debris of a factory fire. By metallographic analysis, the copper spatter on the steel plate was found to imply a short circuit has occurred and that this was the probable ignition source of the fire was supported by the presence of a small amount of copper oxide and by the cavities with the tree-like grain microstructures in the bead. The heat estimated to have been released per unit area of the switchboard in question (approximately 236.29 MJ⁄m2) served as key input data for applying the FDS simulation of the blaze. The simulation indicated that thermal insulation polyethylene (PE) played an important role in the rapid fire spread.

### *21. Chi J.H. (2013). Using Thermal Analysis Experiment and Fire Dynamics Simulator (FDS) to Reconstruct An Arson Fire Scene. *Journal of Thermal Analysis Calorimetry*, Vol. 113, pp. 641- 648.

PU foam samples that had caused fire to spread in an actual arson case were collected for thermal analysis experiments. The experiments were conducted at three different heating rates to obtain thermal reaction parameters including *3,518.23–5,127.81 J g-1 of heat release at temperatures between 395 and 433 _C. The thermal analysis data were treated as the input data for the Fire Dynamics Simulator Program. Results of smoke layers falling in the simulation space were compared and verified with the heights of smoke traces at the actual fire scene to obtain heating rates which are close to the actual conditions for the reconstruction of the entire fire scene. In addition to serving as a reference for the investigation and reconstruction of other fire cases, these research findings can also increase the awareness of the harmful aspects of PU foam for fire prevention in the future.

**22. Cooper L.Y. (1988). Calculating Flows through Vertical Vents in Zone Fire Models Under Conditions of Arbitrary Cross-Vent Pressure Difference. NBSIR 88-3732; 16 p. May 1988.**

In typical compartment fire scenarios, ratios of cross-vent absolute pressures are close to 1. When such is the case, algorithms are available to predict the resulting cross-vent room-to-room flows. There are, however, important situations where this pressure condition does not prevail, for example, in fire scenarios involving relatively small penetrations in otherwise hermetically-sealed compartments of fire origin. It is important for a versatile compartment fire model to have a capability of predicting vent flows for the entire range of possible cross-vent pressure conditions. This paper develops a unified analytic description for flows through vertical vents between pairs of two-layer room fire environments under conditions of arbitrary cross-vent pressure difference. The analysis, which takes advantage of generally useful modeling approximations, leads to a concise result that is not significantly more complicated than the result for simple, low- pressure-difference cases.

**23. Cooper L.Y. and Franssen J. M. (1999). Basis for Using Fire Modeling With 1-D Thermal Analyses of Barriers/Partitions to Simulate 2-D and 3-D Barrier/Partition Structural Performance in Real Fires. NISTIR 6170; 22 p. September 1998. *Fire Safety Journal*, Vol. 33, No. 2, 115-128.**

Computer fire models for simulating compartment fire environments typically require a mathematical formulation that couples the thermal response of the gases that fill the compartment and the thermal response of compartment barriers and partitions. The fire environment characteristics calculated by such models can be used to provide input, via thermal boundary conditions, to an uncoupled thermal-structural computer model for simulating and evaluating the combined thermal/structural performance of the barriers/partitions. The objective of such a combined analysis would be to determine, through analysis, the structural fire resistance of a barrier/partition design.

**24. Floyd J. E. Comparison of CFAST and FDS for Fire Simulation with the HDR T51 and T52 Tests. NISTIR 6866; 111 p. March 2002.**

This work uses three methods: hand calculations, a zone model (CFAST), and a computational fluid dynamics code (FDS), to examine two fire tests from the HDR facility, a decommissioned reactor containment building in Germany. The two tests, T51.23 and T52.14, used different fuels, propane gas and a hydrocarbon solvent, and occurred in two quite different locations, low in the containment and just below the containment operating deck, respectively.

**25. Forney G. P., et al. (2003). Understanding Fire and Smoke Flow Through Modeling and Visualization. IEEE *Computer Graphics and Applications*, Vol. 23, No. 4, pp. 6-13.**

Computer modeling and visualization are important tools for understanding the processes of fire behavior. Fire models range in complexity from simple correlations for predicting quantities such as flame heights or flow velocities to moderately complex zone fire models for predicting time-dependent smoke layer temperatures and heights. Zone fire model calculations can run on today's computers within minutes because they solve only four differential equations per room. Zone models approximate the entire upper layer with just one temperature. This approximation works remarkably well but breaks down for complicated flows or geometries. For such cases, computational fluid dynamics (CFD) techniques are required.

**26. Hostikka S., McGrattan K. B. and Hamins A. (2003). Numerical Modeling of Pool Fires Using LES and Finite Volume Method for Radiation. *Fire Safety Science*, Proceedings. Seventh (7th) International Symposium. International Association for Fire Safety Science (IAFSS). June 16-21, 2003, Worcester, MA, Intl. Assoc. for Fire Safety Science, Boston, MA, Evans, D. D., Editor(s), pp.383-394.**

The thermal environment in small and moderate-scale pool flames is studied by Large Eddy Simulation and the Finite Volume Method for radiative transport. The spectral dependence of the local absorption coefficient is represented using a simple wide band model. The predicted radiative heat fluxes from methane/natural gas flames, as well as methane pool burning rates and flame temperatures are compared with measurements. The model can qualitatively predict the pool size dependence of the burning rate, but the accuracy of the radiation predictions is strongly affected by even small errors in prediction of the gas phase temperature.

**27. Hu Z., et al. (2005). A Comparison Between Observed and Simulated Flame Structures in Poorly Ventilated Compartment Fires. Proceedings of the Eighth (8th) International Symposium. International Association for Fire Safety Science (IAFSS). September 18-23, 2005; Beijing, China, Intl. Assoc. for Fire Safety Science, Boston, MA, Gottuk, D. T.; Lattimer, B. Y., Editor(s), pp. 1193-1204, 2005.**

This study is aimed at characterizing the dynamics of compartment fires under poorly ventilated conditions. The study considers four cases that correspond to different values of the fire room global equivalence ratio and are representative of strikingly different flame behaviors. The study is based on a detailed comparison between experimental and computational data. The numerical simulations are performed with the Fire Dynamics Simulator (FDS) developed by the National Institute of Standards and Technology, USA. The comparative tests serve to evaluate the general ability of FDS to describe the transition from over- to under-ventilated fire conditions, as well as the transition from extinction-free conditions to conditions in which the flame experiences partial or total quenching.

**28. Icove**

Pages 272-304, provides an overview of all types of fire models and describes what each model can provide for each type of testing. It also describes what the realistic and reliable results are of a fire model. Several fire modeling case studies are provided to the reader to provide examples of their use and how they were applied.

***29. Johansson N., Wahlqvist J. and Van Hees P. (2012). Detection of a Typical Arson Fire Scenario-Comparison Between Experiments and Simulations. *Journal of Fire Protection Engineering*, Vol. 22, No. 1, pp. 23-44.**

Between one and two school fires occur in Sweden every day. In most cases, arson is the cause of the fire. The most severe fires generally start outside the building and spread up along the facade and into the attic through ventilation openings in the eaves. Linear heat detectors can be placed on facades to detect these types of fires. Such devices detect fire when short-circuited at a specific temperature. In this article, an attempt to simulate linear heat detectors is presented. Data from small-scale and full scale experiments are compared with these simulations. The small-scale experiments and simulations demonstrate that the cable failure model in Fire Dynamics Simulator can be used to predict detection in linear heat detectors that use short-circuiting as the means of signaling an overheated condition. The full-scale experiments provide a measure of the uncertainties involved, as well as the possibility of using simulations of linear heat detectors in a fire engineering design.

**30. Jones W.W., et al. (2009). CFAST: Consolidated Model of Fire Growth and Smoke Transport (Version 6)". Technical Reference Guide. NIST SP 1026; NIST Special Publication 1026; Version 6; 117 p. (Revision).**

CFAST is a two-zone fire model used to calculate the evolving distribution of smoke, fire gases, and temperature throughout compartments of a constructed facility during a fire. In CFAST, each compartment is divided into two gas layers. The modeling equations used in CFAST take the mathematical form of an initial value problem for a system of ordinary differential equations (ODEs). These equations are derived using the conservation of mass, the conservation of energy (equivalently the first law of thermodynamics), the ideal gas law and relations for density and internal energy. These equations predict as functions of time quantities such as pressure, layer height and temperatures given the accumulation of mass and enthalpy in the two layers. The CFAST model then consists of a set of ODEs to compute the environment in each compartment and a collection of algorithms to compute the mass and enthalpy source terms required by the ODEs. In general, this document provides the technical documentation for CFAST along with significant information on validation of the model. It follows the ASTM E1355 guide for model assessment. The guide provides several areas of evaluation: (*) Model and scenarios definition, (*) Theoretical basis for the model, (*) Mathematical and numerical robustness, (*) Model sensitivity and (*) Model Evaluation.

