FORENSIC SCIENCE ASSESSMENTS
A Quality and Gap Analysis

Fire Investigation: A Plain Language Summary

AUTHOR:
Charlie Hanger

WITH AN INTRODUCTION BY:
Deborah Runkle
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ABOUT THE AUTHOR

Charlie Hanger is a writer, editor and consultant who works on a variety of editorial and digital projects. He previously worked as an editor at The New York Times and Time Inc. He has a master’s in journalism from the University of Missouri and a bachelor’s in English from the University of Notre Dame and lives with his wife and two sons in Maplewood, NJ. Learn more at charliehanger.com.
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INTRODUCTION TO THE PROJECT

Valid and reliable forensic science is an essential tool for apprehending suspected criminals and, at trial, helping to determine guilt or innocence. 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.

In 2009, the “science” in forensic science received a bad review from a National Academy of Sciences (NAS) Report, “Strengthening Forensic Science in the United States: A Path Forward.” The report’s most significant conclusion was that much of forensic science as currently practiced has “little systematic research to validate the discipline’s basic premises and techniques.” The AAAS Report goes beyond the NAS effort by pointing to specific areas where practices are supported by sound research and those where they are not.

While not providing the level of review and detail required to set forth an agenda for researchers to follow, the NAS Report did prompt activities in both Congress and the Executive Branch. In 2009, the National Science and Technology Council’s Committee on Science established a Subcommittee on Forensic Science (SoFS), with the charge to develop “practical and timely approaches to enhancing the validity and reliability...in forensic science.” SoFS submitted a report, partly based on the efforts of an Interagency Working Group, that examined the state of the forensic sciences and produced annotated bibliographies for ten forensic fields.

Senator Jay Rockefeller, Chair of the United States Senate Committee on Commerce, Science, and Technology, held three hearings in 2011-13. In the bill introduced by Senator Rockefeller to address the issue, he called for a “national research agenda to improve, expand, and coordinate Federal research in the forensic sciences.” And in 2011, Senator Patrick Leahy introduced the Criminal Justice and Forensic Science Reform Bill, 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.” Neither bill became law.

In 2013, the federal government further demonstrated its concern over the state of forensic science and the implications for the criminal justice system by establishing a Commission on Forensic Science, a joint effort of the Department of Justice and the National Institute of Standards and Technology. At the Commission’s first meeting, Under Secretary of Commerce for Standards and Technology Patrick Gallagher described the Commission’s purpose as helping to “ensure that forensic science is supported by the strongest possible science-based evidence gathering, analysis and measurement.”
AAAS Project

AAAS embarked on a project to build on the previous government and nongovernment activities described above. This has led to an evaluation of fire investigation and the current assumptions that underlie its practices. Where it has a solid footing in scientific and technical research and where it does not is identified. This gap analysis provides a research agenda.

The evaluation was carried out by a Working Group, consisting of a forensic scientist as well as scientists and engineers drawn from academia, who did or did not have any familiarity with forensic science. In its report, the NAS observed that almost all forensic science originated in crime labs, not in academic scientific or technical settings, where research is subjected to rigorous peer review and critiques. For that reason, the report stated that forensic scientists lack a “culture of science.” The academic scientists serving on the AAAS Working Group were individuals trained in research methods and statistical analysis, a background usually lacking in the practitioners of forensic science.

Fire Science

Fire investigation, the subject of this report, has been the target of well-founded skepticism as relatively new investigative assumptions and practices based on a better understanding of building-fire dynamics have replaced older, scientifically invalid practices. However, some of the old and dispelled “myths” persist in the field, and people are still being wrongly convicted based, at least in part, on scientific methods that have not been validated. According to the National Registry of Exonerations, since 1991, 63 individuals convicted of arson have already been exonerated (www.exonerationregistry.org/).

We will never know for sure how many people have been wrongfully convicted based on the aforementioned methods. The report that follows offers a “plain language” overview of research on fire scene investigation and fire debris analysis and highlights the key findings and recommendations of a more technical report. The audience for this report is judges, lawyers for the prosecution and defense, law enforcement officers, policy makers, funding agencies, the general public, and fire investigation practitioners. It also points to future directions that much-needed research should take.
FORENSIC FIRE SCIENCE: AN OVERVIEW

Fire investigations have two distinct stages: fire scene investigation, which focuses on evidence at the location of the fire, and fire debris analysis, which focuses on evidence removed from the location to be analyzed in a laboratory. While fire scene investigation is one of the most challenging and problematic disciplines in all of forensic science, fire debris analysis is one of the most standardized and reliable.¹

Still, both stages have room for improvement. After this general introduction to fire scene investigation and fire debris analysis, you will find a summary of the Working Group’s conclusions and recommendations for these two branches of forensic fire investigation. (For the Working Group Report, click here).

