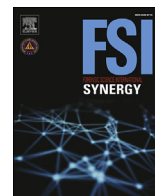




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Interpol review of fire investigation 2016–2019

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ABSTRACT

This review paper covers the forensic-relevant literature in fire analysis and investigation sciences from 2016 to 2019 as a part of the 19th Interpol International Forensic Science Managers Symposium. The review papers are also available at the Interpol website at: <https://www.interpol.int/content/download/14458/file/Interpol%20Review%20Papers%202019.pdf>.

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1. Introduction

This review covers studies related to fire investigation published since the 18th International Forensic Science Managers Symposium in 2016. The literature includes main forensic and fire-related journals and books from June 2016 onward to complete Stauffer's [1] previous review.

Fire investigation is a complex field of forensic sciences as it includes examinations of both the scene as a major component and the laboratory as a minor component. Paradoxically, the number of scientific articles is much greater for the laboratory than the scene.

The complexity of fire investigation also arises from the fact that fire investigators conduct scene examination, and they may not have a formal scientific education even though they apply the scientific method. Conversely, forensic scientists conduct laboratory examinations, and they do not have strong experience in fire scene investigation, but often have a formal background in chemistry.

The literature reflects this dichotomy, as fire scene investigators publish very little in specific journals, although (forensic) scientists saturate the literature with articles on laboratory aspects of fire investigation in non-specific journals. As such, there are only a few publications covering the entire field of fire investigation, from scene to laboratory.

One reference publication that has been guiding fire investigation since 1992 is the NFPA 921 Guide for fire and explosion

investigations. This guide was updated in 2017 [2]. The National Fire Protection Association (NFPA) also published the fifth edition of the study guide for the previously cited documents and for the NFPA 1033 Standard for Professional Qualifications for Fire Investigator, a document detailing the training and qualifications necessary for a fire investigator [3]. Lebera published a very generic book on fire investigation in French, heavily referencing NFPA 921 [4].

Icove and Haynes issued the eighth edition of the reference textbook in fire investigation, Kirk's fire investigation [5]. Lentini issued the third edition of his textbook Scientific protocols for fire investigation [6].

Notably, despite every effort to search for recent literature since the previous Interpol review, a 20% decrease of the number of references was obtained. This may be a sign of saturation in the research fields of fire investigation, notably in the laboratory aspect of investigation.

2. Phenomenon of fire

The study of fire as a phenomenon is crucial to fire investigation. A research topic usually led more by fire engineers or chemists than fire investigators, the results are often valuable to better understanding the combustion properties of materials, their ignition, and fire behavior under different conditions.

As such, this body of literature is a capital asset to the betterment of fire investigation. This chapter has been divided into three sections: combustion studies, fire behavior, and ignition studies,

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with the caveat that a study may extend beyond a single topic.

2.1. Combustion studies

With the development of plant or animal-based natural fibers used in building materials and clothing, Galaska et al. studied their heat release rate [7]. After dividing the fibers into two groups, cellulosic and animal, they used microcombustion calorimetry and found notable differences from a heat release perspective in fiber types from each group. The differences arise from a mix of chemical and physical structural differences, including natural impurities or treatment during processing. Processing treatment, in particular, showed some dramatic effects on the heat release rate.

Hirschler provided a comprehensive up-to-date review of the fire properties of poly (vinyl chloride) or PVC [8]. With more than 50 references, he covered ignitability, ease of extinction (oxygen index), flame spread, heat release, toxicity, and performance in real-scale fires. By comparing some the data with other materials found in a house, he demonstrated that PVC exhibits one of the lowest heat release rate values.

Filkov et al. characterized firebrand production under experimental fires over three year's time [9]. They collected firebrands in three different spots and analyzed them for mass and size distribution. Also, using thermal imagery, they measured velocity, size, and number of fire brands over two year's time. As a result, they found that more than 70% of collected particles were bark fragments. Particles mass ranged from 5 to 50 mg with a maximum found between 10 and 20 mg. Among other parameters studied, the authors found an average firebrand velocity of 2.5 m/s, depending on the wind velocity.

Eftekharian et al. studied the interaction between fire and crosswind flow [10]. They concluded that fire with a higher heat release rate would cause a greater pressure gradient and a lower density. In turn, this would culminate in higher flow acceleration and an increase of wind enhancement.

Fernandez-Pello reviewed the most recent developments in wildland fire spot ignition by sparks and firebrands [11]. The author retraces the processes from particle generation to particle transport, then to fuel bed ignition.

2.2. Fire behavior

The 2017 Grenfell Tower fire in England, with a death toll of 72 people, was a fire that highly affected the fire protection community. Accordingly, there has been a clear emphasis in façade combustion-related publications since 2017.

McKenna et al. wrote a comprehensive paper explaining the fatal June 14, 2017 event [12]. The authors conducted micro- and bench-scale tests on different types of façades to explain the speed, ferocity, and lethality of the fire. They discovered that the polyethylene-aluminum composite panels exhibited a heat release rate 55 times superior to that of the least flammable panels, and a 70-fold total heat release. They concluded that if the data provided in their paper would have been readily available, it could have led to prohibition of combustible materials applied to the outside of tall buildings.

In the light of Frankfurt Fire Department's findings, Hofmann et al. evaluated DIN test 4102–20, used to approve external thermal insulation composition (ETIC) with polystyrene foam insulation [13]. About three quarters of the façade fires started outside the building, with about half from waste containers close to the ETIC. Although the DIN test uses a downscale fire, the authors used a 200 kg wood crib to reflect reality. They discovered that the ETICs showed significant differences in fire spread when exposed to a larger fire than the DIN test calls for. As such, the authors

recommended a larger scale test to validate ETIC and other protection measures.

Wang et al. also investigated glass façades to determine their thermal breakage and influence on fire spread [14]. The authors subjected 10 different single-coated, insulated and laminated glazings to fire and observed their breakage time, glass surface and air temperature, incident heat flux, crack initiation, and propagation. They concluded that insulated and laminated glass can survive longer than single glass. Laminated glass held together after breakage, thus avoiding a new vent.

Asimakopoulou et al. investigated externally venting flames (EVF) and their influences on fire spread on the exposed façade [15]. Using medium- and large-scale compartment-façade fire tests, they found that the proposed norm EN1991-1-2 underestimates the EVF centerline temperature.

Full-scale composite floors were subjected to ISO standard fires in order to study their thermal and mechanical behaviors. Li et al. used four composite slabs with different configurations of secondary beams and reinforcement [16]. They discovered that the highest temperatures of reinforcement and steel deck occurred during the cooling phase. Also, the location of the reinforcement significantly influenced its temperature. They also observed deflection and torsion in some situations.

Hidalgo et al. conducted a series of twelve full-scale open floor plan enclosure fires [17]. Their goal was to determine the energy spread throughout the volume. Their results showed a reasonably uniform dynamic and, as such, the fire compartment characteristics can be represented two-dimensionally by considering a plane perpendicular to the openings.

Lattimer and McKinnon published a comprehensive literature review of fire growth and fully developed fires in railcars [18]. This study includes the standards and requirements used to regulate interior finish materials, research on railcar interior flammability, and the potential heat release rate of railcars. The authors recommended further research on fire in railcars.

Liu et al. investigated temperature distribution and maximum temperature rise of a closed utility tunnel [19]. The authors concluded that the vertical temperature distribution was stratified and symmetrical in the transverse direction. They also observed that Li's formula did not apply to predict ceiling temperature, because it does not consider the temperature of the smoke in closed space. They proposed a modified formula.

Tao et al. investigated the flame height and air entrainment rate of ring pool fire [20]. For their experiments, they used ring pool fires ranging from 15 to 55 cm. They concluded that with ethanol, the flame height changed slightly according to the diameter, while with n-heptane the increase was obvious. They developed a new correlation.

Tschirschwitz et al. conducted a series of destructive tests to study the behavior of mobile gas cylinders exposed to fire [21]. The tanks were filled with 11 kg of liquid propane, and three different fire sources were used to simulate different heat release rates. The pressure release valve was removed on all tanks to ensure failure. All cylinders failed in under 155 s, which led to a fragmentation of several major parts thrown at a maximum distance of 262 m. They performed high-velocity recordings of the failures along with cylinder surface measurements of pressure waves and temperature.