### 31. Kirk

Pages 698-707, provide details of each type of fire modeling, such as mathematical, zone, field and other specialized applications. Also detailed are issues involved in choosing the right model for the job and how to evaluate, validate and verify the results. It discusses the critical analysis of a case to ensure the appropriate application of computer modeling can best be approached.

### 32. Lattimer B.Y., Vandsburger U. and Roby R.J. (1998). Carbon Monoxide Levels in Structure Fires: Effects of Wood in the Upper Layer of a Post-Flashover Compartment Fire. *Fire Technology*, Vol. 34, No. 4, pp. 325-355.

This experimental study was performed to determine the effects of wood pyrolyzing in a high-temperature, vitiated compartment upper layer on the environment inside the compartment and an adjacent hallway. This was done by comparing species concentrations and temperature measurements from tests with and without wood in the compartment upper layer. Experiments were performed with a window-type opening and a door-type opening between the compartment and the hallway. In these tests, the wood in the compartment upper layer caused CO concentrations inside the compartment to increase, on average, to 10.1% dry, which is approximately 3 times higher than levels measured without wood in the upper layer. Down the hallway 3.6 m from the compartment with wood in the upper layer, CO concentrations were measured to be as high as 2.5% dry. The use of the global equivalence ratio concept to predict species formation in a compartment was explored for situations where wood or other fuels pyrolyze in a vitiated upper layer at a high temperature.

### *33. Lentini Scientific Protocols

Chapter 3- Fire Dynamics and Fire Pattern Development, pages 110-122 describe the significant limitations involved with fire models, mainly due to the significant uncertainties involved.

### 34. Liang K. M., et al. (2003). Application of CFD Modeling to Room Fire Growth on Walls. NIST GCR 03-849; 86 pages.

An evaluation of the NIST FDS model was conducted with particular attention for its use in predicting flame spread on surfaces. Over the course of this investigation, the computational model changed from combustion depicted by particles to a mixture fraction based combustion model. The study pertains to version 2.0 released on December 4, 2001. Three aspects were considered in the study. First, we studied the evaluation of the code to predict a combusting plume. Second, the code was applied to a fire plume adjacent to a vertical wall, and then flame spread on the wall. Third, a complementary investigation of an improved algorithm for convective heat transfer at a surface was developed. The first two studies resulted in M.S. theses. Damian Rouson of CCNY performed the third study. The thesis by Ma on the axi-symmetric plume was previously transmitted and will not be included here. However, a recently accepted paper, based on the thesis with updated results is included. The general conclusions are that the FDS code is very good for computing the fluid dynamics, entrainment, and flame height. The temperature in the combustion region appears to be over-estimated at the base of the geometry considered, and any related heat flux is consequently over-predicted. The temperature results are grid dependent. A computation of flame spread on vertical PMMA gave mixed results. The code was benchmarked against fire plume correlations after a review of the literature to obtain the most general results. Most of the experimental correlations have some deficiencies, and should be improved. Particular attention needs to be given to temperature measurements in the flame since these are generally under- estimated due to radiation error. The wall heat flux and flame spread comparisons were made against data we viewed as quality data. The algorithm developed by Rouson is based on the theoretical formulation by Howard Baum, and has not been tested in the FDS code.

### 35. Madrzykowski D. (1997). SFPE Engineering Task Group on Computer Model Evaluations: Status Report – DETACT. Fire Research and Engineering, Second (2nd) International Conference. (ICFRE2). Proceedings. ABSTRACTS ONLY. National Institute of Standards and Technology and Society of Fire Protection Engineers. August 10-15, 1997, Gaithersburg, MD, Slaughter, K. C., Editor(s), pp. 106-106.

In 1995, the Society of Fire Protection Engineers formed a task group to evaluate the scope, applications and limitations of computer models intended for use in the engineering evaluation and design of fire and life safety measures. The Task Group's first objective was to identify an evaluation methodology and select a model to use as a test case. After examining several approaches to evaluating a computer model, the Task Group decided on following the ASTM Standard Guide for Evaluating the Predictive Capability of Deterministic Fire Models, E-1355. The guide "provides a methodology for evaluating the predictive capabilities of a fire model for a specific use." Specifically the method addresses four areas of evaluation: 1) model definition and evaluation scenarios, 2) verification of thereotical basis and assumptions used in the model, 3) verification of the mathematical and numerical robustness of the model, and 4) quantification of the uncertainty and accuracy of the model predictions.

The Task Group chose DETACT as the first model to undergo evaluation. The scenarios for which the model can be evaluated are limited in part by having appropriate full scale test data for comparison. Data which can be used for model evaluation is not widely available, due to many of the uncertainties inherent to large scale fire data sets. The scenarios for DETACT range from a 2.4m x 3.6m x 2.4m high compartment to a 30m x 30m x 12m high space. The later data set resulted from a test program that SFPE funded at Underwriters' Laboratories specifically for this evaluation effort. The resulting evaluation document is intended to supplement the model's user's guide by demonstrating the capabilities and limitations of a given model and highlighting underlying assumptions that are important for users to consider when applying the model. Examples taken from the DETACT evaluation will be presented.

### 36. Madrzykowski D. (2001). State-of-the-Art Research Is the Future of Fire Investigation. *SIU Awareness*, Vol. 15, No. 1, pp. 18-23.

As the legal climate for arson and fire investigations becomes more demanding, the need for a rigorous scientific foundation is growing. Fortunately, federal research efforts are already starting to close the gap.

### 37. Madrzykowski D. (2002). Fire Research: Providing New Tools for Fire Investigation. *Fire and Arson Investigator*, Vol. 52, No. 4, pp. 43-46.

### 38. Madrzykowski D. and Fleischmann C. (2010). Fire Pattern Repeatability: A Laboratory Study on Gypsum Wallboard, in *Proceedings of the 4th International Symposium on Fire Investigation Science and Technology*. National Institute of Standards and Technology (NIST), September 2010.

In 2009, the National Research Council (U.S) published a report identifying the research needs of the forensic science community. In the field of fire investigation, one of the specific needs identified was research on the natural variability of burn patterns. The National Institute of Standards and Technology (NIST) is conducting a multi-year study, with the support of the National Institute of Justice (NIJ) and the NIST Office of Law Enforcement Standards (OLES), to examine the repeatability of burn patterns. The primary objective of the study is assessing the repeatability of burn patterns on gypsum board exposed to a range of source fires. This paper will provide the results from the characterization of the source fires and the results of the pre-flashover fire pattern repeatability experiments. Experiments were conducted with a natural gas fueled burner, a gasoline fueled pan fire, and polyurethane foam. The top surface of the burner or fuel was 0.30 m (1 ft) by 0.30 m (1 ft) with the top surface approximately 76 mm (3 in) above the floor. Replicate source fire experiments were conducted in an oxygen depletion calorimeter with each of the fuels, in order to examine the repeatability of the fires in terms of heat release rate. The flame movement and height for each fire was recorded with photographs and videos. The fire pattern experiments were conducted in a three-sided structure with a full floor and partial ceiling constructed from wood framing and lined with painted gypsum board. The source fires were positioned against the rear wall, midway along its length. Replicate experiments were conducted with each fuel. A new piece of painted gypsum board was used for each experiment. The burn patterns were documented and analyzed for repeatability. The results are presented in terms of the fire pattern height, width, and total area.

### 39. NFPA 921

Pages 176 – 184, provide guidance on Failure Analysis and Analytical Tools. This section covers many items including developing time lines, system analysis, mathematical modeling, zone & field models, and fire testing guidelines. Also included are guidelines for test methods, limitations, type of required data on materials.

### 40. Peacock R. D., et al. (2004). Characteristics of Fire Scenarios in Which Sublethal Effects of Smoke Are Important. *Fire Technology*, Vol. 40, No. 2, pp. 127-147.

A number of simulations were performed using the CFAST zone fire model to predict the relative times at which smoke inhalation and heat exposure would result in incapacitation. Fires in three building types were modeled: a ranch house, a hotel, and an office building. Gas species yields and rates of heat release for these design fires were derived from a review of real-scale fire test data. The incapacitation equations were taken from draft 14 of ISO document 13571. Sublethal effects of smoke were deemed important when incapacitation from smoke inhalation occurred before harm from thermal effects occurred. Real-scale HCl yield data were incorporated as available; the modeling indicated that the yield would need to be 5 to 10 times higher for incapacitation from HCl to precede incapacitation from narcotic gases, including CO COd2, HCN and reduce O2. The results suggest that occupancies in which sublethal effects from open fires could affect escape and survival include multi-room residences, medical facilities, schools, and correctional facilities. In addition, fires originating in concealed spaces in any occupancy pose such a threat. Sublethal effects of smoke are not likely to be of prime concern for open fires in single- or two-compartment occupancies (e.g., small apartments and transportation vehicles) themselves, although sublethal effects may be important in adjacent spaces; buildings with high ceilings and large rooms (e.g., warehouses, mercantile); and occupancies in which fires will be detected promptly and from which escape or rescue will occur within a few minutes.

