Forensic Science International: Synergy 6 (2023) 100310

Contents lists available at ScienceDirect

Forensic Science International: Synergy

journal homepage: www.sciencedirect.com/journal/forensic-science-international-synergy

Interpol review of fire debris analysis and fire investigation 2019–2022

Michelle Evans

Chief, Arson and Explosives Section II, Bureau of Alcohol, Tobacco, Firearms and Explosives, Forensic Science Laboratory-Washington, Ammendale, MD, USA

1. Introduction

This review covers research in the areas of fire debris analysis and fire investigations since the 19th International Forensic Science Managers Symposium in 2019. The literature includes forensic and fire-related articles, standards, and books published since 2019 to complete the previous review by Stauffer in 2016 [1].

In 2020, the United States was not only faced with a pandemic but also with several months of intense civil unrest. The country saw an uptick in violence that primarily manifested itself in the form of property destruction through the use of fire. Incendiary devices (i.e., Molotov Cocktails) were the easiest and quickest way to cause mayhem and burned everything from churches to monuments to police stations. Fire investigators relied heavily on social media and surveillance cameras to catch the perpetrators, but much of the evidence was still submitted to forensic laboratories to analyze for ignitable liquids, fingerprints, and DNA. With the availability of materials needed to make Molotov Cocktails, these have been and will undoubtedly continue to be the “weapon” of choice in riots and general criminal mischief.

There are numerous articles discussing practical applications in the field of ignitable liquid analysis; however, research is dominated by the use of statistics and modeling with simulated data in an effort to remove bias in interpreting results. Bias is also a concern for fire investigators, although many of the papers simply state issues to be aware of and not research results. Other areas of interest in the laboratory include two-dimensional gas chromatography and recovery of fingerprints and DNA following heat exposure. The pathology of burned remains and the challenges posed in determining cause and manner of death have also been thoroughly investigated.

Publications concerning laboratory studies far outnumber those specifically for fire scenes and investigators. While there are entire journals and conference proceedings devoted to the study of fire and its effects on materials and safety, only those articles most relevant to the field of forensic fire investigations were selected for this paper. Other topics of interest relate to fire research, including fire modeling, liquids, furniture, and lithium-ion batteries, as well as scene contamination, ignitable liquid detection canines, and a brief summary on papers dealing with the psychology and behavior motivations of arsonists.

2. Fire debris analysis

2.1. Standards

The following standards related to fire debris analysis have been published by ASTM International:

ASTM E2451-21: *Standard practice for preserving ignitable liquids and ignitable liquid residue extracts from fire debris samples* [2].

ASTM E3245-20e1: *Standard guide for systematic approach to the extraction, analysis, and classification of ignitable liquids and ignitable liquid residues in fire debris samples* [3].

ASTM E3197-20: *Standard terminology relating to examination of fire debris* [4].

ASTM E1412-19: *Standard practice for separation of ignitable liquid residues from fire debris samples by passive headspace concentration with activated charcoal.* [5].

ASTM E1413-19: *Standard practice for separation of ignitable liquid residues from fire debris samples by dynamic headspace concentration onto an adsorbent tube* [6].

ASTM E1618-19: *Standard test method for ignitable liquid residues in extracts from fire debris samples by gas chromatography-mass spectrometry* [7].

2.2. General

Evans-Nguygen and Hutches compiled a book with contributions from numerous authors on various subjects related to fire debris analysis [8]. The book was designed for students and professionals and covers topics on background interferences, alternative fuels, microbial degradation, and ignitable liquid variability.

Another book by Evans-Nguygen contains a chapter specific to ignitable liquid analysis [9]. The chapter offers details on extraction, instrumental analysis, data interpretation, and classification for students interested in becoming forensic chemists.

Mirakovits and Londino-Smolar developed a laboratory manual for forensic science educators [10]. One of the chapters is devoted specifically to fire debris analysis and includes student exercises for identifying ignitable liquid patterns. This book is meant to be used in conjunction with an instructor manual that has more background information and teaching points included.

E-mail address: michelle.evans@atf.gov.

https://doi.org/10.1016/j.fsisyn.2022.100310

Wolstenholme et al. wrote a comprehensive guide for undergraduate and graduate students to bridge the gap between analytical chemistry and forensic science [11]. The book touches on numerous instrumental techniques and their application to different forensic fields, including the analysis of ignitable liquids.

Bueno Carmona et al. prepared activated charcoal pellets (ACP) for the extraction of ignitable liquids by pressing charcoal powder and D-glucose into a pellet form [12]. While the ACPs were able to effectively extract gasoline and diesel fuel from simulated debris, the authors note further study is needed to optimize extraction time and temperature and to better understand the adsorption mechanism.

Baerncopf and Hutches evaluated charcoal strip preservation of ignitable liquids over a two-year period [13]. Two volumes (high and low) of gasoline and a heavy petroleum distillate were spiked onto an inert substrate, collected using passive headspace concentration (PHC), and stored in three different vials at room temperature. The charcoal strips were tested at regular intervals over a two-year period and were found to retain the ignitable liquid in all vial types and with both volumes.

Swierczynski et al. spiked household materials with gasoline, let them dry for set periods of time, and then extracted them using headspace solid phase microextraction (SPME) and gas chromatography-mass spectrometry (GC-MS) [14]. Gasoline was detected in cotton fabric up to seven days after drying, with cardboard and carpet retaining the gasoline for more than three weeks. The authors used small vials for headspace analysis, which they attributed to the improved detection limit and ability to identify residues after such an extended timeframe.