Fire Scene Investigation

Any discussion of fire scene investigation must start with a basic understanding of flashover. This is the moment when the fire gases trapped below the ceiling of a room reach 500-600°C (932-1112°F), so hot that every ignitable surface in a room will burst into flames. At this point, a fire in a room becomes a room on fire, and the investigator’s job becomes exponentially tougher.

When an investigator arrives at the scene, the first question to ask is also the most obvious: Where did the fire start? Before flashover, this question might be the easiest in all of forensic science. Even someone with no training could locate the point of origin.² After flashover, determining a fire’s point of origin is much more challenging. Investigators face extensive destruction and chemical transformation of evidence caused by this complex force of nature. The difficulty of this task is compounded by the fact that many investigators have an inadequate understanding of fire chemistry and physics and continue to rely on methods that have not been validated.

It is no wonder, then, that studies have shown that a fire investigator’s ability to determine the correct origin of a post-flashover fire may be no better than random chance.³,⁴,⁵,⁶ And if an investigator cannot find where the fire started, identifying the cause becomes even less likely.

But these challenges are not insurmountable, and more study of post-flashover fires is warranted. With further research, investigators may someday be able to correctly identify the source and cause of post-flashover fires reliably. Some promising areas of study include test fires to increase knowledge about the reproducibility of post-flashover fire behavior; research on the best methods for training canine units to locate debris for analysis in the laboratory, and assessing their performance after the fact; research that measures investigators’ performance in relation to their training and education, especially as new data from post-flashover fire studies becomes available; and more studies on how best to understand and reduce cognitive and contextual biases in fire investigations.
Such research would greatly strengthen the science of fire scene investigation and, when incorporated into the field, might someday greatly improve investigators’ ability to locate a fire’s point of origin with accuracy. When this location can be correctly identified, the chances of determining the cause of a fire, and whether it was intentionally set, will improve substantially.

Fire Debris Analysis

Once an investigator has identified a potential point of origin, fire debris samples are taken from the scene and sent to a forensic science laboratory for analysis. Before the scientists in the lab can begin their work, however, it is crucial that their colleagues in the field gather the proper samples, package them adequately and transmit them securely, and that everyone involved assures the proper chain of custody.

Once these samples reach the laboratory, fire debris analysis primarily focuses on ignitable liquid residues (ILRs) and aims to identify any potential accelerants. While solids (such as paper) and gases may be used to accelerate a fire, ILR analysis is always restricted to liquids and their residues. The laboratory process involves sample preparation (usually an extraction of the liquid-residue mixture), a separation technique (usually gas chromatography), compound identification (typically mass spectrometry), and interpretation of the data.\textsuperscript{7,8}

The ultimate goal of a fire debris examiner is to determine whether ILRs are present in the debris submitted to the laboratory and, if so, identify the chemical nature of those ILRs. This examination must take into consideration thousands of formulations of ignitable liquid products as well as other chemical mixtures that may be “innocently” present in fire debris. These “innocent” chemical mixtures can be derived from the burning of materials during the fire and can be mistaken for ILRs.

Analytical chemists must be familiar with the wide variety and changing nature of these ILRs and must be able to differentiate combustion and pyrolysis products – chemicals that are created in fires – from ILRs. This is a difficult feat that is not easily mastered.

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 both the knowledge base and in practice.
FIRE SCENE INVESTIGATION: CONCLUSIONS

We still have a lot to learn about the forensic science of fire scene investigation, and a lot to unlearn. These conclusions reached by the Working Group are followed by 16 recommendations to strengthen the field.

Fire Behavior and Evidence at the Scene

Traditionally, fire scene investigators have relied on burn-pattern analysis to locate a fire’s origin. In simplest terms, they looked for the deepest burns to find the likely starting point. If no obvious accidental cause was found near these burns, then the fire was often deemed to have been intentionally set. An arson investigation would follow.

This investigative technique, while still adequate for fires that have not reached flashover, must be modified for post-flashover or “fully involved” fires. Studies have shown that fires burning for even a few minutes beyond flashover produce burn patterns capable of causing erroneous conclusions in determining the origin of a fire in excess of 75%. In one study, only 13 of 53 investigators were able to correctly identify the quadrant of origin in a fire that burned for three minutes beyond flashover. These results are cause for concern.