Hadden et al. studied the effects of exposed cross-laminated timber on compartment fire dynamics using three different configurations [22]. They discovered that two mechanisms would prevent self-extinguishment. First, char fall-off exposes fresh timber to high heat flux and will allow rapid pyrolysis and an increased heat release rate. Second, pyrolysis rate is sufficiently high, due to a heat flux maintained by radiative exchange between the linings, and sustains flaming fire.

Himoto et al. ran a large-scale experiment on fire spread within a group of model houses [23]. The houses were built at 1/3 scale with a square footprint of 3.6 m × 3.6 m, separated by distances ranging from 0.45 m to 0.75 m. The first test, using a flame height of 7.8 m, did not spread the fire to the other houses, while the second test, using an 11 m flame height, spread the fire to 15 of the 18 houses. The authors explained that fire spread depends on the average mass loss rate and the maximum flame height.

Chen et al. studied the fire propagation of a package of multiple lithium-ion batteries (LIB) [24]. They conducted different experiments measuring temperatures, pressure, and analyses of the gas released. They concluded that once one battery in the package catches fire, thermal runaway is unavoidable to the rest of the batteries.

Also using LIB, Ouyang et al. studied their behavior under overcharging [25]. For their experiments, they used nickel-manganese-cobalt oxide and lithium-iron phosphate batteries with different cut-off voltages. They measured surface and flame temperatures, voltage and radiative heat flux. They observed that an overcharged LIB fails at the same temperature as a regularly charged LIB, but it will undergo a more violent combustion process and is less stable.

2.3. Ignition studies

Held and Brönnimann studied battery failure through an internal cell short circuit and its effect on the battery system and the vehicle [26]. The authors used failure mode and effects analysis as well as fault-tree analysis to design and analyze experiments on the battery system level. Among other conclusions, they demonstrated that the use of lithium-iron-phosphate cells, which are deemed safe cells, did not imply a safe battery.

Babrauskas presented a critical review on arc mapping, a method for graphically documenting a fire pattern based on arc marks on the wiring of a structure, to identify the fire's origin [27]. In his comprehensive paper, citing 58 sources, he explains that valid conditions allowing for arc mapping are encountered in less than 1% of building wiring circuits. He reminds the reader that intensity patterns created by arc mapping are influenced by three variables: fuel loading, ventilation, and burn duration. Only burn duration could be correlated to fire origin. His conclusion emphasized that this method should not be used unless very specific conditions demonstrating reliability are met.

Novak et al. studied the failure of a pinched cord under various current loads and pressures as well as the failure of a cable with an overdriven staple [28]. After 200 tests, the authors determined that the failure rate of a pinched cord was approximately 1% under an overload circuit and preexisting damage. They also emphasized that it may take years to occur under normal conditions, and that creating a failure in a relatively short time would be difficult in the absence of extreme conditions.

Babrauskas studied the standards applied to gas-fired space heaters in North America in regards to clothing textiles ignition [29]. He concluded that the American National Standards Institute (ANSI) standards contain inadequate provisions for testing space heaters in regards to clothing ignition potential. As a result, some space heaters that passed that standard can ignite clothing in less than 1 s. In addition, some manufacturers fail to conduct meaningful testing, often considering that providing a product warning is sufficient for public use. Babrauskas used three different models and was able to ignite terrycloth in less than 30 s with two of them. The third model did not permit terrycloth ignition, showing that safe design for that textile exists.

Beasley et al. examined the causes and consequences of refrigerator and freezer fires in residential houses and the evidence

collected by the fire investigator [30]. They observed that fires started by refrigerator and freezer failures are more likely to spread beyond the appliance and the room of origin than other appliances, such as dishwashers or washing machines. Finally, they identified a number of fire causes, such as starter relay failure, PTC switch failure, mechanical defrost switch failure, capacitor failure, solenoid valve failure, and cut-out switch failure.

Plathner and van Hees studied four different means to improve the precision of ignition detection in a cone calorimeter: visual observation, light sensor, peak of the first and second derivatives of the mass loss, and heat release curves [31]. They determined that a light sensor performs well unless surrounding light changes during the test. Results demonstrated that operator-independent method is most suitable with standardized tests.

Larsson et al. assessed the self-heating propensity of 31 different biomass pellet batches by isothermal calorimetry [32]. The authors investigated the influence of pellet composition on its self-heating potential and heat release rate. They found significant differences among different batches of pellets. For highly reactive pellets, maximum HRR ranged from 0.61 to 1.06 mW/g, while for low or non-reactive pellets, HRR reached 0.05–0.18 mW/g. Presence of antioxidants bore a significant influence. Also, pine/spruce mix pellets were significantly more reactive than all other pellet types.

3. Fire scene examination

3.1. Origin determination

The study of fire patterns is at the base of the origin determination of a fire. In the last three years, only one article seems to have been published on this topic. Campaneli and Avato conducted some experiments to determine whether a small fuel package, such as a paper bin, could reliably produce a fire pattern that would persist after flashover [33]. They showed that such a pattern could clearly survive post-flashover conditions. Other fuel packages of similar size and configuration placed away from the origin did not produce such a pattern. The authors also warned that ventilation flow path damage can also produce similar patterns, and, thus, interpretation should include knowledge of the intake vent and fluid flow during fire.

Madrzykowski and Weinschenk conducted a massive series of experiments on the impact of fixed ventilation on fire damage patterns in full-scale structures [34]. More precisely, their goal was to examine how differences in ventilation in structure fire would influence on the resulting fire damages and patterns. They concluded that increasing the ventilation would result in additional burn time, fire growth, and a larger area of fire damage. Also, when considering ventilation during the investigation, the fire patterns were consistent with the area of origin. Finally, they observed that pre-flashover-generated fire patterns persisted post-flashover if the ventilation points were remote to the area of origin.

Maynard et al. expressed their opinions on Carman's well-known publications from 2008: *Improving the understanding of post-flashover fire behavior* and *Progressive burn pattern development in post-flashover fires* [35]. They claim that Carman's work was not intended to be a test for fire investigators' accuracy or error rate, despite some practitioners using it as such in court and in training. They remind readers that Carman's work was designed to illustrate the challenges of examining fire patterns in post-flashover fire scenes and not to conduct a thorough and systematic determination of origin. Moreover, Carman's work did not describe a scientific study, but a demonstration made during a training exercise. Finally, the authors insisted on the fact that the results of Carman's work do not represent an error rate for origin determination in fire

investigation.

As a rebuttal, Beyler et al. exposed a different view on Carman's work value [36]. Among other arguments, they reminded readers that Carman's work is valid and simply demonstrated that if a room is fully involved, investigators should not narrow the origin to less than the whole room based on visual observation alone. They also stated that NFPA 921 includes that reasoning since 2008.

Phelan promoted using a drone to obtain aerial photographs of the scene [37]. His article offers an introduction to drone use, rather than scientific studies demonstrating the extra value of such use.

Finally, Jones and Toth presented wet and dry vacuum systems use as a supplemental technique for sifting through debris layer by layer [38].

3.2. Cause analysis

Novak et al. studied the propensity for the formation of arc melting in receptacles as a result of fire impingement, as well as the failure of receptacles with no attached load [39]. For the first part of the study, two series of tests were conducted on thermoset and thermoplastic receptacles and GFCI receptacles with and without loads. They found that arc melting can occur from fire impingement, particularly on unloaded receptacles. When a load is attached to the receptacle, arcing will preferentially occur on the more exposed power cord. In their second experiment, more than 500 receptacles were subjected to water mist (contaminated by table salt) three times a week for several months. The first failure occurred after six months, which tripped the breaker. Unless furniture or some easily ignitable material is pushed against the receptacle, the authors indicated that it is unlikely that the sparks would retain sufficient energy to ignite the receptacle. Finally, they concluded that the presence of arc melting should not trigger immediate concern, because it may have a perfectly logical explanation.

Sesniak published a paper on the visible effects of high resistance heating on receptacle terminals and their persistence in a post-flashover environment [40]. In a preliminary experiment, he created glowing connections on multiple electrical receptacles placed in different locations in a compartment fire. He found that the general characteristics of a pre-fire glowing connection (e.g., darker color of the terminal, rougher surface due to oxidation and corrosion, and radial pattern around the terminal screw hole) will generally be visually apparent post-fire.