Buchler et al. examined five different collection methods with activated carbon cloth (ACC) and activated charcoal strips (ACS) for sampling ignitable liquids on hands [15]. ACC was shown to be as effective as ACS at recovering gasoline; however, distance between the adsorption material and skin and available headspace during sample collection were two key factors in extraction efficiency for both ACC and ACS.

Totten and Willis used hydrophobic pads to collect ignitable liquids from water samples [16]. The pads could easily recover compounds above n-C_8, but lighter compounds were only present when higher concentrations of ignitable liquids were used.

Carlotti tested 15 different household absorbent materials, including paper towels, shop towels, cotton balls, and cleaning cloths, to determine suitability for the collection of ignitable liquids from porous and non-porous substrates [17]. Seven of the materials analyzed did not have potential interferences with ignitable liquids and were found to be effective at collecting residues from non-porous surfaces; however, recovery from a porous substrate was not as successful. Collection time and method were optimized in an effort to improve efficiency.

Baerncopf investigated the prevalence of ignitable liquids on new and worn shirts containing printing [18]. 141 shirts were analyzed using PHC and GC-MS with 34% having potential heavy normal alkane patterns and 41% containing aromatic patterns. While not all of the aromatic patterns were strong enough to be identified, the high occurrence suggested a caveat should be used when identifying an aromatic product in clothing with printing.

Dhabbah examined burned and unburned fabric spiked with gasoline to determine how long the ignitable liquid could be detected using SPME and GC-MS [19]. Results showed that gasoline persisted longer (up to 4 h) on unburned synthetic fabric (nylon and polyester) than on cotton or wool. Residues on burned fabrics were not detectable after 2 h.

Guerrara et al. analyzed clothing and body products to ascertain if the compounds present would interfere with ignitable liquid analysis [20]. Samples of worn and unworn clothing and a variety of body products were analyzed using PHC and GC-MS. Some body products produced patterns similar to heavy petroleum distillates. The clothing examined contained compounds that are often observed in ignitable liquids; however, while these may interfere with the identification of an ignitable liquid, a trained examiner would be able to determine the difference between substrate and ignitable liquid contributions.

Hutches et al. investigated the presence of ignitable liquids in 86 pairs of new and lightly used athletic shoes [21]. The individual shoes were heated at 40 °C and 65 °C to determine if a lower temperature would prevent the release of the ignitable liquid from the adhesive used to make the shoe. Fewer ignitable liquids were observed at the lower temperature, but overall, only five of the 172 individual shoes heated to 65 °C had an identifiable ignitable liquid, which was a much smaller number than expected. The study also looked at the viability of comparing individual shoes to each other, to different models by the same manufacturer, and to the same models by the same manufacturer. While individual shoes can be compared to each other and potentially to the same model, there were marked differences noted between different models by the same manufacturer with no consistent trends in patterns based on manufacturer or construction.

Whitney tested three different detergents to determine the best way to decontaminate a fire investigator's scene clothing [22]. Various washing machine and dryer conditions were examined to identify the best method for removing trace amounts of ignitable liquids. Using rigorous washing and drying conditions, two of the three detergents tested were able to sufficiently remove trace quantities of gasoline and diesel fuel.

Jess et al. used the QuEChERS method ("Quick, Easy, Cheap, Effective, Rugged, and Safe") to try to extract ignitable liquids from cotton fabric [23]. QuEChERS is an extraction kit that utilizes salt-induced partitioning, followed by solvent extraction and dispersive solid-phase extraction for sample clean-up. The complicated QuEChERs procedure was compared to typical PHC as a proof of concept, and although it worked, QuEChERS samples were consistently less abundant than PHC-extracted samples, which could pose challenging for identifying low concentrations of ignitable liquids.

Hsieh et al. analyzed cloth containing vegetable oils by pyrolysis GC-MS to identify the presence of fatty acids [24]. Small quantities of the cloth samples were directly pyrolyzed, without extraction or derivatization to fatty acid methyl esters. Data indicated that the amount of unsaturated fatty acids present were directly related to the length of heating of the cloth samples and could indicate the potential of a spontaneous ignition event.

Bryant et al. identified triglycerides in liquid and debris samples using liquid chromatography (LC) with a triple quadrupole MS [25]. Samples were extracted in solvent and then directly analyzed on the instrument, without the need to derivatize into methyl esters. Two or more triglycerides were identified in all samples tested, both pristine and degraded. The identification of triglycerides would allow the analyst to report the presence of a triglyceride-based oil or fat.

Letendre et al. compiled references relating to studies on transfer traces of a variety of different materials, including ignitable liquids [26]. The articles discussed were taken from a database related to trace material transfers and covered 1977 to 2020. There were 77 publications concerning background levels of ignitable liquids, transfer, persistence, and collection, but the authors note that these were limited in scope and more work needs to be done on the topic.

Jin et al. used target compounds in an effort to distinguish between gasoline and various types of polystyrene-based rubbers [27]. Pyrolysis products included numerous compounds that were similar between the materials with the most common interferences being from alkylbenzenes.