### 41. Rein G., et al. (2009). Round-Robin Study of *a priori* Modelling Predictions of The Dalmarnock Fire Test One. *Fire Safety Journal*, Vol. 44, No. 4, pp. 590-602.

An international study of fire modelling was conducted prior to the Dalmarnock Fire Test One in order to assess the state-of-the-art of fire simulations using a round-robin approach. This test forms part of the Dalmarnock Fire Tests, a series of experiments conducted in 2006 in a high-rise building. The philosophy behind the tests was to provide measurements in a realistic fire scenario involving multiple fuel packages and non-trivial fire growth, and with an instrumentation density suitable for comparison with computational fluid dynamics models. Each of the seven round-robin teams independently simulated the test scenario a priori using a common detailed description of the compartment geometry, fuel packages, ignition source and ventilation conditions. The aim of the exercise was to forecast the fire development as accurately as possible and compare the results. The aim was not to provide an engineering analysis with conservative assumptions or safety factors. Comparison of the modelling results shows a large scatter and considerable disparity among the predictions, and between predictions and experimental measurements. The scatter of the simulations is much larger than the error and variability expected in the experiments. The study emphasizes on the inherent difficulty of modelling fire dynamics in complex fire scenarios like Dalmarnock, and shows that the accuracy to predict fire growth (i.e. evolution of the heat released rate) is, in general, poor.

### 42. Reneke P.A., et al. (2001). Comparison of CFAST Predictions to USCG Real-Scale Fire Tests." NISTIR 6446; 16 p. *Journal of Fire Protection Engineering*, Vol. 11, No. 1, pp. 43-68.

The zone model CFAST was used to make predictions of single room pre-flashover tire tests conducted in a steel enclosure. These results were then compared with previously published measurements obtained in fire tests. Tests included diesel pool fires, polyurethane slab fires, and wood crib fires. Half of these tests used natural ventilation (window, 1/4 door, and full door) while the remaining tests used forced ventilation (0.25 m3/s, 0.38 m3/s, and 0.61 m3/s). With the exception of heat release rates, all CFAST inputs were selected without knowledge of the experimental results. Key variables compared include the upper layer temperature, the hot layer interface location, and ceiling temperatures. Overall, predictions made by CFAST were in good agreement with the data. There was a general tendency to over predict both the hot gas layer temperature and the boundary surface temperature that may be due to under prediction of boundary heat losses. Experimental results showed that heat release rates varied with ventilation configurations by as much as a factor of 3. This observation indicates that the wide practice of using free bum heat release rate data in compartment fire predictions can result in over prediction of compartment fire conditions.

### 43. Ritchie S.J., et al. (1997). Effect of Sample Size on the Heat Release Rate of Charring Materials. International Association for Fire Safety Science. Fire Safety Science. Proceedings. Fifth (5th) International Symposium. March 3-7, 1997, Melbourne, Australia, Intl. Assoc. for Fire Safety Science, Boston, MA, Hasemi, Y., Editor, pp. 177-188.

The burning of a horizontal wood slab situated atop an insulating substrate was modeled using three coupled submodels for the gas-phase, wood, and substrate processes. A global analytical model was used to determine the radiative and convective heat feedback from the gas-phase combustion to the wood surface. The char-forming wood model was a one- dimensional numerical computation of the density change as a function of position and time. The backside boundary condition of the wood was treated as conductive heat loss into a substrate material modeled by the heat conduction equation. The condensed-phase model results were tested by exposing Douglas Fir samples to an external flux in a nitrogen environment (no combustion). Heat release rate calculations are compared to experimental results for Douglas Fir samples of 0.1 m and 0.6 m diameter. Both theory and experiments show that, for the conditions studied, the heat release rate is nearly independent of the specimen diameter except for the initial peak and the effect of this peak on the first portion of the quasi-steady settling period. Model predictions also indicate that the second peak, which follows the settling period, is very sensitive to the thickness of the insulating substrate.

### *44. Salley M.H. (2014). Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications. *NUREG-1824 Supplement 1*, U.S. Nuclear Regulatory Commission- Office of Nuclear Regulatory Research (RES).

The authors compared measurements from test fires with predictions provided by different kinds of models. The NRC researchers found deviations of up to 60% between the predictions and the measured results.

### 45. Shanley J.H. Jr. and Kennedy P.M. (1996). Program for the Study of Fire Patterns. NISTIR 5904, *Annual Conference on Fire Research: Book of Abstracts*. National Institute of Standards and Technology, Gaithersburg, MD, pp.149-150.

Fire and arson investigators often rely on fire patterns to determine the origin of fires. Fire patterns are visible manifestations of the heat and smoke produced by the fire which remain on room interior surfaces and furnishings after the fire is extinguished. This program, which was sponsored by the US Fire Administration, included a series of ten full-scale compartment (room) fire tests that were designed to evaluate the fire characteristics of room fires under actual fire conditions and the effect those conditions had on fire pattern formation. Particular inquiry and analysis was made into the unique and distinguishing characteristics of fire patterns on ceilings, walls, and floors caused by accelerated (i.e. arson) versus non-accelerated fires. There is no known or current fire research to evaluate the fire patterns that fire investigators and analysts are commonly using to assess fire origins and fuels. This program set forward a protocol for a series of initial tests that will set a standard of background research that the professional fire investigation community can use to assess the appropriateness of their fire pattern opinions. The production of this program for the study of fire patterns involves the specification of the test room, ignition source, test fire(s), instrumentation, test procedures, safety, observations and data gathering, analysis and reporting of results. The full-scale laboratory testing utilized two baseline runs where the test room was not furnished. Eight pattern analysis tests followed where the test room was furnished. A total of four tests were conducted in the NIST-BFRL full scale fire test facility. The remaining six tests were done in residential structures in Alabama and California.

**46. Stroup D. W. and Madrzykowski D. (1995). Modeling Smoke Flow in Corridors. National Institute of Standards and Technology (NIST) and Society of Fire Protection Engineers (SFPE). *Proceedings of the International Conference on Fire Research and Engineering* (ICFRE). Orlando, FL, SFPE, Boston, MA; Lund, D.P., Angell, E. A., Editor(s), pp. 377-382.**

**47. Sugawa O., Kawagoe K. and Oka Y. (1989). Burning Behavior in a Poorly-Ventilated Compartment Fire--Ghosting Fire. NISTIR 4449; U.S./Japan Government Cooperative Program on Natural Resources (UJNR). Fire Research and Safety. 11th Joint Panel Meeting. Berkeley, CA, Jason, N.H.; Cramer, D.M., Editor(s), pp. 163-172.**

We have investigated fire behavior in a poorly ventilated compartment using a methyl alcohol pool fire as a source in a box of 2m(W) x 3m(L) x 0.6m(H). Temperatures, gas concentrations of CO, CO2 , and O2 fuel consumption rate were measured simultaneously. The level or the fuel surface was kept constant during the tests by means of automatic fuel supply system. The flame began to detach from the fuel surface as the oxygen concentration decreased to about 16 vol.%, it color then becoming pale blue. The flame later detached completely from the fuel and a blue "ghosting flame" was observed just under the ceiling like an aurora. The oxygen concentration measured under the ceiling in the ghosting period under the ceiling was 9 - 10 vol.%, and the CO2 was 4.5 vol.% so that the oxygen acted as an inert gas. The CO2 gas concentration was almost uniform with a gradient in the upper part in the ghosting period. Temperatures in the same layer decreased after ghosting occurred also with a gradient. For these fires, the air exchange rate as 1.6 - 2.4 times/hr was estimated, and the burning rate decreased finally to about 1/6 of that of the fuel controlled fire.

**48. Suuberg E.M., Milosavljevic I. and Lilly W.D. (1994). Behavior of Charring Materials in Simulated Fire Environments. Final Project Report.1990-1992., NIST GCR 94-645; 651 p.**

The focus of this study was the behavior of thick charring solids in fire situations. Clearly one of the most important parameters governing the fire phenomenon is the rate of release of combustible volatiles into the gas phase, in which they actually burn. Over the years, fire researchers have learned how to model the processes in the gas phase, so that the rate of heat feedback to the solid surface can be reasonably well predicted. Likewise, there exists the ability to model the heat transfer processes at the solid surface and within the solid itself. Finally, there is a large literature on the laboratory-scale pyrolysis of various charring polymers. It might appear that predicting the course of the fire would involve carefully coupling these different models together. There have unfortunately not been any successful demonstrations of the ability to do this, though in broad stroke, some models capture the key features of the processes. This study was concerned with the possibility that the inability to come to complete closure on the charring polymer fire problem might derive from difficulties in applying laboratory scale kinetics to actual fire conditions. Specifically, we were concerned about how well small scale laboratory experiments used to derive the kinetics of pyrolysis could be used to predict the behavior of charring solids in fire situations

### 49. Vettori R.L. and Madrzykowski D. (2000). Comparison of FPE Tool: FIRE SIMULATOR with Data From Full Scale Experiments. (1586 K), *NISTIR* 6470; 73 p.