Iwashita et al. reported the characterization of arc beads on energized conductors exposed to radiant heat [41]. More precisely, the authors conducted experiments on the differences in the bead formation between a physical short (i.e., allowing the current flow through metal-to-metal contact) and an arcing short (i.e., current flow through charred insulation). They used Japanese and US wires of different compositions and exposed them to radiant heat flux of 35, 45, and 55 kW/m² either until a short occurred or for 20 min. They observed different results: Although the Japanese wire resulted mostly in a physical short, the older US wire mostly resulted in arcing shorts. They also concluded that larger beads tend to occur more with physical shorts than arcing shorts.

Wagner produced a general review on dryer appliance fires to assist fire investigators [42]. It consists in a guide for the investigator to examine the scene and the appliance. It provides some tips and a checklist.

3.3. Case reports

Xie et al. reported a case for which three aluminum wires with different melted marks were found inside a burned distribution board [43]. They conducted a series of analyzes on the wires,

including visual and microstructure/metallographic, chemical composition of the bead surface, and evaluation of the state of the polymeric insulation. As a result, they were able to determine which circuit was originally involved.

Lee reported a car fire case for which the overheating a diesel filter was the cause [44]. He also reported two other car fire cases for which the lithium battery caught fire [45]. He proposed a technique for determining whether the lithium battery is the cause of the fire or was subsequently damaged by the fire.

3.4. Ignitable liquid residues detection

Fire investigators perform detection of ignitable liquid residues (ILR) at a fire scene before sampling. To this effect, there are different techniques that can be used.

De Araujo et al. published a comprehensive review of portable analytical platforms for forensic chemistry, citing the use of portable GC-MS for analyzing ILR [46]. Burlachenko et al. wrote a comprehensive review of the sample handling technology for an electronic nose [47].

Lam et al. evaluated the use of a portable GC-MS, a Torion T-9 from Perkin-Elmer [48]. They collected air samples using an active air sampling needle trap device for 2 min, and analyzed them in about 4 min. They also analyzed water samples from the extinguishment using SPME in both headspace and direct immersion modes for 10 min each. The authors concluded that the technique was useful for providing advice at the fire scene and orienting the investigation.

More originally, Leitch et al. reported the use of *Drosophila melanogaster* olfactory receptors [49]. In their initial investigation, they subjected the flies to three distinct odor spaces (i.e., ILR, human decomposition, and living human scent) representing 24 individual compounds. These new odors elicited receptor responses. Also, they identified individual olfactory receptors sensitive to aromatic compounds found in ILR.

Ljungkvist and Thomsen assessed the use of ultraviolet light based on 25 years of research, 11 fire investigations, and approximately 1'000 experiments [50]. They used a 365-nm light source. The authors concluded that UV light can support the collection of fire samples and is particularly useful in combination with the use of an accelerant detection canine. They added that it is possible to visualize pour pattern to enhance debris sampling.

Hall et al. developed a new adsorbent to collect ILR by direct sampling at fire scenes [51]. They used a mixture of limestone and British Fuller's earth in a 10:1 (w/w) ratio. They conducted a series of experiments, comparing theirs to other potential adsorbents. They desorb their new adsorbent using a charcoal strip. The authors concluded that their new adsorbent covers a wide range of compounds from ethanol to docosane.

Chen reported the interference of desiccant packets that would be used to collect ignitable liquids at a scene [52]. Chen conducted the experiments using a Bode Technology SecurSwab, typically used to collect DNA at crime scenes. A mixture of gasoline and diesel fuel and a mixture of oxygenated compounds were spiked on the swabs. Analysis was carried out by passive headspace concentration followed by GC-MS. While the swab itself showed significant contribution to the chromatogram, it did not mimic any ignitable liquid patterns. Swabs were analyzed with and without desiccant packets, and different times were applied between spiking and analysis, ranging from 6 h to 1 week. As a result, the author was able to recover gasoline after one week, and diesel fuel after 48 h without desiccant (no recovery with desiccant). As for the oxygenated mixture, the desiccant prevented the recovery of most compounds. The author concluded that these swabs should not be used to collect ignitable liquids at fire scenes.

Finally, Evans and Trimber examined the decontamination procedures used by the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) [53]. The washing procedure for trowels used at fire scene includes: 1. Rinsing with a water stream to remove debris, 2. Vigorous scrubbing for 30 s with water and detergent, 3. Rinsing with water, and 4. Drying overnight. The authors observed that the detergent used since the mid-1990s seems to be less effective now, and that trace amounts of ignitable liquid can stay on the trowel. However, further cross-contamination scenarios could not be produced. They concluded that ATF procedures are valid and that cross-contamination is unlikely to occur. Among different detergents tested, they recommended the use of Simple Green Go HD as a detergent.

4. Laboratory examination

4.1. General

Gruber et al. wrote a critical review of the use of comprehensive two-dimensional chromatography in forensic science [54]. They dedicated a very small chapter on ignitable liquid residues (ILR).

Kim et al. conducted a comparison of the composition of volatile compounds extracted by Solid-phase microextraction (SPME) in headspace to the true composition of that headspace (HS) [55]. Their experiment used a PDMS fiber between 100 and 130°C. Using inverse gas chromatography, coupled with an HS-SPME sampling method, they demonstrated that the relative composition of n-heptane, toluene, and 1,2,4-trimethylbenzene was comparable to the true compositions obtained from direct headspace vapor analysis.

Sandercocock surveyed 2723 fire debris samples from 930 cases submitted to the Royal Canadian Mounted Police forensic laboratory between 2011 and 2016 [56,57]. His first observation was that 326 samples from 4.73% of the cases were refused due to improper packaging. As such, problems with improper packaging should not be underestimated. In 63.21% of the cases, at least one sample tested positive for an ignitable liquid; 1159 samples tested positive. Gasoline was the most common liquid found, representing 78.34% of the positive samples, followed by medium petroleum distillate (7.51%), heavy (5.09%), and light (2.42%); other distillates represented 6.64%.

4.2. Extraction techniques

ASTM standard practices were updated: E1388 (headspace sampling) in 2019 [58] and E1413 (dynamic headspace concentration) in 2019 [59].

A new ASTM standard practice E3189 concerning the separation of ILR from fire debris samples by static headspace concentration onto an adsorbent tube was published in 2019 [60]. This was a long-expected update of this ASTM standard that mainly covers the common use of Tenax with thermal desorption.

Kerr wrote a general review of extraction techniques for fire debris samples, covering technique perspectives, such as solvent extraction, headspace, solid drop micro-extraction, activated carbon, and SPME, and also ignitable liquid and the sample perspectives [61].

Suzuki et al. used a Needlex (i.e., an extraction needle that contains an adsorbent – the composition of which is not described in the paper – but is possibly a methacrylate co-polymer) to extract volatile organic compounds (VOCs) from fire victims' blood [62]. They found a series of VOCs compatible with ignitable liquid as well as interfering products within the victims. They were able to readily differentiate victims of building fires, self-immolation with kerosene, and self-immolation with gasoline. They concluded that

analysis of blood combustion-derived volatile substances enabled them to identify the type of fire-related death, otherwise impossible with a conventional autopsy.

Grafit et al. developed a protection device for SPME fiber as an application to ILR extraction [63]. In order to counteract the delicacy of the SPME fiber, often a problem during extraction, the authors explored the use of a protector made of aluminum 6061 with 18 holes that comes over the fiber. Because this protector reduces the direct exposure of the fiber to the headspace, the authors conducted different tests to ensure the propensity of the SPME fiber to adsorb ILR. They observed that the chromatograms were only partially similar between the fiber with and without the protector, a distortion toward low molecular weight being present with the protector. They explain that phenomenon through a heat sink effect of the protector around the fiber, which will decrease the temperature around the fiber. Given that the SPME fiber will naturally induce a shift toward the heavy end of the ILR compared to other extraction techniques, they concluded that the protector cancels some of this effect.

Sandercocock explored the use of activated charcoal cloth (ACC) as an alternative to activated charcoal strip (ACS) [64]. Using Zorflex double weave CC, originally made from viscose rayon, he performed simultaneous extraction with an ACS in the same can. Careful attention was placed on using ACS and ACC of the same weight. He observed that ACC extract was consistently more concentrated than its ACS counterpart, which may be the result of more available active sites per gram. He tested the influence of moisture, which was similar for ACS and ACC. Overall, the extraction performance between ACS and ACC showed that the compounds were extracted in similar relative ratios, except for a smaller amount of lighter alkanes with ACC, while ACC provided a more concentrated extract throughout the tests.