Jin et al. burned and then reheated gasoline residues to determine the effects of fire on the stability of the target compounds [28]. Alkylbenzenes were the most stable upon reheating, whereas polycyclic aromatic hydrocarbons (PAHs) and indanes were more susceptible to being destroyed by the additional high heat.

Barnett et al. used direct analysis in real time mass spectrometry (DART-MS) to identify ignitable liquids on substrates [29]. Two different types of DART-MS were used, QuickStrip and thermal desorption, with thermal desorption providing better detection of residues in the presence of substrates. DART-MS generated mass spectra with more peaks in the higher mass range than regular GC-MS, which improved detection of less volatile compounds.

Yadav et al. compared the solvent extraction efficiency of hexane and diethyl ether for the recovery of diesel fuel from partially burned substrates [30]. Diethyl ether was determined to be best at extracting diesel from the porous matrices tested, including wood, ceramic-based tile, and cotton. Neither solvent was successful on the non-porous plastic material tested.

Bordbar et al. developed an optical nose with metallic nanoparticles dropped on a paper substrate for the detection of ignitable liquids [31]. Vapors from gasoline, diesel fuel, kerosene, paint thinner, and oxygenates were found to change the color of the nanoparticles and could be differentiated using statistical analysis. Contaminants in gasoline could be detected and identified, based on color changes, as to the type and concentration of the contaminant.

Harries et al. used a simulated diesel fuel sample (five-component surrogate) to evaluate flow rate and temperature on headspace vapors collected using a porous layer open tubular (PLOT) capillary cryoadsorption system [32]. Based on their analyses, they determined that this surrogate mixture was a suitable material for comparisons to real diesel fuel.

Zhang et al. simulated a fire in a bus using diesel fuel and analyzed samples for the presence of ignitable liquid residues using both solvent extraction and headspace analysis followed by GC-MS [33]. While diesel fuel could be identified in the samples collected, solvent extraction was determined to be best suited for substrates with little matrix interference. Headspace analysis reduced the impact of the matrix interferences.

Roberson's doctoral dissertation was the basis for the following two publications below [34]. In an effort to improve efficiency, Roberson examined micro-bore capillary columns to decrease separation times and GC coupled with a vacuum ultraviolet spectrometer (VUV) to enhance specificity.

Roberson and Goodpaster created micro-bore capillary columns with thick films but a high separation efficiency for fast GC analysis [35]. The columns were prepared in the authors' laboratory and were tested using a variety of ignitable liquids. GC-MS analysis using these columns was successfully conducted on the samples in less than 3 min.

Rael et al. used GC-VUV to analyze ignitable liquids [36]. The research focused on the alkylbenzenes, since they are a prominent compound class in petroleum products. GC-VUV was shown to have better specificity than GC-MS in full scan mode and could identify all alkylbenzenes correctly, even the structural isomers. Detection limits for both GC-VUV and GC-MS were comparable.

Torres et al. compared the extraction and analysis of ignitable liquids using a portable and benchtop GC-MS that had each been coupled to a capillary microextraction of volatiles (CMV) device [37]. The CMV-portable set-up did not have sufficient chromatographic resolution due to the type of portable GC-MS used; however, the CMV-benchtop set-up was successful at extracting and identifying specific ignitable liquid components. The research showed proof of concept for the CMV extraction technique, which has the potential to be used in combination with other portable and benchtop GC-MS systems.

Torres and Almirall followed up the previous work with further evaluation of a CMV and paper cup extraction mechanism that was coupled to a portable GC-MS for field sampling [38]. The CMV and paper cup method successfully extracted numerous target ignitable liquid components, was more efficient than the portable GC-MS sampling wand, and was more sensitive than traditional ignitable liquid headspace extraction techniques.

Nims et al. utilized stable isotope ratio analysis of aromatic compounds in diesel fuel to determine if the fuel was adulterated [39]. Of the four isolation and purification methods tested, ionic liquid coated solid phase microextraction was the quickest and easiest for separating the specific aromatics from diesel fuel. Toluene exhibited sufficient isotopic variability and allowed native toluene to be differentiated from adulterated toluene.

2.3. Two-dimensional gas chromatography (2D GC or GC x GC)

In a book edited by Cordero, DuBois et al. discussed the use of 2-dimensional GC for a wide variety of applications, including ignitable liquids [40]. The authors reviewed numerous publications where GC x GC has successfully identified ignitable liquids from different classes, evaporation levels, and quantities.

Pandohee et al. used 2D GC with a flame ionization detector (FID) to analyze numerous ignitable liquids, both neat and weathered, to evaluate differences in chromatographic data [41]. Different classes of ignitable liquids were able to be differentiated based on the 2D patterns generated and the use of principal component analysis.

Boegelsack et al. optimized a flow-modulated GC x GC method for the analysis of ignitable liquids from wildfire debris [42]. Different GC columns and parameters, including flow rate and oven programming, were assessed with the final method using a 5% diphenyl column coupled to a 50% diphenyl column. MS was used to help resolve matrix interferences. The GC x GC-MS utilized in this research was able to successfully resolve target compounds listed in ASTM 1618 and classify ignitable liquid residues within a complex matrix.

Boegelsack et al. developed a retention time index system for use with GC x GC analysis of ignitable liquids [43]. A contour map was created for neat liquids and scene samples by ASTM E1618. This contour map and retention index system proved useful in standardizing and comparing data.