A comparison of the compartment zone fire model FPE Tool: FIRE SIMULATOR is made with data from three different full scale experimental compartment fire studies. These three studies represent a variation of room geometry, ventilation factors, thermal physical properties, fuels, fire geometry, and fire growth. Depending on the experimental data presented, comparisons were made for the following parameters: ceiling jet velocity, ceiling jet temperature, upper layer depth, detector link temperature, time to sprinkler activation, and heat release rate at time of sprinkler activation. Results for predicted sprinkler activation times ranged from 74% to 159% of measured times depending on the RTI chosen for the sprinkler, characteristics of the fire, and fire growth rate. All predicted ceiling jet velocities differed by approximately a factor of two from measured values. Generally, upper layer depth predictions were good only for situations where there was not a large vent from the room. For the full scale experiment conducted in a large room with a high ceiling, predicted link and ceiling jet temperatures had better agreement with measured values if consideration was given to the time required for the transport of the products of combustion from the fire to the link. For experiments which had varying fire growth rates predictions for upper layer temperature increase were better for experiments with the slower fire growth rates.

### 50. Wickstrom U., Duthinh D. and McGrattan K.B. (2007). Adiabatic Surface Temperature for Calculating Heat Transfer to Fire Exposed Structures", Volume 2; Interflam 2007. (Interflam '07). International Interflam Conference, 11th Proceedings. London, England, pp. 943-953.

A basic and common understanding of heat transfer to solids is very important for the advancement of fire safety engineering in areas such as the prediction of the temperature and load bearing capacity of structural components as well as the burning behaviour of real materials. However, because researchers and test standard developers have different ways of expressing and measuring the various forms of convective and radiative heat flux, confusion often arises. This paper is intended to address this issue. The new concept of adiabatic surface temperature is introduced as a practical means to express the thermal exposure of a surface. The concept is particularly useful when calculating temperatures in fire exposed structures, as is shown in this paper. It can be used successfully when the exposure conditions are obtained either from a fire model or directly from measurements. In the latter case, the so called plate thermometer (PT), defined in the fire resistance standards ISO 834 or EN 1363-1, may be employed. This implies that the temperature of structural components tested according to these standards may be predicted using the plate thermometer measurements which are inherently designed to follow specified time- temperature curves.

### *51. Yin Yuen A.C., et al. (2014). Fire Scene Investigation of an Arson Fire Incident Using Computational Fluid Dynamics Based Fire Simulation. *Building Simulation*, Vol. 7, No. 5, pp. 477-487.

Fire simulation using computational fluid dynamics (CFD) techniques was employed to reconstruct the aged-care facility fire incident that occurred in Quakers Hill, Sydney, in Nov 2011. Based on the sentence descriptions by the suspect and witnesses, the fire was intentionally lit on hospital bed sheets in an empty room and eventually spread to the entire building. The main objective of this simulation is to determine the fire origin and to gain insights into the fire development that resulted in three fatalities in the burn room. Preliminary numerical studies were initially performed in the model to investigate possible locations of the fire sources before the mock-up experiment was carried out in an actual size test room facility. The measured and predicted gas temperature from the thermocouple readings compared well, particularly with the peak temperature reaching approximately 900°C. Numerical simulation indicated that fire spread within the room was quickly established due to large amount of combustible materials being present and ample entrainment of air from the surroundings into the room through the window and doorway. This article illustrates the promising application of CFD for building fire modeling and simulation to provide evidences of criminal identification for fire investigation.

## V. Some Aspects of Fire Debris Investigations Appear To Be Measureable (i.e., burn thickness in wood, location of origin, etc.). What literature exists that describes how reproducible these effects are? An example might be a study that burned ten 2x4 boards for 5 minutes, another ten for 7 minutes and another ten for 15 minutes, then documented the results.

****Almirall J.R. and Furton K.G. (2004). Characterization of Background and Pyrolysis Products that may Interfere with the Forensic Analysis of Fire Debris. *Journal of Analytical and Applied Pyrolysis*, Vol. 71, pp. 51-67.**

An important aspect of an investigation of a suspected arson case involves the chemical analysis of the debris remaining after the fire. Forensic chemists apply the tools of analytical chemistry for the extraction, isolation and analysis of the target compounds that characterize ignitable liquid residues (ILR). Complex organic mixtures such as automobile gasoline, diesel fuel and other volatile mixtures that could be used to accelerate an intentionally set fire are routinely identified in forensic laboratories. The presence of these target compounds suggests the presence of ILR originating from these mixtures and this information could aid a fire investigator in determining the cause of the fire, including whether or not arson is suspected. The current study aims to characterize the background and pyrolysis products resulting from controlled burns of materials commonly found in homes and businesses in order to determine their chemical composition. A list of compounds found from the pyrolysis (and combustion) of different substrate types is compared with the target compound list for the identification of ILR. The results show that the burning of some types of commonly found materials creates some of the target compounds commonly found in ILR mixtures. The sources of these compounds are: substrate background products (in the substrate matrix prior to burning), pyrolysis products and, possibly, combustion products.

****Beyler C.L. and Hirschler M.M. (1995). Thermal Decomposition of Polymers in, *SFPE Handbook of Fire Protection Engineering*, 2nd edition, Chapter 7. Quincy, MA: NFPA, pp. 1-110 – 1-131.**

Solid polymeric materials undergo both physical and chemical changes when heat is applied; this will usually result in undesirable changes to the properties of the material. A clear distinction needs to be made between thermal decomposition and thermal degradation. The American Society for Testing and Materials' (ASTM) definitions should provide helpful guidelines. Thermal decomposition is "a process of extensive chemical species change caused by heat."

Thermal degradation is "a process whereby the action of heat or elevated temperature on a material, product, or assembly causes a loss of physical, mechanical, or electrical properties. In terms of fire, the important change is thermal decomposition, whereby the chemical decomposition of a solid material generates gaseous fuel vapors, which can burn above the solid material. In order for the process to be self-sustaining, it is necessary for the burning gases to feed back sufficient heat to the material to continue the production of gaseous fuel vapors or volatiles. As such, the process can be a continuous feedback loop if the material continues burning. In that case, heat transferred to the polymer causes the generation of flammable volatiles; these volatiles react with the oxygen in the air above the polymer to generate heat, and a part of this heat is transferred back to the polymer to continue the process. This chapter is concerned with chemical and physical aspects of thermal decomposition of polymers. The chemical processes are responsible for the generation of flammable volatiles while physical changes, such as melting and charring, can markedly alter the decomposition and burning characteristics of a material.

***52. Bruno T.J., Lovestead T.M. and Huber M.L. (2011). Prediction and Preliminary Standardization of Fire Debris Constituents with the Advanced Distillation Curve Method. *Journal of Forensic Sciences*, Vol. 56, No. S1, pp. S192- S202.**

The recent National Academy of Sciences report on forensic sciences states that the study of fire patterns and debris in arson fires is in need of additional work and eventual standardization. We discuss a recently introduced method that can provide predicted evaporation patterns for ignitable liquids as a function of temperature. The method is a complex fluid analysis protocol, the advanced distillation curve approach, featuring a composition explicit data channel for each distillate fraction (for qualitative, quantitative, and trace analysis), low uncertainty temperature measurements that are thermodynamic state points that can be modeled with an equation of state, consistency with a century of historical data, and an assessment of the energy content of each distillate fraction. We discuss the application of the method to kerosenes and gasolines and outline how expansion of the scope of fluids to other ignitable liquids can benefit the criminalist in the analysis of fire debris for arson.

***53. Bruno T.J. and Allen S. (2013). Weathering Patterns of Ignitable Liquids with the Advanced Distillation Curve Method. *Journal of Research of the National Institute of Standards and Technology,* Vol. 118, pp. 29- 51.**

One can take advantage of the striking similarity of ignitable liquid vaporization (or weathering) patterns and the separation observed during distillation to predict the composition of residual compounds in fire debris. This is done with the advanced distillation curve (ADC) metrology, which separates a complex fluid by distillation into fractions that are sampled, and for which thermodynamically consistent temperatures are measured at atmospheric pressure. The collected sample fractions can be analyzed by any method that is appropriate. Analytical methods we have applied include gas chromatography (with flame ionization, mass spectrometric and sulfur chemiluminescence detection), thin layer chromatography, FTIR, Karl Fischer coulombic titrimetry, refractometry, corrosivity analysis, neutron activation analysis and cold neutron prompt gamma activation analysis. We have applied this method on product streams such as finished fuels (gasoline, diesel fuels, aviation fuels, rocket propellants), crude oils (including a crude oil made from swine manure) and waste oils streams (used automotive and transformer oils). In this paper, we present results on a variety of ignitable liquids that are not commodity fuels, chosen from the Ignitable Liquids Reference Collection (ILRC). These measurements are assembled into a preliminary database. From this selection, we discuss the significance and forensic application of the temperature data grid and the composition explicit data channel of the ADC.