4.3. Analytical techniques

ASTM standard test method E2881 for the extraction and derivatization of vegetable oils and fats from fire debris and liquid samples with analysis by gas chromatography-mass spectrometry was updated in 2018 [65].

Martin Fabritius et al. investigated thermal desorption of an activated charcoal strip used in passive headspace concentration extraction [66]. After conducting a regular passive headspace concentration extraction using a traditional ACS, the authors used a fraction (about 8 mm²) of the ACS to place it in a glass tube for automated thermal desorption (ATD). Desorption was carried out for 10 min at 265°C, and analytes were concentrated on the cold trap of the ATD. They compared their thermal desorption to a solvent desorption with pentane using GC-MS analysis. A visual comparison of the chromatograms demonstrated that the thermal desorption provides identical results to solvent desorption. It presents the advantage of not having a solvent peak and, consequently, low molecular weight compounds can be identified. Though, it has the disadvantage of not being able to extract heavy weight compounds, such as the C20+ from candle wax in this study. The increase of the thermal desorption to 300°C did not change these findings.

Sampat et al. experimented on ignitable liquid profiling using GCxGC-FID and GCxGC-TOFMS [67]. They analyzed 32 neat white spirit samples from six different manufacturers in order to study their differences and variations between brands and over time. In both techniques, they used a DB-1 column followed by a DB-17. They applied principal-component clustering analysis on a total of 67 target-compounds in order to characterize each sample. Aside from one liquid, which was clearly differentiated from the others, it was not possible to obtain discrimination based on brand. They

concluded that their findings provided some valuable forensic information by demonstrating the temporal variation in white-spirit products and recommended further research in this regard.

Nizio et al. used a GCxGC-TOFMS to achieve near-theoretical maximum in peak capacity [68]. As a result, they reached a level 17% below the system's theoretical maximum of 11.2. The chromatograms produced were ordered, displaying distinct patterns of structurally-related compounds, which allows for the rapid classification of ignitable liquids.

Barnett et al. explored direct analysis in real time mass spectrometry (DART-MS) as a new, faster, technique for analyzing ignitable liquid and their residues [69]. In their study, after optimizing the temperature of the helium gas stream to 350C, the authors conducted a series of neat ignitable liquid analyzes using the Quickstrip sampling technique. For ignitable liquid on substrates, the authors used a thermal desorption of a small portion of the sample or Q-swabs to collect samples from the flooring surfaces. Although the technique allows for an excellent discrimination between neat ignitable liquids, application of multistep classification with partial least discriminant analysis was necessary to classify ignitable liquid residues from different substrates with a rate of 98%. The authors concluded that DART-MS offers promising results and can even offer complementary information to GC-MS in some instances.

Roberson and Goodpaster presented a new and fast analysis of ignitable liquid using a micro-bore capillary column with thick films and low phase ratio as an alternative to a traditional GC column [70]. Using their homemade column with a 50 µm i. d. And a 1.25 µm stationary phase at a 5 m length, the authors were able to perfectly analyze the ASTM E1618 test mixture (up to C14) in under 3 min. All 13 compounds were perfectly separated. Given the small volume capacity of the column, injection volume was reduced to 200 nl. The authors concluded that their column surpassed the regular GC columns in a very fast analysis time of 3 min.

Yang attempted to confirm Mach 1977's demonstration of GC-MS for ILR analysis [71]. The author conducted three experiments to identify gasoline traces on wood flooring, glazed tiles, and concrete using an uncertain sample preparation, which appears to be acetone-based solvent extraction. Using an awkward data analysis based on the evaluation of some disparate ions, the author claimed to identify gasoline's components.

Alianó-Gonzalez et al. investigated the use of headspace gas chromatography-ion mobility spectrometry (GC-IMS) [72,73]. A small portion of the debris is placed in a vial from which headspace will be taken and injected in the GC. The technique generates a 2D chromatogram with retention time on the x-axis and drift time on the y-axis. Hierarchical cluster analysis and linear discriminant analysis were used to analyze the data. The authors were able to differentiate diesel, paraffin, ethanol, and gasoline (98% good classification results). The authors concluded that this technique offers the advantage of a short analytical time (less than 15 min) and no sample preparation.

Ferreiro-González et al. explored the use an e-Nose fingerprint non-separative analytical method to perform ignitable liquid analysis. In a first paper, they analyzed burned substrates with and without different ILR on them [74]. The e-Nose system was composed of a headspace autosampler and a Kronos quadrupole MS. Samples were placed in a 10 ml vial from which 4.5 ml of headspace was analyzed. According to the authors, when they heated the samples at 115C, they interestingly agitated them in order to generate headspace. Total analysis time would be 12 min. Using a series of chemometrical tools, such as hierarchical cluster analysis (HCA) and linear discriminant cluster analysis (LDA), the authors were able to partially discriminate between some liquids. However, overlap occurred between some liquids and between

burned substrates and some liquids. In a subsequent paper, Ferreiro-González et al. used the same technique to characterize different ignitable liquids that were poured onto different substrates [75]. Analytical conditions were identical, except for sample heating, which was performed at 145C. Samples were spiked with 80 µl of ignitable liquid. Later principal component analysis (PCA) was added to HCA and LDA as post-analytical treatments, which allowed the authors to fully discriminate between the different ignitable liquids. In another paper, Ferreiro-González compared their headspace-MS (HS-MS) eNose technique to GC-MS for the ignitable liquid and ILR analysis [76]. They concluded that both methods led to a 90% correct classification rate according to ASTM E1618, but that the HS-MS performed faster and more ecofriendly than GC-MS as it does not require sample pre-concentration.

Choi and Yoh used laser-induced breakdown spectroscopy (LIBS) to determine whether ignitable liquid was used on fire debris or not [77]. They tested five types of material (i.e., electric wire, two types of floor materials, mats, and sheets). The authors also attempted to identify the ignition source (i.e., gas stove, disposable lighter, candle, electric stove, and aroma incense [through conduction]) and compared the effects of extinguishment techniques (oxygen starvation vs. water). Their experiment showed mitigating results, and the authors concluded that if LIBS may assist fire investigators, it cannot fully replace usual analytical methods.

4.4. Interpretation

For about 10 years, chemometrics has taken an important place in the interpretation of complex fire debris data. On that topic, Bovens et al. published the first part of a review of the use of chemometrics in forensic chemistry [78].

Because of the data complexity obtained in GCxGC-MS, Lopatka et al. developed a new graphical representation to look at data by dividing the chromatograms into non-overlapping spatially delimited regions, each of which generate a local ion signature [79]. The authors then used a univariate score-based likelihood ratio approach in order to discriminate pairs of samples. Each ILR is then classified using linear discriminant analysis (LDA). They analyzed 155 samples of ignitable liquids and substrate compounds. These preliminary findings demonstrated an ILR detection rate with 84% accuracy and less than 1% of false positive results.

Because using total ion spectrum (TIS) for chemometric analysis removes the data obtained from separation, Adutwum et al. investigated the potential use of segmented total ion spectrum (STIS) to identify ILR in fire debris samples [80]. STIS retains the advantage of TIS while accounting for some retention information. As a result, while TIS achieved 96% model prediction, STIS reached 98%. Furthermore, the authors used a baseline removal model prediction to reach accuracies of 97% and 99%, respectively.

Peschier et al. used a different approach to identify gasoline as an ILR in fire debris samples [81]. Rather than comparing the typical aromatic profile of gasoline, the authors investigated the high-octane blending component alkylate as a characteristic feature of gasoline. Samples were neat and 75% evaporated gasoline. Additionally, a fire debris simulation was made by spiking 75% evaporated gasoline on carpet. Analysis of neat and evaporated liquids was carried out by HS-GC-MS, while analysis of fire debris sample was carried out by ATD-GC-MS. Alkylate profiles were detected in 99% of the gasoline samples. They mentioned the advantage that highly branched alkylates were less distorted by microbial degradation than aromatic compounds. The disadvantage of alkylates is that they will no longer be present with highly weathered gasoline. However, at 75% weathered gasoline, their analytical technique allowed them to detect low amounts in the simulated fire debris.