Kates et al. applied GC x GC with time-of-flight (TOF) MS to the analysis of fire debris samples taken from wildfires [44]. The authors found that using GC x GC-TOFMS allowed for better separation of ignitable liquids from interfering compounds in the matrices, due to lower detection limits. Debris originally analyzed by GC-MS was re-analyzed by GC x GC-TOFMS, which reduced the tentative results to 6% and successfully identified ignitable liquids in 76% of the re-analyzed samples.

2.4. Instrument review articles

Young and Lurie wrote a review article covering literature published between 2015 and 2020 on forensic applications of enhanced separation methods, including GC, LC, and supercritical fluid chromatography [45]. One section of this paper was devoted to fire debris analysis and primarily discussed the use of comprehensive 2D GC with different detectors for the identification of ignitable liquids.

Kammrath et al. discussed forensic applications of portable spectrometers in Volume 1 and Leary et al. reviewed portable GC-MS applications in Volume 2 of a two-volume book edited by Crocombe et al. [46]. The sections on fire debris analysis were brief in both chapters but touched on the detection and identification of ignitable liquids using portable hydrocarbon sniffers and GC-MS instruments.

Sisco and Forbes reviewed literature concerning the forensic application of DART-MS [47]. DART-MS has been shown to provide a fast alternative for screening for the presence of ignitable liquids. In general, chemometric methods need to be used for differentiation of neat liquids and evaporated samples due to the lack of chromatographic separation capabilities.

Patel and Lurie provided a review of portable separation devices used in forensics [48]. Articles were listed that discussed the recent use of portable GC and GC-MS systems for fire debris samples. While analysis of volatiles by portable systems may be faster and provide higher temperature ranges, the detection limits are also greater.

DeHaan discussed the application and limitations of portable GC-MS systems for fire investigations [49]. A variety of systems designed for use by hazardous materials teams were tested, and all could provide GC separation, reproducible retentions times, and sensitivity levels on par with traditional benchtop GC-MS models. However, the primary limiting factor was data interpretation in the field, as this typically requires significant training not available to most fire investigators and scene personnel.

2.5. Statistics/chemometrics

Sauzier et al. discussed chemometrics in forensic science, which reviewed various chemometric techniques and provided examples of studies published prior to 2020 where chemometrics have been utilized [50]. A small section was devoted to fire debris and referenced numerous articles utilizing a number of different chemometric methods.

Sigman and Williams reviewed chemometrics in fire debris analysis over the past 30 years [51]. Changes in its use and applicability from simple classification to same-source determination were discussed. The authors noted that much of the work using chemometrics has not yet made it into forensic science laboratories and remains driven by the research and academic field.

Akmeemana introduced the idea of using likelihood ratios calculated from the Naïve Bayes approach for identifying ignitable liquids in fire debris [52]. Data from the National Center for Forensic Science Substrate and Ignitable Liquid Reference Collection was used to calculate the frequency of occurrence of compounds in substrates and ignitable liquids. The Naïve Bayes approach successfully classified pure substrates and ignitable liquid samples, but not mixtures of both, due to the effects of burning on the presence of certain compounds.

Bogdal et al. presented a two-part study on recognizing gasoline in fire debris using machine learning [53,54]. Part 1 focused on the development of a machine learning tool using various algorithms. Part 2 created a convolutional neural network of searchable bitmap images of GC-MS data. Both techniques required training the machine with known samples and testing it on unknown samples. The datasets in both studies were limited to gasoline, but each approach showed the ability to screen and classify samples correctly up to 98% of the time.

Park et al. developed three different machine-learning models using GC-MS data from 728 samples of actual fire debris [55]. The classification accuracies for the models ranged from 63 to 84%. The dataset was limited in size for some ignitable liquids, making the accuracy lower for those particular liquids.

Korver et al. combined machine learning, advanced thermodynamic modeling, and quantum chemical calculations in an effort to predict the original (unevaporated) composition of a weathered gasoline sample [56]. The goal of the project was to be able to compare evaporated ignitable liquids to unevaporated ignitable liquids, such as those that might be found at a fire scene and in a suspect's possession. The accuracy of the predictions depended on the sample's degree of weathering and could be improved with more data being input into the system.

de Figueiredo et al. used an untargeted chemometric approach with data obtained from 190 unique gasoline samples to attempt to differentiate the liquids [57]. Headspace concentration using Tenax TA tubes followed by automated thermodesorption GC-MS was used to collect the data. All 190 samples could be distinguished from each other with this methodology; however, the authors note that further work needs to be done on weathered samples and with different extraction techniques in order to validate it for broader use.

Allen statistically evaluated classifier performance on known and unknown ground truth fire debris samples [58]. Computationally mixed datasets were generated, which created 10,000 samples to help improve the relevancy of the population and classification used in forensic casework. The partial least squares discriminant analysis (PLS-DA) model was shown to be the best for determining if a sample contained an ignitable liquid.

Allen et al. generated 9000 total ion spectra of pyrolyzed substrates mixed with and without ignitable liquids for use with a PLS-DA model [59]. Once the model was validated, it was tested on fire debris samples from simulated real-life burn tests that had been evaluated by an experienced analyst. The PLS-DA model was successful and demonstrated the possibility of introducing probability statements in court for fire debris evidence.