***54. Cacho J.I, et al. (2014). Headspace Sorptive Extraction for the Detection of Combustion Accelerants in Fire Debris. *Forensic Science International*, Vol. 238, pp. 26-32.**

A novel method for separation and identification of ignitable liquid residues in fire debris by gas chromatography and mass spectrometry is presented. Preconcentration of the analytes was carried out using the simple headspace sorptive extraction (HSSE) technique. Polydimethylsiloxane stir bars were used as the enrichment phase, and parameters affecting both the adsorption and desorption stages were carefully optimized. Extraction was carried out at 50 8C for 1 h. Stir bars were desorbed thermally in the GC injection port, thus avoiding the use of organic solvents. The results for five ignitable liquids, including gasoline and diesel fuel, using HSSE were compared with those obtained with a solid-phase microextraction method, with HSSE appearing as a more sensitive alternative.

****Lentini J.J. (1998). Differentiation of Asphalt and Smoke Condensates from Liquid Petroleum Distillates Using GC/MS. *Journal of Forensic Sciences*, Vol. 43, No. 1, pp. 97-113.**

A method of comparing selected ion profiles of fire debris extracts for the purpose of differentiating background residues produced by burning asphalt from liquid petroleum distillates is discussed. Passive headspace concentration (ASTM E 1412) has the capacity to fractionate asphalt condensates, resulting in the production of chromatographic patterns remarkably similar to fuel oils. By examining the alkenes produced when asphalt burns, the smoke condensates can be differentiated from kerosene or diesel fuel.

****Lentini J.J., Dolan J.A. and Cherry C. (2000). The Petroleum-Laced Background. *Journal of Forensic Sciences*, Vol. 45, No. 5, pp. 968-989.**

Using passive headspace concentration (ASTM E-1412) and gas chromatographic/mass spectrometric (GC/MS) analysis as described in ASTM E-1618, the authors have studied the volatile components detectable in several kinds of otherwise uncontaminated substrata, including clothing, shoes, household products, building materials, paper products, cardboard, and adhesives. Due to the use of petroleum-derived liquids in the manufacture of these materials, it is frequently possible to detect the liquids, even when the products are several years old. These results point out the need for the use of comparison samples whenever possible.

****Lentini J.J. (2001). Persistence of Floor Coating Solvents. *Journal of Forensic Sciences*, Vol. 46, No. 6, pp. 1470-1473.**

Using passive headspace concentration as described in ASTM E 1412 and gas chromatographic/mass spectrometric (GC/MS) analysis as described in ASTM E 1618, the author has studied the persistence of solvents in floor coating materials. Both oak and pine flooring boards were tested using stain, stain with polyurethane varnish, and oil finish after a period of ten months and 24 months. The solvents from all three floor-coating substances were easily detectable after 24 months, and showed no signs of diminution when compared with the samples tested earlier. These results point out the need for the submission of comparison samples whenever wood flooring samples are submitted for fire debris analysis in suspected arson cases.

**55. Lentini J.J., CFEI, F-ABC.“The Mythology of Arson Investigation”, available at** http://firescientist.com/Documents/The%20Mythology%20of%20Arson%20Investigation.pdf

“…progress in fire investigation is held back by the burden of an entrenched mythology. Despite the fact that it has been fifteen years since NFPA 921 was first published, some fire investigators still rely on ‘misconceptions’ about the meaning of various fire effects and fire patterns.” This reference explores the development and promulgation of the myths and how they are being weeded out.

****Newman R.T., Dietz W.R. and Lothridge K. (1996). The Use of Activated Charcoal Strips for Fire Debris Extractions by Passive Diffusion. Part 1: The Effects of Time, Temperature, Strip Size, and Sample Concentration. *Journal of Forensic Sciences*, Vol. 41, No. 3, pp. 361-370.**

The introduction of commercially produced activated charcoal strips into fire debris analysis has provided and easy, efficient and cost effective method for accelerant extraction. Several parameters associated with passive diffusion extraction of fire debris using activated charcoal require consideration in order to obtain a truly representative sample of the accelerant. This study investigated the effects of time, temperature, charcoal strip size and sample concentration on the adsorption of common accelerants. Notable displacement of specific volatile components, similar to the breakthrough noted in dynamic systems, occurred under certain extreme conditions. An analysis protocol was developed to minimize these effects.

***56. Nichols J.E., et al. (2014). Analysis of Arson Fire Debris by Low Temperature Dynamic Headspace Adsorption Porous Layer Open Tubular Columns. *Journal of Chromatography A*, Vol. 1334, pp. 126-138.**

In this paper we present results of the application of PLOT-cryoadsorption (PLOT-cryo) to the analysis of ignitable liquids in fire debris. We tested ignitable liquids, broadly divided into fuels and solvents (although the majority of the results presented here were obtained with gasoline and diesel fuel) on three substrates: Douglas fir, oak plywood and Nylon carpet. We determined that PLOT-cryo allows the analyst to distinguish all of the ignitable liquids tested by use of a very rapid sampling protocol, and performs better (more recovered components, higher efficiency, lower elution solvent volumes) than a conventional purge and trap method. We also tested the effect of latency (the time period between applying the ignitable liquid and ignition), and we tested a variety of sampling times and a variety of PLOT capillary lengths. Reliable results can be obtained with sampling time periods as short as 3 min, and on PLOT capillaries as short as 20 cm. The variability of separate samples was also assessed, a study made possible by the high throughput nature of the PLOT-cryo method. We also determined that the method performs better than the conventional carbon strip method that is commonly used in fire debris analysis.

****Putorti Jr. A.D., McElroy J.A. and Madrzykowski D. (2001). Flammable and Combustible Liquid Spill/Burn Patterns. NIJ Report 604-00, NCJ 186634, pp. 1-44.**

Discussions with fire investigators indicate that it would be beneficial to have the ability to predict the quantity of liquid fuel necessary to create a burn pattern of a given size. Full-scale spill and fire experiments were conducted with gasoline and kerosene on vinyl, wood parquet, and carpet covered plywood floors using various quantities of fuel. Spill areas were measured, and for nonporous floors the results were compared to analytical predictions. Burn pattern areas are correlated with the spill areas, resulting in a method for predicting the quantity of spilled fuel required to form a burn pattern of a given size. The heat release rates of the fuel spill fires were determined through experiment and compared to an existing reference for burning liquid pools of the same surface area. The peak spill fire heat release rates for nonporous surfaces were found to be approximately 1/8 to 1/4 of those from equivalent area pool fires. The peak heat release rates for spill fires on carpet were found to be approximately equal to those from equivalent area pool fires. The heat release rates can be used as inputs for fire modeling or for evaluating fire scenarios.

***57. Rankin J.G., Greely D.L. and Sullivan B. (2012). Ignitable Liquid Residue Distribution in Pour Patterns. *International Symposium on Fire Investigation Science and Technology*, pp. 525-534.**

Collection of fire debris evidence from a fire scene most commonly falls on the shoulders of the fire investigator in charge of the scene. The sample is then sent to the lab to be analyzed by a fire debris analyst for the presence of ignitable liquid (IL) residues. For the best chromatographic results the evidence samples must be collected from an area of the pour pattern suspected to contain the highest concentration of IL residue. The question is whether it is best to collect from the center of the burn pattern, the edges of the burn pattern, or somewhere in between. Most texts and manuals to date suggest collecting from the edge of the pattern. One factor to consider is whether the substrate the IL was poured onto has any effect on the prime area to collect the sample from. Carpeting, for example, can wick the IL away from the original pour pattern diluting the IL over a larger area. Some newer synthetic carpets can also self-sustain combustion beyond the edge of the original pour pattern leaving a completely unrelated pattern. Sampling from the edge of this pattern could potentially give negative results. Cut pile carpet with raised or lowered patterns in it may also have an effect on the way in which the IL disperses and burns off. An experiment was designed to test the concentrations of IL residues in different specified areas of pour patterns post burn. A circular pour pattern representing a central dump of IL was tested, as well as a linear pattern representing a trailer. Substrates were allowed to burn to 70% completion and were extinguished with water. Multiple samples were collected at designated areas across the pattern. Any volatile IL residues present were collected by passive headspace analysis on activated charcoal strips and submitted to analysis by gas chromatography mass spectrometry (GC/MS). Total ion chromatograms for each sample were analyzed qualitatively and quantitatively. Ratios of target compounds in the IL to the peak area of the 3-phenyltoluene internal standard were calculated to normalize the chromatographic data to the amount of IL residues present. Full scale test burns have also been performed in two bedrooms of a house. New low pile carpet was laid in each room and contents from the property were added to the rooms to increase the fuel load. Diesel fuel was poured in a large “S” shaped pattern on the floor of each room and ignited. The fires were allowed to progress to flashover before extinguishing. Samples were taken around the ends of the “S” pattern in Room 1 (the larger room) and straight across the entire pattern in Room 2 (the smaller room.) Initially, the results have shown that higher concentrations of IL residues can be found toward the center of the pour patterns compared to the outer edges under these conditions. The residues found near the center are also more similar chromatographically to neat injections of the IL used. This would suggest that, when possible, the center of a pattern would be the best place for fire investigators to sample for the best results. Differences in relative concentration of IL residue due to substrate, actual pour pattern and class of IL will be presented.