Tracing a post-flashover fire to its point of origin is possible, but it requires an advanced understanding of the science of fire. The moment a room becomes fully involved, every ignitable surface catches fire, and all the oxygen in the room is quickly consumed. At this point, the deepest burns may occur wherever there are ventilation paths into the room – a door, vent or window where oxygen fed the fire – and not necessarily at the point of origin. In addition to the potentially misleading burn patterns caused by ventilation, the evidence found after fully involved fires will vary because of structural differences, fuel loads, ignition circumstances, airflow, and a host of other variables.

That is just the start of what makes post-flashover fire investigation so difficult. The longer a fire burns after becoming fully involved, the more evidence is destroyed. To compound the loss of evidence, the destruction can lead to the creation of chemicals that were not present at the scene before the fire. Because of this destruction and creation, the only chemical markers investigators can consider are ILRs.

While all this is known about the behavior of post-flashover fires, there is still much we do not know. What is the best methodology for determining the origin of a post-flashover fire? How do we estimate the statistical uncertainty of burn-pattern analysis? What can we do to learn more about the reproducibility of fire behavior? Answering questions like these should be a priority for the field.
**Fire Models**

Computer-based fire models are currently used as a tool for testing different hypotheses about the origin and development of a fire, but they should not be used alone to determine the cause of a fire.\(^{11}\) Uncertainties exist concerning the use of these fire models when they are applied to fire cause determination.

**Problematic Literature, Mistaken Beliefs**

Fire investigation is notable for the amount of widespread, persistent, and problematic literature affecting the beliefs and the behavior of practitioners.\(^ {12}\) While the situation has continued to improve since the National Fire Protection Association (NFPA) *Guide for Fire and Explosion Investigations* was first published in 1992, mistaken beliefs caused in large part by the problematic literature continue to hamper fire origin and cause determinations. As long ago as 1977, a survey pointed out that “burn indicators” had received little or no scientific testing. This survey led researchers to pursue “a program of carefully planned scientific experiments” and the creation of a handbook “for field use by arson investigators.”\(^ {13}\)

Three years later, the recommended experiments had not been conducted, but the United States National Bureau of Standards (NBS), (renamed the National Institute of Standards and Technology (NIST) in 1988), published a fire investigation handbook anyway. In the first chapter, the NBS handbook repeated most of the mistaken beliefs about burn indicators that had prevailed for years.\(^ {14}\) Given the imprimatur of such an esteemed organization, some fire investigators continued to rely on these mistaken assumptions along with other questionable techniques.

The most important knowledge, which was often used to distinguish between arson and accidental fires in the past, can be briefly summarized as follows:

- In post-flashover fires, artifacts once thought to indicate an incendiary fire have been proven to be of little value when considered alone. In other words, the evidence left behind by fully involved accidental fires is often indistinguishable from the evidence left behind by fully involved incendiary fires.\(^ {15}\)
- For years, a fire that spread quickly was often assumed to have been intentionally set, but this has been rendered false when modern furnishings, which burn much more quickly than older furnishings, are taken into account.\(^ {16}\) For example, experiments have shown that rooms containing upholstered furniture with polyurethane or polyester fiberfill cushions can become fully involved in less than five minutes.

**Canines and Technology**

When it comes to locating samples at the scene of a fire, dogs are a fire investigator’s best friend. A well-trained canine detection team is the current gold standard for finding materials that have a likelihood of testing positive for ILRs in the laboratory.\(^ {17}\) Canines are advantageous
compared to existing field tools because they provide instantaneous feedback and can search a large space in a very short time.

This is not to say that canine units are infallible or without room for improvement. Additional training aids and methods of measuring canine performance could also enhance their effectiveness.\textsuperscript{18} While the electronic “noses” (hydrocarbon detectors) available today cannot match canine performance, the development of new detection devices and methods could pay dividends. Technologies that could surpass canine units include solid phase microextraction (SPME); field-based mass spectrometers and ILR analysis that allows for rapid feedback to investigators; and more sensitive electronic noses that can generalize the broad spectrum of potential ILRs.

\textit{Bias and Separation of Duties}

Research on performance of forensic examiners has led to quantitative measures of their reliability and susceptibility to bias, and has demonstrated the biasing impact of irrelevant cognitive information.\textsuperscript{19} It is reasonable to conclude that bias also affects fire investigators to at least the same degree. Many fire investigators receive little or no cognitive education as part of their basic training or subsequent professional development.

Clearly, 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.\textsuperscript{20} This is to keep the former as neutral as possible in order to reduce cognitive contamination of conclusions.

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.”\textsuperscript{21} These procedures aim to keep the forensic examiner as bias-free as possible.