Thurn et al. used artificial neural networks to attempt to classify ground-truth fire debris samples [60]. Ions that were representative of typical ignitable liquid compound classes were the basis of the input data for the neural network. An optimal decision threshold was developed that enabled discrimination between ground truth ignitable liquid samples and ground truth substrate samples.

Sigman et al. trained and validated five supervised machine learning tools using 767 laboratory-generated ground truth fire debris samples [61]. Classifications given to the samples by an experienced analyst were compared to the classifications generated by the machine learning models, of which two of the five models most closely aligned with the examiner's conclusions.

Eklund and Eklund et al. used kinetic modeling to predict the evaporation of gasoline [62,63]. Experimentally evaporated gasoline samples were prepared and used as the basis to improve the predictive accuracy of the model. Instrument method modifications were necessary in order to increase correlation between predicted and experimental data.

Capistran and Capistran et al. built on the research completed by Eklund and used kinetic modeling to predict evaporation rate constants of compounds found in isoparaffinic products, naphthenic-paraffinic products, and aromatic products as a function of the GC retention index [64,65]. Using experimentally evaporated liquids as a basis, the model was able to successfully predict extracted ion profiles and total ion chromatograms corresponding to the various compound classes for each liquid.

Burkhart, McGuffin and Smith, and Burkhart et al. examined kinetic and thermodynamic models to measure the evaporation rate constants of highly volatile compounds found in gasoline [66–68]. Theoretical calculations were initially performed in order to safely evaporate samples experimentally. Data obtained from the kinetic model was compared to data obtained experimentally and correlated well, which could be useful when the rate of evaporation of certain ignitable liquids is of interest.

Christy et al. examined chromatographic features in 150 samples of gasoline to develop quantitative criteria to aid in the identification of samples up to 90% evaporated [69]. Peak height ratios from 64 chromatographic peak groupings were subjected to statistical analysis to determine their relative significance. The scores generated were used to create a sufficiency graph, which provided a graphical representation of the data supporting a gasoline identification. The ultimate goal of the research was to provide the foundation for strengthening the data interpretation process in fire debris analysis.

Vergeer et al. used a likelihood ratio system to compare gasoline residues to liquid samples [70]. Clean, unburned substrates, instead of burned matrices, were used to simulate debris and to alleviate issues potentially caused by pyrolysis products. The research was generally a proof of concept to show the potential for using the likelihood ratio to compare residues to liquids; however, further work is needed to overcome numerous limitations mentioned in this work with regards to sample preparation, evaporation and matrix effects, and experimental design.

Falatova et al. investigated the use of an electronic nose (headspace-MS eNose) and chemometric tools to identify ignitable liquids in simulated fire debris samples [71]. Only two substrates (cotton and cork) and two ignitable liquids (ethanol and diesel fuel) were tested, and while results indicated that the applied chemometrics could successfully discriminate the samples, the chosen ignitable liquids do not overlap in chemical composition and would have been readily distinguishable without statistical treatments.

Sudol et al. comprehensively reviewed GC and GC x GC techniques and chemometrics used for the forensic analysis of petroleum products [72]. In the publications discussed, GC x GC has proven to be analytically superior to GC in that it provides significantly more chemical information; however, as a result, this requires the use of higher-dimension chemometric tools to aid in data interpretation, making it a challenge to implement in most forensic laboratories.

Deng et al. used mathematical methods applied to data obtained from thermogravimetric-differential scanning calorimetry and GC-MS in order to differentiate between gasoline and pyrolysis products from styrene butadiene rubber (SBR) [73]. By using principal component analysis, gasoline was easily distinguished from the various pyrolysis stages of SBR.

de Figeiredo et al. evaporated and burned gasoline samples on a substrate and then used chemometrics to try to link the residue to the source liquids [74]. Chemometrics were key in associating evaporated, burned, and unburned samples by selecting the most discriminating ratios for comparison. This study was exploratory and further work needs to be done on a larger sample and substrate population.

Willis et al. applied a thermodynamic model to an artificial gasoline mixture and gasoline evaporated in a lab environment in order to predict the extent of weathering [75]. Results indicated that temperature had an effect on the compounds present in the remaining residues, with gasoline evaporated at room temperature having a different profile from gasoline evaporated at higher temperatures, like those in a fire situation.

Wensel continued the work of Willis et al. by using the same model applied to gasoline weathered at elevated temperatures on wood and carpet [76]. The research focused on examining the effects of the weathering temperature, substrate porosity, and depth of ignitable liquid penetration on the resulting data. Laboratory-derived data was compared to the thermodynamic model, which worked well for predicting evaporation of pure liquids but was not as successful with the addition of substrates. The author theorized that the entrapment of the ignitable liquid in the substrate caused the differences seen between the experimental data and the model.

2.6. Other

Yadav et al. discussed the use of infrared and Raman spectroscopy in examining fire debris samples [77]. The article primarily focused on using these techniques to identify polymers in the debris and not on ignitable liquids. The authors noted that further research needs to be performed to better evaluate spectroscopic instrumentation for ignitable liquid identification.

Huang and Yu used portable Raman to identify and differentiate neat and weathered liquid gasoline samples [78]. Using a transfer learning technique, the 50% weathered gasoline samples could be accurately classified 73% of the time and 25% weathered gasoline was accurately classified 53% of the time.