### *58. Salgueiro P.A.S., Borges C.M.F. and Bettencourt da Silva R.J.N. (2012). Valid Internal Standard Technique for Arson Detection Based on Gas Chromatography- Mass Spectrometry. *Journal of Chromatography A*, Vol. 1257, pp. 189-194.

The most popular procedures for the detection of residues of accelerants in fire debris are the ones published by the American Society for Testing and Materials (ASTM E1412-07 and E1618-10). The most critical stages of these tests are the conservation of fire debris from the sampling to the laboratory, the extraction of residues of accelerants from the debris to the activated charcoal strips (ACS) and from those to the final solvent, as well as the analysis of sample extract by gas chromatography–mass spectrometry (GC–MS) and the interpretation of the instrumental signal. This work proposes a strategy for checking the quality of the sample conservation, the accelerant residues transference to final solvent and GC–MS analysis, using internal standard additions. It is used internal standards ranging from a highly volatile compound for checking debris conservation to low volatile compound for checking GC–MS repeatability. The developed quality control (QC) parameters are not affected by GC–MS sensitivity variation and, specifically, the GC–MS performance control is not affected by ACS adsorption saturation that may mask test performance deviations. The proposed QC procedure proved to be adequate to check GC–MS repeatability, ACS extraction and sample conservation since: (1) standard additions are affected by negligible uncertainty and (2) observed dispersion of QC parameters are fit for its intended use.

### *59. Sinkov N.A., Sandercock P.M.L. and Harynuk J.J. (2014). Chemometric Classification of Casework Arson Samples Based on Gasoline Content. *Forensic Science International*, Vol. 235, pp. 24-31.

Detection and identification of ignitable liquids (ILs) in arson debris is a critical part of arson investigations. The challenge of this task is due to the complex and unpredictable chemical nature of arson debris, which also contains pyrolysis products from the fire. ILs, most commonly gasoline, are complex chemical mixtures containing hundreds of compounds that will be consumed or otherwise weathered by the fire to varying extents depending on factors such as temperature, air flow, the surface on which IL was placed, etc. While methods such as ASTM E-1618 are effective, data interpretation can be a costly bottleneck in the analytical process for some laboratories. In this study, we address this issue through the application of chemometric tools. Prior to the application of chemometric tools such as PLS-DA and SIMCA, issues of chromatographic alignment and variable selection need to be addressed. Here we use an alignment strategy based on a ladder consisting of perdeuterated n-alkanes. Variable selection and model optimization was automated using a hybrid backward elimination (BE) and forward selection (FS) approach guided by the cluster resolution (CR) metric. In this work, we demonstrate the automated construction, optimization, and application of chemometric tools to casework arson data. The resulting PLS-DA and SIMCA classification models, trained with 165 training set samples, have provided classification of 55 validation set samples based on gasoline content with 100% specificity and sensitivity.

### **Smith R.M. (1982). Arson Analysis by Mass Chromatography. *Analytical Chemistry*, Vol. 54, No. 13, pp. 1399A-1409A.

Ions were chosen to represent major hydrocarbon families normally present in common arson accelerants and included m/z 57 + 71 + 85 + 99 (aliphatics), 55 + 69 + 83 + 97 (alicyclics and olefinics), 91 + 105 + 119 + 133 (alkylbenzenes), 104 + 118 + 132 + 146 (alkystyrenes/ alkyldihydroindenes), 128 + 142 + 156 + 170 (alkylnapthalenes), 178 + 192 + 206 (alkylanthracenes), and 93 + 136 (monoterpenes). Further mass chromatography for individual molecular ions often identified single components. Crude quantitative data were obtained from ion current measurements provided with the mass chromatograms by the data system. The range and pattern of aliphatic compounds, ratio of aliphatics to alicyclics (olefinics), relative concentrations of alkylbenezenes and alkynaphthalenes, and presence or absence of unusual hydrocarbon families were found to distinguish between an assortment of standard accelerants and their evaporated residues.

### ****Stauffer E. (2003). Concept of Pyrolysis for Fire Debris Analysts. *Science & Justice*, Vol. 43, No. 1, pp. 29-40.**

This paper introduces the mechanisms of pyrolysis to fire debris analysts. Pyrolysis products are produced during the combustion of substrates that are submitted to forensic laboratories for ignitable liquid residues recovery. These products, among others, create interferences and complicate the interpretation of chromatograms. Pyrolysis follows certain rules, depending mainly on the substance involved. These mechanisms are presented and illustrated with practical examples of burned substrates analyzed according to ASTM standards. Bond dissociation energies represent an important factor in the route taken by a polymer to produce pyrolysis products. These are presented, as well as the structures of some polymers commonly encountered in fire debris. The understanding of these concepts should improve the interpretation of fire debris chromatograms.

### ***60. Vergeer P., et al. (2014). Likelihood Ratio methods for Forensic Comparison of Evaporated Gasoline Residues. *Science & Justice,* Vol. 54, No. 6, pp. 401-411.**

In the investigation of arson, evidence connecting a suspect to the fire scene may be obtained by comparing the composition of ignitable liquid residues found at the crime scene to ignitable liquids found in possession of the suspect. Interpreting the result of such a comparison is hampered by processes at the crime scene that result in evaporation, matrix interference, and microbial degradation of the ignitable liquid. Most commonly, gasoline is used as a fire accelerant in arson. In the current scientific literature on gasoline comparison, classification studies are reported for unevaporated and evaporated gasoline residues. In these studies the goal is to discriminate between samples of several sources of gasoline, based on a chemical analysis. While in classification studies the focus is on discrimination of gasolines, for forensic purposes a likelihood ratio approach is more relevant. In this work, a first step is made towards the ultimate goal of obtaining numerical values for the strength of evidence for the inference of identity of source in gasoline comparisons. Three likelihood ratio methods are presented for the comparison of evaporated gasoline residues (up to 75% weight loss under laboratory conditions). Two methods based on distance functions and one multivariate method were developed. The performance of the three methods is characterized by rates of misleading evidence, an analysis of the calibration and an information theoretical analysis. The three methods show strong improvement of discrimination as compared with a completely uninformative method. The two distance functions perform better than the multivariate method, in terms of discrimination and rates of misleading evidence.

## VI. What is the literature that describes the types of measurement uncertainty involved with data collection and interpretation for burn pattern analysis and arson investigations? What literature exists that describes error rates for any aspects of fire investigation including burn pattern interpretation error. This includes literature describing statistics about consistency of conclusions among experienced investigators for the same case.

### **61. Babrauskas V. (2000). Heat Release Rate: Precision. Fire Science and Technology, Inc., available at: http://www.doctorfire.com/precision.html**

Discussion of precision and rates of error in determining the heat release rate for various heat release rate test methods. Heat release rates are an important component in understanding the development of fire patterns, fire dynamics, and fire modeling.

**62. Bryant R., et al. (2001). Estimates of the Uncertainty of Radiative Heat Flux Calculated from Total Heat Flux Measurements. Interflam '01, International Fire Science and Engineering Conference, 9th . Proceedings September 17-19, 2001, Edinburgh, Scotland.**

Specific to uncertainty measurement calculations related to heat flux which is a factor in the production of burn patterns.

LINK: http://www.bfrl.nist.gov/866/heatflux/pubs/Bryant_Estimates_of_the_Uncertainty_Interflam_01.pdf

**63. Carman S. "Progressive Burn Pattern Development In Post-Flashover Fires", available at:** http://carmanfireinvestigations.com/Publications_files/Progressive%20Burn%20Pattern%20Development%20in%20Post-Flashover%20Fires.pdf

In 2005, fire investigators from the U.S. Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) designed and presented a seminar on fire dynamics. Two identical, one-room burn cells with standard-sized doorways were each burned for seven minutes. Later, fifty-three experienced fire investigators from the public and private sectors (who had not observed the fires) were asked to briefly examine the cells and identify in which quadrant they thought each fire had started. 5.7% of the students correctly selected the quadrant of origin in each cell.