Using the data from the Ignitable liquid reference collection

(ILRC) from the National Center for Forensic Science (NCFS) and the Technical/Scientific Working Group for Fire and Explosions (T/SWGFEX), Coulson et al. investigated a new model for assessing the evidentiary value of fire debris based on the total ion spectra of neat and weathered ignitable liquids as well as from interfering products from substrates [82]. They analyzed 261 weathered samples, 625 neat liquids, and 199 substrates. They calculated base 10 log of likelihood ratio values using a one-level Gaussian kernel density model. The authors recommended modifying ASTM E1618 to remove analyst bias.

Akmeemana et al. identified the major chemical compounds found among the 647 ignitable liquids and 106 burned substrates contained in the ILRC and substrate database of the NCFS [83]. Based on readily available data, the authors identified 221 major compounds by selecting the first five main peaks on each chromatogram, 36 of which were identified in both ignitable liquids and burned substrates; 47 compounds were identified only in substrates while 102 were identified only in ignitable liquids. The most common compound in both substrate and IL is *n*-Nonane, 1,2,4-TMB, *n*-Decane, *n*-Tetradecane, *n*-Dodecane, *n*-Undecane and *n*-Tridecane.

Hondrogiannis et al. evaluated the threshold for gasoline identification by GC-MS from fire debris [84]. After burning a carpet, the authors spiked it with gasoline at different concentrations. They performed extraction by passive headspace concentration, eluting the strip with 1 ml of CS₂, which provides a final gasoline concentration ranging from 20 to 0.5 ppt. Analysis was carried out by GC-MS. They chose six target compounds and defined a base peak and two qualifier ions. The authors calculated a set of ion ratios using these values based on the full scan chromatogram. The compound is deemed identified when the ion ratio measures within 20% of the one from the neat gasoline. The authors concluded that their results support the application of their method for identifying compounds in gasoline, claiming that it can be used to go beyond pattern matching.

Black et al. evaluated substrate contamination by ignitable liquid spills in flooded compartments [85]. They explained that in a common house garage, many different ignitable liquids may be present on shelves, and, during fire extinguishment, flooding could occur and, presumably, spillage of these liquids, potentially contaminating flooring surfaces. Using a set-up that simulated a flooded compartment, the authors tested eight different types of substrates and three different IL. They subsequently used passive headspace concentration extraction followed by GC-MS analysis. The authors were able to identify ILR in all samples but plywood (except two occurrences of submerged plywood with charcoal lighter as an IL). They underscored the difficulty of collecting a comparison sample under these conditions.

Baerncopf and Beals examined the persistence of ignitable liquids on unburned fabrics [86]. The authors varied the type of ignitable liquid and fabric, the spill volume, and the time until collection to better understand the influence of these different variables. As such, they tested cotton, nylon, and a 65/35 polyester-cotton blend. Samples were cut into 6-inch squares onto which three IL (i.e., gasoline, MPD, and HPD) were spiked with volumes of 500 µl and 5 ml. Samples were kept indoors at room temperature for 2, 12, 24, 48 h, and 7 days prior to headspace concentration extraction followed by GC-MS analysis. HPD was found on all samples while MPD could no longer be identified after 2 h. Gasoline (500 µl) was only identified on cotton in the 2-h sample, while the 5-ml volume would be identified until 7 days. Notably, in some instances with MPD and gasoline, another ignitable liquid was identified due to weathering.

Dhabbah performed experiments to evaluate the amount of gasoline remaining on cotton, wool, nylon, and polyester before and

after burn using SPME-GC-MS analysis [87]. The author spiked samples after burning and kept them in a sealed bag before analysis at different times ranging from 0 to 4 h. The author concluded that no trace of ignitable liquid on burnt fabric could be detected after 2 h, and that synthetic fibers showed a higher retention capacity for gasoline than natural fibers.

Lampf and Evans studied the persistence of IL on unburned substrates [88]. Polyester carpeting, OSB, and concrete were spiked with gasoline and diesel fuel and placed outdoors or indoors for up to a year prior to passive headspace concentration extraction followed by GC-MS analysis. Diesel fuel was identified on all substrates after one year on both indoor and outdoor samples, while gasoline could no longer be identified on carpet indoors or outdoors after 6 months.

Aqel et al. also studied the persistence of gasoline and diesel fuel on wool, cotton, silk, and polyester [89]. The authors poured the liquid on the samples before burning them and analyzed them by SPME-GC-MS. They analyzed seven compounds for gasoline and seven for diesel fuel after placing samples in nylon bags at different times up to 15 h. They concluded that diesel fuel persists longer than gasoline. They did not observe significant evaporation differences between polyester, cotton, wool, and silk samples.

Because sometimes investigators collect fire debris in unsuitable bags, Borusiewicz et Kowalski compared the volatile organic compounds content of 28 different commercially-available polyethylene bags [90]. After confirming their composition by FTIR, they used passive adsorption on Tenax followed by GC-MS analysis. Among all bags, 60 different VOCs were found, but only 15 were present on more than two bags. Dodecane was present in all bags, followed by decane and tetradecane.

Belchior and Andrews evaluated the cross contamination of two brands of nylon bags used by fire investigators to collect fire debris [91]. The authors conducted the experiment with gasoline and automotive paint thinner (made of oxygenated solvent). A cotton rag with 10-ml gasoline or paint thinner was placed in the bag, which was, in turn, placed in a plastic crate with 8 other bags. They analyzed gasoline samples after 2, 4, 6, 24 h, 4 days, 1 week, and weekly up to 8 weeks. They analyzed paint thinner samples daily for 7 days. The authors used SPME-GC-MS extraction and analysis on both types of samples. Toluene was detected in the one manufacturer's empty bags after 4 days and after two weeks with the other. *C*₂-alkylbenzenes crossed over after 3–4 weeks; 2-propanone crossed to the empty bags after 2 days. The authors reminded readers that cross-contamination can occur with heavily-loaded samples and they advised readers to transport such samples separately from regular fire debris samples or to double-bag them to minimize cross contamination.

Cheenmatchaya and Kungwankunakorn investigated gasoline permeation on four types of soils to determine optimum soil sampling depth [92]. The authors simulated fire scenes by pouring 40 ml of a mixture of gasoline and ethanol on a 1600 cm² surface of soil, setting it on fire, and letting it burn for 40 min by adding fire wood. They waited 24–48 h before sampling at 5, 10, and 15 cm depths. Some tests were extinguished, and some were left to burn themselves out. Passive headspace concentration extraction followed by GC-MS analysis on five compounds confirmed the presence of gasoline. The authors concluded 5 cm to be the optimum collection depth and that fine-textured soils were better retainers than coarse-textured soils. Also, soils with high sand composition did not retain gasoline well.

Turner et al. studied the alteration of 50 different ignitable liquids from the Ignitable liquid reference collection by weathering and microbial degradation [93,94]. Weathering was accomplished through evaporation by reducing the original volume by 25, 50, 75, 90, and 95% under nitrogen steam. Microbial degradation was

carried out by spiking 20 µl on 100 g of soil inside a quart can. Soil was left at room temperature for 7, 14, and 21 days. Through (passive headspace concentration extraction)-GC-MS analysis, the authors concluded that weathering resulted in the loss of all lower boiling point compounds without bias and that bacteria prefer to utilize n-alkanes and lesser substitutes alkylbenzenes, with toluene degrading first, followed by C2-, C3-, and C4-alkylbenzenes. Iso-paraffinic and naphthenic-paraffinic products were the least affected.

Birks et al. studied the effect of temperature on gasoline weathering [95]. Gasoline samples were weathered 75, 90, and 95% under vacuum, a stream of nitrogen gas, and at three different temperatures of 25, 60, and 90°C. They used GC-MS laboratory analysis *t*-tests and principal component analysis for statistical comparison. They conducted mathematical simulation to weather gasoline at 120, 150, 230, and 500°C. The authors concluded that vacuum- and nitrogen stream-assisted weathering had negligible influences on relative distribution. When liquids are evaporated at significantly elevated temperature, heavy distortion of the distribution can be observed. For example, the authors cited how gasoline weathered to 95% at 500°C will show the same pattern as gasoline weathered to 70% at room temperature.