Aliano-Gonzalez et al. investigated the use of ion mobility mass spectrometry sum spectrum (IMSSS) in conjunction with chemometrics for the detection of ignitable liquids in fire debris samples [79]. IMSSS was utilized following headspace analysis on burned substrates with and without different ignitable liquids. By using chemometrics (linear discriminant analysis), the presence or absence of an ignitable liquid could be accurately determined, and each class could be discriminated with a characteristic data fingerprint.

3. Fire-related forensic analyses

3.1. General

Aviassar et al. examined the recovery of fingerprints from glass using black magnetic powder [80]. Ignitable liquid extraction temperatures of 60 °C, 90 °C, and 130 °C and 0.5 mL and 2 mL volumes of kerosene, diesel fuel, and gasoline were used. Results showed that temperatures greater than or equal to 90 °C and ignitable liquid concentrations of 2 mL had a detrimental effect on latent print development, as higher temperatures caused loss of water from the fingerprint ridges and lipid interaction with gasoline.

Bastide et al. modified a digital single-lens reflex (SLR) camera in order to visualize soot-covered bloodstains with reflected infrared photography [81]. Regular photography was unable to penetrate dense soot layers, but reflected infrared photography successfully captured these bloodstain images, thus allowing crime scene examiners to have a better method for locating bloodstains in heavily soot-damaged fire scenes.

Bastide et al. observed the spectral characteristics of blood exposed to fire and used spectrophotometry to determine that the appearance, viscosity, and infrared absorption properties of blood are related [82]. The findings indicated that blood in post-fire scenes, especially on darkened substrates, like soot, could be visualized using reflected infrared photography.

O'Hagan and Calder provided a review of literature and techniques for the recovery and identification of DNA and fingerprints from fire scenes [83]. Numerous different successful methods were listed, but the authors pointed out that since every fire scene is unique, no one set technique will work for every situation.

McGann explored the possibility of obtaining DNA profiles on samples that were initially subjected to ignitable liquid analysis via PHC [84]. DNA recovery was somewhat affected by increased oven temperature (90 °C) and extraction time (16 h) during PHC but was overall successful, even on samples showing charring. This research helps to support the idea of analyzing evidence for ignitable liquids prior to DNA analysis.

Hady et al. exposed fabric samples stained with blood and semen to different temperature grades (−20 °C to 100 °C) in an oven to simulate heat from a fire [85]. Presumptive tests were able to identify bloodstains at higher temperatures but were not successful at identifying semen stains at the same temperatures. The DNA extracted from both the blood and semen stains was comparable at all temperatures tested, with degradation noted for both at 100 °C.

Klein et al. used liquid latex to better visualize bloodstains at fire scenes [86]. Traces of blood were detectable with luminol and liquid latex up to 1000 °C. The latex appeared to remove extraneous debris and allow for better luminescence properties of the blood. While DNA analysis was performed on samples tested with luminol only, due to cost reasons, this was not done on samples treated with the liquid latex. Thus, the effect liquid latex could have on further exams still needs to be examined.

Bourn studied the effect of heat on the recovery of DNA from teeth [87]. Pigs' teeth were subjected to temperatures between 500 °C and 900 °C for 10–30 min and then analyzed for DNA. Degradation of DNA quality and quantity was noted after 500 °C for 15 min.

Federchook et al. examined the color changes in teeth due to thermal exposure and how this would affect DNA recovery [88]. Results showed that the color of the tooth had a high correlation with the quantity and quality of DNA obtained. Teeth that were beige, yellow, or orange in color were likely exposed to temperatures less than 200 °C and had a better likelihood of viable DNA. Brown, black, or gray-colored teeth gave poor DNA results due to higher temperature exposure.

McKinnon et al. reviewed relevant literature regarding the DNA analysis of burned bone, to include impacts on sample collection and challenges with DNA extraction [89]. Ultimately, the published research shows that the thermal effects on bone and the subsequent DNA recovery are not completely understood, and more research is needed to optimize protocols.

Solodov and Solodov discussed recovering data from hard disk drives (HDDs) and solid-state drives (SSDs) that are damaged by fire [90]. The authors described a case where data from numerous HDDs and SSDs from different manufacturers were successfully recovered even after fire exposure and subsequent suppression efforts. Time was noted as a key factor in avoiding data loss due to corrosion.

Constantine et al. examined charcoal using FTIR and a multivariate statistical model in order to determine charring intensity [91]. While the study only used charcoal produced in the laboratory, results indicated this could correlate to many different types of real-world wood samples and aid in determining fire severity.

Sharma et al. utilized various non-destructive light sources to evaluate charred documents [92]. Even after charring, many of the document security features could still be visualized and differentiated from forgeries, depending on the light source used.

3.2. Pathology

A chapter in a book by DiMaio and Molina covers the effects seen on bodies as a result of burns and fire-related deaths [93]. The book is written by forensic pathologists for pathologists, law enforcement officers, and attorneys so that they can have a better understanding of manner and cause of death. Numerous photos depicting fire trauma to the body help explain the various types of burns and evidence that should be collected.

Spitz and Diaz wrote an extensive chapter detailing fire and scalding injuries [94]. The authors provide numerous photos and descriptions of the different types of damage that will be seen on burn victims.

McGarry et al. utilized a portable X-ray fluorescence (XRF) to differentiate burned bone fragments [95]. Bones were burned for 30 min at temperatures between 200 °C and 900 °C and then elementally analyzed with the XRF. Elemental profiles were found to vary based on the degree of burning and could be successfully distinguished with statistical treatment.