A subsequent review of experienced investigators' responses to similar, post-flashover exercises at the Federal Law Enforcement Training Center in Georgia revealed that since the early-1990s, about 8-10% of students correctly located the origins of similar fires. Those who were mistaken typically reported they were misled by burn patterns generated in fully involved, ventilation-controlled conditions. In 2008, three follow-up tests fires were designed and conducted in single-room cells (similar to those from 2005) at the ATF Fire Research Laboratory in Ammendale, Maryland. The tests were used to evaluate burn pattern development in fully involved, ventilation-controlled fires with similar physical layouts, furnishings and ignition scenarios. The principle variable between the tests was time of exposure to full fire involvement. Analyses of heat flux, temperature and gas concentration data as well as examination of burn patterns were conducted to better understand the various mechanisms involved. Information from the tests was also used as the basis of a new Internet-based training module on Post- Flashover Fires at the training site, *CFITrainer.net.*

****Madrzykowski D. and Fleischmann C. (2010). Flame Heights and Heat Transfer from Gaseous, Liquid and Solid Fuels for Burn Pattern Repeatability Research. *Proceedings of the 12th International Conference on Fire Science and Engineering*, July 2010, pp. 1-12.**

In 2009, the National Research Council of the National Academies (U.S) published a report identifying the research needs of the forensic science community. In the field of fire investigation, one of the specific needs identified was research on the natural variability of burn patterns. A multi-year study to examine the repeatability of burn patterns has been started. This presentation will provide the results from the initial phase of the study in which fires from three different fuels were characterized. These fires will serve as the source fires for the residential scale, pre-flashover fire pattern repeatability experiments. Experiments were conducted with three different fuels: natural gas, gasoline and polyurethane foam. Replicate experiments were conducted with each of the fuels, in order to examine the repeatability of the fires. Heat release rate, temperatures in the plume, and a heat flux measurement along the centerline of the plume were measured. Flame movement and height was recorded with photographs and videos. Years of fire research have provided many methods, ranging from simple algorithms to computational fluid dynamics models for predicting flame characteristics such as median flame height, plume temperatures, and radiant heat flux. Popular algorithms that have been identified for use in fire investigations or fire hazard analysis have been applied to the three different fuels and the predictions compared with the results of the fire experiments.

****Madrzykowski D. and Fleischmann C. (2011). Fire Pattern Repeatability: A Study in Uncertainty. *Journal of Testing and Evaluation*, Vol. 40, No. 1, pp. 1-11.**

The National Institute of Standards and Technology (NIST) is conducting a multi-year study, with the support of the National Institute of Justice (NIJ) and the NIST Office of Law Enforcement Standards (OLES), to examine the repeatability of fire patterns. The primary objective of the study is assessing the repeatability of fire patterns on gypsum board exposed to a limited range of source fires. The focus of this paper is an overview of the uncertainties of the measurements. The study required the use of a variety of measurements to determine the repeatability of the source fires in terms of heat release rate, temperature, heat flux, and flame height. Replicate source fire experiments were conducted in an oxygen consumption calorimeter in order to examine the repeatability of the fires in terms of the heat release rate. The flame movement and height for each fire were recorded with photographs and videos. The fire pattern experiments were conducted in a three-walled structure with a full floor and partial ceiling constructed from wood framing and lined with painted gypsum board. The source fires were positioned against the rear wall, midway along its length. Replicate experiments were conducted with each fuel. The fire patterns were documented and analyzed for repeatability. The fire pattern height results are then compared to the mean flame height results to examine the level of agreement.

**64. NFPA 921**

**Section 18.4 through Section 18.8** refers to analyzing the data with discussions regarding fire pattern analysis. The entire chapter 1, NFPA 921, Chapter 8 also applies.

**65. Putorti A.D. Jr., McElroy J.A. and Madrzykowski D. (2001). Flammable and Combustible Liquid Spill/Burn Patterns. NIJ Report 604-00; NCJ 186634; 71 pages.**

This report discusses the uncertainties in measurements made during the experiments.

LINK: http://www.crime-scene-investigator.net/flammableliquidspilburnpatterns.pdf

**The following comment applies to all the cited literature and web resources below:**

**Burn patterns would be subjective by the author. Any error rate rests on the investigator's ability to look at the total data surrounding the analysis of any burn patterns. Fire origin determination by pattern analysis is the core competency claimed by fire investigators, yet their ability to correctly determine even a quadrant of origin in a fully involved compartment (room) has been demonstrated to have a shockingly high error rate.**

**66. Website at:** http://www.interfire.org/ "Fire Scene Investigation: The Daubert Challenge by Guy E. Burnette, Jr., Esquire and Fire Investigation Myth Understandings *Examining Long-Held Truths About Fire Dynamics, Physical Indicators of Incendiary Fires, and Fire Investigation Techniques* By Cathleen E. Corbitt-Dipierro

**67. Icove**

**68. Kirk**

**69. NFPA 921**

## VII. What is the literature describing any quality assurance/controls used in the cognitive evaluation of physical evidence at the scene to generate a fire investigator's conclusion.

### 70. NFPA  921

18.4 through Section 18.8, refers to analyzing the data with discussions regarding fire pattern analysis. The entire Chapter 1, NFPA 921, Chapter 8 also applies.

"An investigator should read and understand the concepts of fire effects, fire dynamics, and fire pattern development----. This knowledge is essential in the analysis of a scene to determine the origin of a fire"

### 71. NFPA 921

Chapter 4**,** Basic Methodology

"The systematic approach recommended is that of the scientific method, which is used in the physical sciences."

Chapter 17, Physical Evidence

"The fire investigator should be thoroughly familiar with recommended and accepted methods of processing such evidence."

## VIII. Are there databases available to standardize interpretations of fire patterns/damage at scenes and support fire investigators' conclusions and are they useful?

No literature.

## IX. What literature exists that describes studies on understanding how cognitive bias may affect burn pattern analysis and arson investigations?

****Dror I.E. (2013). Practical Solutions to Cognitive and Human Factor Challenges in Forensic Science. *Forensic Science Policy & Management*, Vol. 4, No. 3-4, pp. 1-9.**

The growing understanding of the central role of human factors and cognition in forensic science has paved the way to develop and implement practical solutions to enhance work in forensic laboratories. Cognitive insights provide relatively simply practical solutions to minimize bias by increasing examiners' independence of mind. These derive from understanding the spectrum of biases—not only those that can arise from knowing irrelevant case information, but also biases that emerge from base rate regularities, working 'backwards' from the suspect to the evidence, and from the working environment itself. Cognitive science's contribution to forensic work goes beyond fighting bias, it suggests ways to enhance examiners' work with technology (distributed cognition), as well as how best to select candidates during recruitment. Taking human cognition into account, such as with a triage approach and case managers, can enhance the quality and effectiveness of the work carried out by forensic examiners. This paper details practical solutions that emerge from a cognitive perspective that understand human expertise and performance. Such cognitively informed approaches should be integrated within forensic work on an ongoing basis.

### *72. Lentini Scientific Protocols

Chapter 9, entitled "Sources of Error in Fire Investigation," is a study of twelve cases where the original investigator made one or more interpretative errors, often due to cognitive bias.

**73. "The Mythology of Arson Investigation", John J. Lentini, CFEI, F-ABC, available at:** http://firescientist.com/Documents/The%20Mythology%20of%20Arson%20Investigation.pdf

## WORKING GROUP QUESTIONS- FIRE SCENE INVESTIGATION

1. How do post-flashover fire conditions influence the reliability of origin and cause determination?
    - A. Can you determine the point of origin for a fire that burned 5 or 10 minutes after the room became fully involved?
    - B. How can you identify when a room has become fully involved?
    - C. Is there a point in time after a room becomes fully involved when it becomes impossible to determine the point of origin?

2. Does training and experience influence the accuracy of the determination?
    - A. Is there research that shows a correlation between education and accuracy?
    - B. Are there sufficient educational and proficiency testing requirements for fire scene investigators?

3. What chemical markers would aid in the determination of origin and cause?
    - A. Do we have the technology to analyze those markers?
    - B. Do we have validated instrumentation to detect different chemical markers?
    - C. Can we use current advanced deterministic fire models (e.g., CFAST, FDS) to improve post-fire analysis?

4. Do we know what information/factors are needed to determine the origin and cause of a fire?

    To what extent is the information we have now sufficient?

5. How does the stage of fire development affect the information that can be inferred from a fire scene investigation?

6. Is there a good estimate of the uncertainty in burn pattern analysis associated with the burning of different materials under a range of realistic fire conditions?

7. Is there a need for additional research and peer-reviewed literature that measures the consistency of conclusions among experienced investigators and the factors that mediate it when presented with the same data?