Smith et al. developed a mathematical model to predict the chemical composition of evaporated ignitable liquid [96]. They experimented on petroleum distillates and gasoline evaporated to 30/90% of mass and analyzed samples by GC-MS. In order to function, the model only requires the neat liquid chromatogram. The authors demonstrated a Pearson product-moment correlation ranging from 0.920 to 0.998 with lamp oil, although the model was limited for gasoline due to the mass of highly volatile compounds present in the liquid but not observed in the chromatogram.

DeHaan et al. analyzed the VOCs from burned human and animal remains in fire debris samples through passive headspace concentration extraction followed by GC-MS analysis [97]. The authors identified a series of predominant homologous aldehydes (C5 to C9) as a significant indicator of the presence of burned animal remains. They also identified the presence of acetone and alcohol in low concentrations in most samples. Finally, they did not observe significant differences between volatiles produced from human cadavers and those produced from porcine material.

Guerrera et al. investigated the interference of clothing and endogenous body secretions and body products using ILR [98]. The authors used four different types of clothing materials and six body products, three of which (Vaseline, baby oil and perfume) they used on the clothing in addition to deodorant. Women wore clothing articles for 12 h before collection and extraction by passive headspace concentration using GC-MS analysis. The authors concluded that components from worn clothing and transferred body products can interfere with ILR identification. Some will mask the presence of ILR, and others exhibit a pattern similar to ILR.

Falatová et al. evaluated the effect of two suppressions agents (foam and powder) on ILR analysis [99]. Using an HS-MS eNose technique combined with chemometrics, the authors found that the agents affected the mass spectrum of gasoline residues. However, a linear discriminant analysis was able to identify gasoline at all times.

After a fire in the largest illegal tire landfill in Spain, Escobar-Arnanz et al. studied the aromatic compounds found in soil after a tire fire [100]. Soil samples of 20 g were collected at different locations of the fire. They extracted samples by pressurized liquid extraction, and analyzed them using GCxGC-TOFMS. The authors detected 118 volatile and semi-volatile aromatic compounds, including 104 that were identified. Polyaromatic hydrocarbons and their alkylated derivatives were the most relevant family of compounds detected.

Frauenhofer et al. studied the adsorption of hydrocarbons from gasoline residues on household materials by inverse gas chromatography [101]. They experimented on six compounds and three household materials (i.e., carpet fibers, cotton fabric, and cardboard). They estimated the molar enthalpies of adsorption and their specific components, determined isotherms, and evaluated solubility coefficients. The authors observed that hydrocarbons with larger molar mass had more negative molar enthalpies of adsorption and higher solubility coefficients, thus stronger adsorption affinity regardless of the substrate. They found cardboard to be a better adsorbent than carpet fibers and cotton fabric.

4.5. Other liquids, materials and characterizations

A first study by Martín-Alberca et al. [102] aimed to determine the alteration of spectral characteristics of gasoline and diesel fuel when acidified. Attenuated total reflection (ATR) Fourier transform infrared spectroscopy (FTIR) analysis demonstrated that when sulfuric acid is mixed with gasoline, oxygenated compounds are hydrolyzed and aromatic compounds are alkylated, though alkanes do not seem to be affected. As such, the spectrum of diesel fuel did not vary significantly.

In another paper, Martín-Alberca et al. [103] researched the effect of fuel acidification on the identification of the IL from a fire debris perspective. As such, the authors stated that it is important for fire debris analysts to be aware of these effects. Ten ignitable liquids from the literature never before analyzed in an altered state were chosen. The authors used FTIR and GC-MS analyzes and observed major changes in thinners that contained oxygenated compounds, such as alcohols, esters, and ketones. Longer reaction times led to sulfonation of aromatic compounds. The authors warned analysts that acid alteration of ignitable liquids can lead to a misclassification.

In the same vein, Parsons et al. used GCxGC-TOFMS to characterize diesel fuel for acid alteration [104]. To alter fuel color and avoid taxes, some end users alter fuel color by adding an acid. To better identify altered fuel from unaltered fuel, the authors investigated the chemical composition changes when subjected to acid. They mixed six diesel fuel samples with concentrated sulfuric acid. They analyze data using an in-house tile-based F-ratio software. The authors concluded that the changes with sulfuric were subtle but of forensic value. They observed removal of alkenes and alkynes in the acid-altered version and consistent generation of sulfur dioxide.

Barnett and Zhang also explored DART-MS to discriminate between brands of gasoline [105]. Using Quickstrip sampling, they analyzed 39 gasoline samples from 5 gas stations over a period of 8 weeks. Because DART-MS spectra present ion clusters corresponding to the polymeric compounds in fuel additives, the authors were able to reach 99.9% classification rates. Further experiments on weathered gasoline allowed them to reach 100% classification rates. They noted that polymeric ion patterns were brand- and weathering-dependent.

Based on the premise that the stable carbon isotope ratios ($\delta^{13}\text{C}$) of n-alkanes can be used to characterize and differentiate diesel fuel sources, Novak et al. used gas chromatography-isotope ratio mass spectrometry (GC-IRMS) to analyze samples and discriminate them from one another [106]. They prepared and measured 25 samples of diesel fuel three times each. They applied chemometrics to evaluate the stable isotope ratios through HCA, PCA, and combined cluster and discriminant analysis (CCDA). The latter demonstrated that each diesel fuel sample was chemically unique, and the authors were able to fully discriminate between the 25 samples.

In order to further investigate the possibility of identifying the source of a gasoline sample extracted from fire debris, de

Figueiredo analyzed 190 different gasoline samples from 19 gas stations collected over a year [107]. He first placed each sample in a glass jar and extracted samples using passive static headspace concentration on a tube of Tenax, then analyzed samples using ATD-GC-MS. He used a set of chemometric tools to analyze data based on a list of 13 unique ions selected to establish comparative ratios. It should be noted that the author chose these ions to correspond to real physico-phenomena used in the refining process. The author concluded that his technique showed good prediction performances to decide whether two samples share a common source or not.

In a further study, de Figueiredo et al. investigated the influence of evaporation and combustion on the propensity to identify gasoline sources between two samples [108]. Using the same samples from the previous study, the authors evaporated them to 50, 90, and 99%. They burned the gasoline down to 50, 90, and 99% in a cone calorimeter, stopping combustion by oxygen-starvation. They analyzed all samples using ATD-GC-MS. The authors used different sets of ratios depending on the weathering condition of the samples. They concluded that gasoline weathering or combustion may drastically modify the chromatographic profile. However, it did not compromise the possibility to link samples sharing a common source.

Damavandi applied peak topography maps to GCxGC chromatograms to identify petroleum source [109]. This technique allows analysts to account for a broader and more diverse range of target and non-target biomarker compounds.

Kerr et al. used Raman spectroscopic mapping to identify the individual material components of a fused mass in fire debris [110]. They constituted fused masses from different common household polymeric materials. Raman spectroscopy was obtained by acquiring spectra on a $10\ \mu\text{m} \times 10\ \mu\text{m}$ region. As a result, the authors used Raman mapping to identify different sources of material in a fused mass when it was visually unidentifiable, which could greatly help fire debris analysts in interpreting data.

Green et al. evaluated fire debris samples that may originate from clandestine drug laboratories [111]. In particular, they studied the « One pot » methamphetamine production method, which uses highly flammable materials based on the premise that if one can detect methamphetamine or its precursors in a fire debris sample, it is possible to demonstrate the illegal activity. In order to achieve this goal, the authors analyzed fire debris samples by passive headspace concentration extraction followed by GC-MS for ILR while they used LC-MS/MS preceded by a solvent extraction for the drug part. Additionally, they performed GC-MS drug analysis on the carbon disulfide extracts and were able to positively identify methamphetamine and pseudoephedrine in one setting. Thus, the authors concluded that methamphetamine and pseudoephedrine can be detected in fire debris samples.

On a different topic, Klein et al. experimented on the influence of heat on blood traces that are subsequently detected by the use of luminol [112]. Blood was applied to 11 objects that might be found in fires before exposing them to temperatures of 300, 700, and 1'000C. After cooling, they applied luminol, and classified luminescence on a qualifying scale. They also performed DNA analysis after luminol application. Interestingly, blood was still visible, even after exposure to 1'000 C. For all objects, except for a copper pipe exposed to 300C, evidence of chemiluminescence with luminol was shown. However, among the 33 comparison samples without blood, 25 of them also showed a chemiluminescent reaction. At 700C, 10 of the 11 test objects with applied blood revealed a full DNA profile while at 1'000C, six objects still revealed a full DNA profile. The authors concluded that luminol can be used to localize blood traces even after exposure to fire at 1'000C, however, it requires an experienced examiner to differentiate between true and

false-positive reactions. They concluded that DNA was much more resistant to fire than originally believed.