Rahmat et al. used a handheld portable spectrophotometer and X-ray diffractometer (XRD) to examine the color and crystallinity changes in burned dental remains [96]. Pigs' teeth were incinerated at different temperatures and then analyzed. By using both techniques, researchers were able to estimate the maximum temperature at which the teeth were exposed.

Rahmat et al. developed an online tool to predict the temperature at which teeth are exposed [97]. Pigs' teeth were used to simulate human teeth and were exposed to 300 °C, 600 °C, 800 °C, and 1000 °C. Data from colorimetric tests, hydroxyapatite crystal size, and appearance were used to create a statistical model, which was found to have a prediction accuracy of 95%.

Krap et al. subjected various bone samples to temperatures ranging from room temperature to 900 °C and then scanned the samples with a flatbed scanner and photographed with a digital SLR camera [98]. Using colorimetric techniques, the authors were able to estimate the temperature at which the bones were exposed. This method is less destructive than chemical tests and would meet the Frye and Daubert court standards.

McKinnon et al. used both XRD and scanning electron microscopy (SEM) to examine the crystalline profile of bones exposed to temperatures between 100 °C and 1000 °C [99]. Samples heated above 500 °C showed significant changes in crystallinity, whereas samples burned at less than 500 °C, while visually different, had no significant changes in crystallinity. The results of this have implications for DNA extractions, as samples exposed to lower temperatures could be treated as "fresh", but higher temperature exposure may require more rigorous DNA extraction protocols.

In Williams doctoral dissertation, a system was developed to classify burned human remains, both soft tissue and bone [100]. The method assessed thermal damage per area on the body and gave an overall score that was then used to estimate exposure time and fire conditions. Results provided insight on how time, temperature and environment affected the body in a fire.

Galtes and Scheiers evaluated fractures on long bones to differentiate between perimortem blunt trauma and heat-induced bone damage [101]. Close examination of the long bone fracture patterns can help determine the source of the damage.

Malainey and Anderson burned vehicles containing decomposing pig carcasses to determine the effect of fire on the survivability of insect evidence [102]. Vehicles were completely destroyed by fires that were set with gasoline, but large amounts of undamaged insect evidence were still present in the carcasses, thus allowing for valuable information on estimating time since death.

Conway et al. reviewed fire-related homicides from the medical examiner's office in Detroit, Michigan [103]. A majority of the 38 cases showed that deaths were related to inhalation during dwelling fires. Eight cases were a result of thermal injury after being burned, and eight other cases were from traumatic deaths with burning, either subsequently or contemporaneously. The authors note that there is no one single diagnostic factor to determine cause or manner of death, and medical examiners should rely on a combination of carboxyhemoglobin levels, the circumstances surrounding the death, and the presence or absence of fatal trauma in order to categorize the death.

Simonit et al. examined self-immolation (setting fire to oneself) cases involving "complex suicides," which are deaths having more than one suicide method [104]. Differentiating between bodies burned as part of a complex suicide and those burned by someone trying to cover up a crime is an important determination that needs to be made regarding cause of death. While these cases are rare, they do occur, and the authors pointed out that more research on the topic is necessary to improve knowledge on the subject.

de Bakker et al. studied past use of post-mortem computed tomography (PMCT) to determine if it has had value for burn victims prior to autopsies [105]. PMCT was useful to show hidden signs of trauma, to identify the presence of foreign material, and to collect gases; however, it does not replace the actual autopsy, which still needs to be conducted.

Kranioti et al. presented a case where PMCT proved useful in determining injuries suffered during a car accident where the victim was subsequently incinerated [106]. PMCT helped to identify skull fractures, a hemorrhage and fluid collection, which could be observed even through the burned remains.

Mahe et al. discussed another instance where PMCT proved valuable in determining the cause of death after a vehicle accident where the vehicle and victim caught on fire [107]. Distinguishing between pre- and post-mortem bone lesions was critical to show that the lesions were a result of the thermal effects and not external trauma. The use of the PMCT in conjunction with the autopsy findings was useful in showing that the victim died as a result of being trapped in a burning vehicle and not necessarily from injuries sustained during the crash.

Hammarlebiod et al. used PMCT to assess if bone damage was the result of heat exposure or a traumatic injury [108]. The CT findings of 25 bodies with thermal bone lesions were reviewed, and it was determined that these could be differentiated from bones subjected to injury.

Tutor et al. created a visual guide and a flow chart to document heat-induced changes to bones in contrast to sharp force trauma [109]. The researchers were able to demonstrate that macroscopic differentiation between the types of damage is possible by following the flow chart.

In another study by Tutor et al., researchers attempted to determine the survivability of toolmarks on bone after dismemberment and burning have occurred [110]. Cadavers were cut with a machete and a serrated bread knife and then cremated. Only 13% of the marks made prior to burning were visible after cremation.

Vachirawongsakorn et al. examined marks made on bones with different knife blades to determine the effects of heat on the cuts [111]. Pig ribs were cut 240 times with three different knife types and then subjected to heat. Marks were able to be analyzed and identified even after burning.

Siegert et al. looked at various materials that can be used on burned bone fragments to secure them together prior to transporting them to a laboratory for analysis [112]. The authors tried four different consolidants (fixatives) and determined that Acryloid™ B-72 was the most suitable for stabilizing burned remains.