\textit{Education, Certification, and Experience}

Fire scene investigators are subject to very little proficiency testing, and the field’s requirements call for no more than a high school education. Further, there is no scientific basis for concluding that the accuracy of certified fire investigators, in particular, is better than the accuracy of non-certified fire investigators. The reliability (consistency) and validity (accuracy) of trained fire investigators’ conclusions have not been scientifically established.
RECOMMENDATIONS TO IMPROVE THE SCIENCE OF FIRE SCENE INVESTIGATION

1. To improve the analysis of a fire’s origin and cause, tests should be run in both reduced and full scale, with multiple compartments and multiple openings, with the aftermath fully documented; 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 computer-based 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.

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 canines should be a research priority.

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 the 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 be established, but research should also be done on the validity of those conclusions. The use of “test fires” (described in recommendation 1 above) 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 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.
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.

10. Case management interventions should be adopted that shield fire scene investigators from information that is irrelevant and potentially biasing. These investigators should only consider scientific evidence that is critical to determining a fire’s 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.

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.
FIRE DEBRIS ANALYSIS: CONCLUSIONS

The following conclusions reached by the Working Group are followed by nine recommendations to strengthen the field.

Forensic scientists rely on several standard methods established by the American Society for Testing and Materials (ASTM) to detect, extract, analyze, and interpret ILRs. These methods are generally, but not uniformly, used by the forensic science community. This standardization is a positive step in the field, but each case is different, so flexibility in deciding which standard methods to apply is warranted.

While these methods are effective, the chemical evidence found at the scene of a fire can still be confusing and misleading. The difficulty of interpreting these data cannot be overstated. The composition of fuels and other consumer products is constantly changing, so scientists must be vigilant in monitoring potential sources of ILRs. For example, “environmentally friendly” fuels such as biodiesel and plant-based lamp oils, must be accounted for in detection and analysis.

Fires can also produce chemicals that are hard to distinguish from ILRs. Pyrolysis (burning without oxygen) and combustion (burning with oxygen) can cause innocuous objects to produce chemicals that resemble ILRs. For example, burning vinyl produces aromatic compounds that are indistinguishable from the aromatic compounds found in petroleum products.

Fire debris can also contain “background” products that can be mistaken for ILRs. These background products are volatile organic compounds (VOCs) commonly found in home and office furnishings. Examples include solvents that are byproducts of the manufacturing process. Studies have shown that there is a risk of false positives – calling something an ILR when it is not – when pyrolysis, combustion, and background products are confused with ILRs.22,23,24,25

It is clear, then, that the forensic science community should strive to continually improve the interpretation of chemical data derived from fire debris. Although the existing standards are more than adequate for the vast majority of forensic casework, they can still be improved.

There is also a risk of missing ILRs because of weathering, such as exposure to extreme heat or dousing with water by firefighters.26 The degree to which false negatives can be attributed to weathering is not known. Biological degradation of samples can also play a significant role in the loss of chemical data, and is typically associated with soil samples. There are various other conditions, parameters and sample types that might exhibit sample degradation. Finally, there is debate in the field on whether to limit the sensitivity of the standard test methods to avoid false positives (incorrect claims of an incendiary cause for a fire). Some argue that the most sensitive tests are more likely to result in the confusion of background, combustion and pyrolysis products with ILRs.
RECOMMENDATIONS TO IMPROVE THE SCIENCE OF FIRE DEBRIS ANALYSIS

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.

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. Inter-laboratory 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.

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 is also needed to determine the background levels of ILRs present in substrates encountered everywhere.
REFERENCES


APPENDICES

A. Working Group Roster

B. Project Advisory Committee Roster
A. 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. (Forensic Science) CFI, D-ABC

Frederick Mowrer, Ph.D - (California Polytechnic State University) (Fire Protection Engineering / Fire Science)

Janusz Pawliszyn, Ph.D - University of Waterloo (Chemistry)
B. PROJECT ADVISORY COMMITTEE

Martha Bashford, JD  
Chief, Sex Crimes Unit  
New York County District Attorney

Shari Seidman Diamond, JD, Ph.D  
Professor of Law and Psychology  
Northwestern University School of Law  
Research Professor, American Bar Foundation

Itiel Dror, Ph.D  
University College of London & Cognitive Consultants International Ltd.

Jules Epstein, JD  
Professor of Law  
Widener University School of Law

Barbara Hervey, JD  
Judge, Texas Court of Criminal Appeals

Gilbert S. Omenn, MD, Ph.D  
Director, Center for Computational Medicine and Bioinformatics  
University of Michigan

Hal Stern, Ph.D  
Professor of Statistics  
University of California, Irvine