8. Is there a need to incorporate more exercises with known ground truth for fire scene investigators?

9. Is there scientific research that supports the idea that masking from irrelevant cognitive information would improve the performance of fire investigation teams, and can we generalize what we have learned about cognitive bias from other disciplines?

10. What new data would be of value within the field of fire scene investigation?

    What available databases would be useful in assessing fire pattern determination?

## FIRE DEBRIS ANALYSIS

1. Are the current analytical methods for the examination of fire debris adequate in the determination of ignitable liquid residues?

2. Is there enough research to validate current sample preparation prior to determination?

3. Does the current scientific literature support the use of gas chromatography/mass spectrometry as the principal instrumental method for determination?
    - A. Can improvement in the language of the existing ASTM Test Methods result in better classification of ILRs?
    - B. Can additional research in the chemical characterization of background, combustion, and pyrolysis products improve the classification of ILRs and avoid confusion between ILRs and these products?
    - C. What can further research in weathering effects on ILRs reveal to forensic scientists working to identify ILRs in fire debris?
    - D. Is there a need to improve the sensitivity of the extraction and analysis of ILRs, or should we limit the sensitivity of our analytical protocols to avoid confusing ILRs with background products and combustion/pyrolysis products?
    - E. Is there sufficient research that supports the interpretation criteria currently used in fire debris analysis?

## D. WORKING GROUP

**José Almirall, Ph.D (CHAIR)** - Florida International University
(Chemistry)

**Hal Arkes, Ph.D** - Ohio State University
(Cognitive Psychology/Human Factors)

**John Lentini -** President and Principal Investigator at Scientific Fire Analysis, LLC.
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**Frederick Mowrer**, **Ph.D** - (California Polytechnic State University)
(Fire Protection Engineering / Fire Science)

**Janusz Pawliszyn, Ph.D** - University of Waterloo
(Chemistry)

## E. WORKING GROUP BIOS

### JOSÉ ALMIRALL

Professor José R. Almirall joined the Dept. of Chemistry and Biochemistry at Florida International University as a faculty member in 1998 after working with the Miami-Dade Police Forensic Laboratory for 12 years as a forensic chemist. Professor Almirall and his research group are interested in the development of analytical chemistry methods to better detect and characterize materials of interest to forensic investigators such as drugs, fire debris, explosives and transfer (trace) evidence. He co-edited one book on the topic of Fire Scene Investigation and authored over 120 peer-reviewed scientific publications in the field of analytical and forensic chemistry. He has also co-authored the initial drafts of five ASTM standard methods that are now published and in use. He has mentored over 50 graduate students and post-doctoral fellows in research over the last 17 years. Professor Almirall is a Fellow of the American Academy of Forensic Sciences (AAFS), the founding chairman of the Forensic Science Education Programs Accreditation Commission (FEPAC) of the AAFS, past Chair of the SWGMAT Glass subgroup, was appointed to the Scientific Advisory Committee of the Commonwealth of Virginia by the Governor of that state, and serves on the editorial boards of three journals. He has also served as a consultant to the United Nations Office on Drugs and Crime and to the International Atomic Energy Agency on forensic analysis of materials. He is the current vice-chair of the Scientific Area Committee on Chemistry and Instrumental Analysis for the NIST-sponsored Organization of Scientific Area Committees (OSAC). Dr. Almirall is also a member of the American Chemical Society (ACS), the American Association for the Advancement of Science (AAAS), and was appointed to chair the Fire Scene Investigation Working Group at AAAS.

### HAL ARKES

Hal R. Arkes is an Emeritus Professor of Psychology at Ohio State University. He received his B.A. from Carleton College in 1967 and his Ph.D. in cognitive psychology from the University of Michigan in 1971. He was a faculty member at Ohio University for 28 years and at Ohio State University for 11 years. He was the chair of the Department of Psychology at Ohio University, the interim chair of the Division of Health Services, Management, and Policy and also the Center for Health Outcomes, Policy, and Evaluation Studies at Ohio State University. He has also served as the President of the Society for Judgment and Decision Making and Chair of the Society’s Publication Committee. For four years he served as program co-director at the National Science Foundation for the Program in Decision, Risk, and Management Science. He has also participated in or directed various panels and given presentations to many venues within the United States government including the Department of State, Department of Education, Environmental Protection Agency, the Central Intelligence Agency, the National Academy of Science, the National Institutes of Health, and others. Dr. Arkes’ research interests are in judgment and decision making, particularly economic, legal, and medical decision making. He has co-taught in the Department of Economics and the College of Law at Ohio State University and has won several teaching awards at Ohio University. He has served on the editorial board of every major journal in the domain of judgment and decision making and is currently an associate editor of *Psychological Science*. One of his most productive and appreciated endeavors was serving as a cook in the United States Army where he helped prepare thousands of meals.

## JOHN LENTINI

John Lentini is one of a handful of people certified to conduct both fire scene investigations and fire debris analysis. He has personally conducted more than 2,000 fire scene inspections and has appeared as an expert witness on more than 200 occasions. He is a frequent invited speaker on fire investigation science, and an active proponent of standards for fire and other forensic investigations. He is a member of the NFPA Technical Committee on Fire Investigations (921), the Technical Committee on Fire Investigator Professional Qualifications (1033) and has served three terms as chair of ASTM Committee E30 on Forensic Science. John is the current Chairman of the American Academy of Forensic Sciences (AAFS) Criminalistics Section. He also serves on the NIST/OSAC Subcommittee on Fire and Explosion Investigations. He received the Society of Fire Protection Engineers (SFPE) 2015 "Person of the Year Award" in recognition of his work in moving the fire investigation profession forward and in helping to prevent or reverse miscarriages of justice in arson cases. So far, he has helped ten wrongly convicted citizens win their release from prison. He is now an independent consultant living in the Florida Keys and doing business as Scientific Fire Analysis. His book, ***Scientific Protocols for Fire Investigation,*** now in its second edition, was published by CRC Press in 2013. His website is www.firescientist.com.

## FRED MOWRER

Fred Mowrer is currently the Director of Fire Protection Engineering programs at Cal Poly in San Luis Obispo, CA, where he has helped to develop and establish the graduate program in FPE since 2009. Fred served on the faculty of the Department of Fire Protection Engineering at the University of Maryland for 20+ years before retiring with emeritus status in 2008. Dr. Mowrer received his BS degree in Fire Protection and Safety Engineering from the Illinois Institute of Technology and his MS and PhD degree from the University of California, Berkeley, where he focused on Fire Protection Engineering and Combustion Science. Dr. Mowrer currently serves as Chair of the Technical Steering Committee of the Society of Fire Protection Engineers. He is a Fellow of the Society and served on its Board of Directors from 1995 to 2003, including a term as President of the Society in 2002. He is a Life Member of the National Fire Protection Association and served on the NFPA Fire Test Committee for 10 years. Dr. Mowrer has performed research on a number of topics related to fire investigation. This includes research on the flammability characteristics of materials, the calcination of gypsum wallboard exposed to fire heat fluxes, window breakage induced by fire, and fire modeling. Dr. Mowrer also maintains a consulting practice specializing in fire protection and fire science applications, with a focus on post-fire investigation and analysis. He has been involved in the investigation and analysis of many of the major fires that have occurred in the United States since 1980, including the fires at the MGM Grand Hotel, the Las Vegas Hilton, the Dupont Plaza Hotel, the First Interstate Bank, One Meridian Plaza, the Branch Davidian compound, the World Trade Center, The Station nightclub and the Cook County Administration Building.

## JANUSZ PAWLISZYN

Dr. Pawliszyn is a professor of analytical chemistry at the University of Waterloo, and is a Canada Research Chair, a professorship awarded by Canada Research Chairs Program (CRCP) . Professor Pawliszyn has mentored 45 Ph.D and 64 M.S. students over the last several years. He has authored over 550 scientific publications and a book on Solid Phase Microextraction. His Hirsch Index (H-index) is 84.

The primary focus of Professor Pawliszyn's research program is the design of highly automated and integrated instrumentation for the isolation of analytes from complex matrices and the subsequent separation, identification and determination of these species. His current research is focusing on eliminating organic solvents from the sample preparation step to facilitate on-site monitoring and in-vivo analysis. Several alternative techniques to solvent extraction are investigated including use of coated fibers, packed needles, membranes and supercritical fluids. Dr. Pawliszyn is exploring application of the computational and modeling techniques to enhance performance of sample preparation, chromatographic separations and detection. His major area of interest involves the development and application of imaging detection techniques for microcolumn chromatography, capillary electrophoresis and microchip separation devices. He is a Fellow of Royal Society of Canada and Chemical Institute of Canada, editor of Analytica Chimica Acta, Trends in Analytical Chemistry and a member of the Editorial Board of Journal of Separation Science and Journal of Pharmaceutical Analysis. He has received numerous awards and is presently the Natural Sciences and Engineering Research Council of Canada Industrial Research Chair in New Analytical Methods and Technologies.

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