In a follow-up paper, Klein et al. further studied how the application of liquid latex to remove soot influences the visualization of bloodstains by luminol [113]. Using the same experimental conditions as their previous paper, the authors applied liquid latex after cooling. The authors first observed that the application of liquid latex lowered the rate of false positive results. Then, the use of liquid latex increased the true luminescence of blood traces, thus facilitating their localization. They concluded that using liquid latex constitutes a clear advantage.

Vineyard et al. evaluated Bluestar forensic magnum and other traditional blood detection methods [114]. The authors studied an ambitious quantity of parameters: blood dilution, burn time, presence/absence of gasoline, extinguishment by oxygen-starvation or water, testing location, and testing method. To test 116 pine wood samples, the authors used luminol, Bluestar magnum, and a combined phenolphthalein. They had difficulties obtaining a positive result for all techniques, although luminol and Bluestar were more likely to give positive results than phenolphthalein. Extinguishing the wood block with water severely impacted the potential for a positive result.

Gardner et al. compared soot removal and fingerprint enhancement techniques following fires [115]. The authors used two car burns and a cremation oven to experiment at temperatures of 300, 450, and 600C. They removed soot by tape lifting, NaOH solution, and liquid latex casting. They enhanced fingerprints by black magnetic powder, aluminum powder, black suspension powder, and superglue fuming with BY40 dye. They classified recovered fingerprints as unidentifiable or identifiable. No fingerprints were identifiable at 600C. At 450C, 54% of prints were identifiable, and 77% were at 300C. Black magnetic powder and superglue fuming gave the best results.

Havey et al. studied the persistence of sonic deposition on smoke detector horns to determine whether the smoke alarm sounded during the fire or not [116]. The authors subjected 60 smoke alarms to smoke from fires of different fuels and post-fire conditions and actions. They observed that smoldering fires from wood and polyurethane foam left sticky resin that was not affected by any post-fire actions. Flaming foam and toluene-heptane fires left soot that could easily be wiped off. Pressing the button showed minimal effect. The authors concluded that the absence of sonic deposition does not necessarily mean that the horn did not sound during the fire.

5. Fire modeling

Jahn published a study of conventional detection and suppression devices for the estimation of fire characteristics using an inverse modeling framework [117]. Using inverse computational fire dynamics (CFD), the author determined the growth rate and the location of the fire origin based on sprinkler or smoke detector activation times.

Kurzawski developed a Bayesian inversion statistical technique to create a more rigorous approach to coupling fire scene data and computational tools [118]. The author determined location, size, and fire time-to-peak using two models: consolidated model of fire and smoke transport (CFAST) and fire dynamics simulator (FDS). As a result, FDS performed better than CFAST in predicting the maximum energy release rate. Both models predicted equally on locating the fire origin.

Wegrzynski and Lipecki published a literature review of wind and fire coupled modeling as part one of a more general study [119]. They explained that most fire phenomena are influenced by the wind, and, accordingly, to understand fires one needs to

understand wind as well.

Anderson et al. modeled fire exposure in façade fire testing [120]. The authors performed a comparative simulation on three large-scale façade testing methods: SP fire 105, BS 8414–1, and ISO 13785–2. They observed generally good correspondence between simulations and experimental data. However, deviations were seen in close proximity of the fire source.

Nilsson et al. investigated the impact of protective measures against external fire spread using a numerical approach with FDS [121]. The authors concluded that FDS 6.2.0 could reproduce the experimental results with a reasonable level of details. In the subsequent comparative analysis, the authors showed that façade solutions based on a horizontal projection or an upper façade setback configuration resulted in comparable or better protection compared with a defined sprandrel height.

Shi et al. conducted a series of pool fire tests in a full-size tunnel to develop an accurate model for predicting surrounding temperatures [122]. They used three types of petroleum (i.e., sweet crude oil, high sulfur crude oil and heavy naphta) on a standard-size pan of 0.5 m². They developed a modified model that estimated the thermal radiation of pool fires on surrounding objects with sufficient accuracy and reliability.

Finally, Tohir et al. studied prediction of time to ignition in a multiple vehicle fire spread [123]. The author applied flux-time product ignition criterion and the point source flame radiation model to predict time to ignition in scenarios involving multiple vehicle spread. They used 10 experiments from the literature and concluded that the point-source model (PSM) and flux-time product (FTP) methods have done very well.

6. Aspects of forensic pathology and toxicology in fire investigation

Stec provided a comprehensive review of fire toxicity [124]. The author's review included statistics, fire scenarios, fire hazards, and assessment of fire toxicity through VOC, PAH, isocyanates, halogenated dioxins, and particulates. Additionally, she covered fire retardants as well as future challenges.

Giebutowicz et al. analyzed 263 fire death cases that occurred between 2003 and 2011 in Poland to determine the factors contributing to death [125]. Interestingly, approximately 70% of fatalities were male. About 50% of the victims had inhaled lethal doses of toxic gases, while about 80% had soot in their airways, thus were alive for some time during the fire. A majority of fatalities resulted from causes other than CO inhalation, which includes burns and/or effects of other gases.

Simonsen et al. studied cases of carbon monoxide poisoning in Denmark from 1995 to 2015 [126]. Out of 22'930 patients, 9.2% died within 30 days after poisoning. About 40% of the deaths were due to inhalation of smoke from fire, of which 87% were accidental and 7.2% were intentional.

Hampson provided a summary of four examples of myth busting regarding CO [127]. These include the belief that symptoms correlate with carboxyhemoglobin (COHb) levels, that residents are safe from CO poisoning in the absence of fuel-burning appliances, that COHb levels must be measured on arterial blood quickly, and that CO poisoning predisposes one to premature death from cardiac disease.

Lisbona et al. studied carbon monoxide deaths from 2007 to 2016 in Scotland [128]. The authors looked into 209 CO-positive deaths and found no correlation between CO saturations and age, gender, alcohol, and preexisting disease. Furthermore, they found were no relationships between %COHb and age, blood alcohol, and preexisting disease. However, the authors observed that the main source of CO was fire, followed by vehicle exhausts, portable BBQ

grills, generators, and gas supply systems.

Birngruber et al. reported case of cyanide poisoning on a 71-year old victim [129]. The victim was discovered in a smoke-filled apartment with the mattress on fire. Even though she did not present soot inhalation or swallowing, and the COHb concentration in her heart blood was about 3%, 4.3 mg/l of cyanide was found in heart blood and 1.9 mg/l in lung tissue. The authors concluded that lethal amounts of cyanide can be inhaled during a fire, even without inhaling or swallowing soot, with no significant increase in COHb level.

To determine CO poisoning, Oliverio and Varlet investigated the use of total blood carbon monoxide (TBCO) as an alternative to HbCO [130]. The authors used an airtight gas syringe to perform GC-MS analysis. They concluded that their technique is a good alternative to traditional HbCO, because the later can underestimate the total burden of CO in blood, as 10–60% of CO may be found in free form in the blood.

Stoll et al. studied the cyanide level in 92 blood samples from fire death and/or smoke inhalation victims [131]. The highest concentration of cyanide was discovered in victims found in enclosed-fire spaces (50%) and motor-vehicle fires (9%). Among these two groups, cyanide level was toxic in 47% and lethal in 13%. In victims of charcoal grills and exhaust gases, no or only trace amounts of cyanide were found.

Truchot et al. investigated toxic gas emission from vehicle fires [132]. The authors first reviewed the emission factors dealing with recent cars. Then, they proposed a method to define a carbon monoxide equivalent emission factor. Finally, they conducted two experiments, the first one on plastics and tires, and the second one on a car. They performed smoke analysis and compared it to the previously defined emission factors.

Doberentz et al. investigated the expression times of heat shock proteins (hsp) as an indicator of thermal stress during death due to fire [133]. After examining 48 fire victims of excessive heat and comparing them to a control group of 100 deaths without thermal stress, the authors discovered a correlation between hsp expression and survival time. More precisely, hsp27 is expressed rapidly within seconds or minutes after the stressful thermal influence and in large amounts. Hsp70 takes up to an hour to reach optimal expression levels, and its persistence is greater in the cell.

Karakasi et al. reported a case of sexual murder involving human arson and provided a literature review on the phenomenon [134]. The authors reported the incidence rate, crime scene patterns, offender characteristics, and victim selection. They observed that most offenders and victims were in their late 20s to early 30s, were Caucasian, and that this type of crime is underpinned by the expression of displaced anger or sexual sadism and/or a way to elude detection. The authors realized that their case, unprecedented in Greece, incorporated many of the characteristics discovered throughout literature.

Costagliola et al. wrote a short review of the forensic pathologist's role and responsibilities when examining burned victims [135]. The authors insisted on the fact that the forensic practitioner must take into account fire investigation results and toxicological and histological analyses in determining the cause and manner of death.

Tumran et al. reported a case in which a victim died while performing routine fire extinguisher servicing [136]. The CO₂ cartridge of the device exploded, turning the fire extinguisher into a missile that struck the victim, killing him from hemorrhagic shock.

7. Human behavior

Leong et al. studied 41 individuals who had been found not guilty of arson by reason of insanity and, thus, were sentenced to a

psychiatric institution [137]. Eighty percent were male. Participants' mean age was 35.9 years at the time of offence and about 90% were not participating in psychiatric treatment at the time of offence. About 12% of them were previously found not guilty by reason of insanity for arson or had been convicted of arson. The authors concluded that in order to lower the likelihood of committing arson, earlier identification and psychiatric intervention or treatment could be beneficial, though impossible to implement. However, treatment non-participation was identified as the greatest factor in the genesis of arson by reason of insanity.

The study of human behavior in fire (HBiF), which is intrinsically linked to fire protection, can benefit greatly from traditional social science. With that scope in mind, Kuligowski presented research from social psychology and sociology, introducing pre- and post-fire studies [138]. She concluded with a discussion on possible ways to integrate social science in HBiF.

Xiong et al. interviewed 182 individuals who had survived an accidental residential fire without serious injuries in order to determine what alerted them and what actions they took upon fire discovery [139]. The smell of smoke was the first cue that alerted victims, followed by seeing flames or glow, and hearing fire/explosion. Only 12% of individuals first saw smoke, and the same proportion was alerted by the smoke detector. The authors reported most individuals behaved proactively instead of leaving the burning property immediately (i.e., attempting to extinguish the fire, trying to alert others, investigating fire, attempting to rescue others, and attempting to rescue pets). The authors concluded that human behavior is based on the individual's perceived needs more than adherence to fire safety training advice.

8. Diverse publications

Bruenisholz et al. developed a method of detecting a series of repetitive deliberate fires by the same perpetrators that relies on intelligence-led policing and forensic intelligence [140]. Their method was validated by a dataset of 8'000 arson cases collected over a 12-year span in Switzerland. They documented a combination of elements that are constant between arsons from the same perpetrator: geographical, temporal, forensic trace, and modus operandi or scene behavior. The authors concluded that their method showed very promising results as 20 possible series were retroactively identified, including 9 previously known series of which 6 were solved.

In a subsequent paper, Bruenisholz et al. presented a two-fold procedure developed to produce intelligence based on a dataset of arson or undetermined fires [141]. The authors proposed a foundation for developing an integrated real-time intelligence process. This requires close collaboration between fire and police departments and a certain exhaustiveness in collecting data, as missing data increases the uncertainty of the intelligence obtained. The authors concluded that monitoring fires and establishing patterns in real-time would be greatly beneficial to law-enforcement agencies.

Feb and Jones reported on the difference between an origin and cause fire investigator and a subject-matter expert and how they may interact according to NFPA 921 [142].

Ost-Prisco, a district attorney, described the steps to take to ensure the successful prosecution of an arson case in what he proposes as a roadmap for the public investigator [143]. The author explained that public investigators should prepare before the fire occurs by understanding the resources available to them, the needs and experience of local fire and police department investigators, and by developing a strong relationship with the local prosecutor. Schudel reacted to this paper reminding readers that fire investigators have a duty to the court and to seek the truth, not to

make a case, prosecution or otherwise [144]. As such, he considered the Ost-Prisco's article as promoting a tactic of prejudice against a defendant. He concluded by reminding readers of the IAAI code of ethics.

O'Brien conducted a survey of 16 successful investigations that identified and captured serial arsonists responsible for 500 fires [145]. He attempted to identify any aspects that may enhance the probability of success in a fire investigation. He deduced that there was no simple blueprint for an effective framework. He concluded that the most important aspect was investigator competency and available resources, along with regular communication among jurisdictions.

Andrews discussed the process of elimination and negative corpus in the light of the 2017 edition of NFPA 921 [146]. The process of elimination is an integral part of the scientific method. However, the author concluded that if the process of elimination is scientific, it must be based on evidence and facts, meaning that supporting evidence must exist for each cause eliminated, otherwise one falls into a state of negative corpus or call the fire cause "undetermined."

Cox et al. conducted an experiment with 77 observers who watched a staged fire scene and subsequently responded to a questionnaire based on their observation [147]. The researchers' goal was to explore witness testimony relevance and reliability. They concluded that open questions may lead to the fire investigator obtaining new knowledge, but they also may solicit irrelevant information. Conversely, structured questions reduce the likelihood of the investigator discovering anything beyond his or her initial track. Accordingly, the authors recommended using a combination of both open-ended and structured questions.

Burke described investigative statement analysis, which is the structured examination of an individual's exact words in order to conduct more in-depth interviews [148]. The author described it as a multistep process that can readily be applied to arson investigation. He recommends simply examining statements for balance, "I" pronouns, and equivocations. This works on witnesses, victims, and suspects.

Dioso-Villa and Lentini wrote a book chapter about Cameron Todd Willingham's case studies. The authors reviewed the inaccuracies in fire cause determinations, notably the lack of qualifications, invalid methodology, validity of fire origin, and common misinterpretations of fire artifacts [149]. Lentini also wrote a short review of what fire litigators need to know [150]. Finally, the same author wrote a larger review on the historical perspective of fire investigation and its recent developments [151]. The author insists on the need for science since the turning point in 2000 with the acceptance of NFPA 921 and the standardization, certification, and accreditation in fire investigation.

Smith and Jaeger shared their concerns about the next generation of fire investigators [152]. Based on a result from an IAAI membership survey, their paper addressed the demise of an entire generation of experienced fire investigators, as more than 60% of all fire investigators are over 50 years old and only 4% are under the age of 34.

Pauley proffered some general tips and tricks for fire investigators [153]. Rullan emphasized that fire investigators must be leaders at the fire scene in order to exercise the job properly and guarantee good collaboration with partners [154].

Kobayashi studied the influence of building size on the frequency of ignition [155]. The author took fire statistics data from 1995 to 2003 in order to obtain the distributions of floor area of the fire origin.

Xie et al. studied the oxidation behavior of carbon steel in a simulated kerosene combustion atmosphere [156]. They used carbon steel Q235 in air and under kerosene combustion at various

temperatures and studied the oxidation kinetics, morphologies, microstructure, and compositions. The authors showed that the presence of kerosene significantly accelerated the oxidation of Q235. Also, the oxides produced were significantly different from those formed in air alone. The authors concluded that their work also showed that oxide scale formation may be subjected to contamination and spallation, and, as such, a combination of macroscopic observation and microscopic analysis is required.

Finally, the International Association of Arson Investigators published the best practices for fire investigator health and safety [157]. This guide applies to the employer as well as to the employee.

Disclaimer

This is a republication in journal form of a conference proceeding that was produced for the 19th Interpol Forensic Science Managers Symposium in 2019 and was originally published online at the Interpol website: <https://www.interpol.int/content/download/14458/file/Interpol%20Review%20Papers%202019.pdf>. The publication process of this was coordinated for the Symposium by the Interpol Organizing Committee and the proceeding was not individually commissioned or externally reviewed by the journal. The article provides a summation of published literature from the previous 3 years (2016–2019) in the field of fire investigation and does not contain any original, experimental data. Any opinions expressed are those solely of the authors and do not necessarily represent those of their agencies, institutions, governments, Interpol, or the journal.

Declaration of Competing Interests

The authors declare that they have no competing interests.

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