Salesse et al. used isotopic and infrared analyses to determine the position of bodies found on a pyre and to assess if the deceased was wearing closed-toe leather shoes during cremation [113]. Shoes appeared to provide a protective layer that delayed the burning of the underlying tissues, thus changing the oxygen isotope ratios when compared to feet without shoes. By analyzing the burned bones of the pigs used in this study, the authors were able to determine if shoes were on or off during the burning process, which can be important for understanding certain cultures and rituals.

Keyes examined the reliability of the charred body scale, which is used to quantify the decomposition of burned remains [114]. Pigs were burned and decomposed to different stages using the Crow Glassman Scale levels 1 to 3 (out of 5 total levels). Photographs of the pigs were then ranked by participants using the charred body scale. Results showed that the scale was reliable for remains at level 1 but not for higher burn levels, indicating that more work needs to be done creating a universal burn scale.

Juarez et al. developed a classification system for thermally damaged human remains by examining the body in segments [115]. The system breaks the body down into head, torso, arms, and legs and provides illustrations and worksheets that can be used at the scene by appropriate personnel.

Labuschagne attempted to distinguish between burned human and non-human bones via a histological examination [116]. Bones from humans, baboons, wildebeests, pigs, and cows were exposed to a temperature of 600 °C or 800 °C and then examined microscopically. Human bones could easily be distinguished from all but the baboon bones, and temperature did not seem to have any impact on the analysis.

Krap et al. studied the photoluminescent characteristics of burned bone to determine if thermally altered human bones visibly phosphoresced and if this characteristic could assist with estimating exposure temperature [117]. Results indicated that burned bones phosphoresce, with the amount of phosphorescence being more dependent on temperature, not exposure time. By evaluating the emission bandwidth, temperatures above and below 800 °C can be differentiated.

Ost et al. examined 1,760 cases processed by Mercyhurst University in Erie, PA, between 1983 and 2020 to determine the role of forensic anthropology and forensic archaeology at fatal fire scenes [118]. The study showed that there is a greater awareness of the contributions anthropologists and archaeologists can provide, as well as an increased utilization of their services in fire investigations involving fatalities.

3.3. Case studies

Wegner et al. presented the case of a 49-year-old woman who was found dead after a fire in her apartment building [119]. The autopsy noted burns on the body, but all indications pointed to her death prior to the fire. Based on unexplained bleeding in the organs and organ putrefaction, it was determined that the woman died a few days before the fire of hypothermia. The case highlighted the need to perform an autopsy to determine the cause of death.

Hehna et al. discussed a case where an elderly woman set herself on fire using matches and an ignitable liquid [120]. The burns to the victim suggested a spontaneous combustion event, given the almost complete destruction of her body with minimal damage to the surrounding area. However, these unusual burn characteristics were attributed to the location of the body, which was positioned in a hollow on the ground, leaning next to a thick tree trunk, and the chimney and wick effects created by the tree and her clothing, respectively.

Simonit et al. presented a case involving an adult male found in a burning vehicle with a gunshot wound to his head [121]. Based on the autopsy findings and the investigation of the fire scene, it was determined that the victim shot himself in the mouth without causing lethal injuries but then unintentionally pressed the accelerator for an extended period of time, resulting in the car catching on fire.

Monetti et al. shared a case of human remains found in a cemetery that had distinctive burn patterns on the bones, which were inconsistent with the position of the remains during the fire event [122]. Anthropologists that examined the remains determined that the bones were burned after they were skeletonized, likely as a result of a ritual. The case highlighted the need to understand the burning process and effect on bones and showed that macroscopic analysis of the patterns can still provide valuable information.

Alexandri et al. described a case where a 64-year-old man was found burned to death on a type of altar created from wood and a pile of money [123]. The man set his house and vehicle on fire before shooting himself. The scene presented as a suicide with ritualistic characteristics.

Nath et al. shared a case where a deceased, burned victim was found on the roof of a house [124]. The scene had been staged to look like suicide by burning, but the evidence and autopsy results pointed to the woman being doused in kerosene by her husband and then set on fire.

Ishigami et al. discussed the order of events surrounding a decapitated body that had also been burned [125]. Based on the scene and autopsy findings, it was determined that the victim committed suicide using a self-constructed guillotine that was activated when a nearby vehicle was set on fire and burned through cords connected to the guillotine. The burns to the victim's body were a post-mortem effect from the close proximity to the car fire.

4. Fire investigation

4.1. Standards

The following standards related to fire investigation have been published by the National Fire Protection Association (NFPA):

NFPA 921–21: *Guide for fire and explosion investigations* [126].

NFPA 1033–22: *Standard for professional qualifications for fire investigator.* [127].

NFPA 1321: *Standard for fire investigation units.* (proposed standard) [128].

The Fire and Explosion Investigation Working Group of the European Network of Forensic Science Institutes published a best practice manual for the investigation of fires and explosions [129]. The document provides numerous protocols and procedures for training personnel and investigations of fire scenes.

4.2. General

Harris and Lee edited a book on forensic science and criminalistics that includes a chapter on arson and explosives [130]. The chapter covers topics relating to fire, origin and cause determinations, evidence collection and packaging, and ignitable liquid analysis.

Kumar et al. wrote a book chapter covering fire investigations and ignitable liquid analysis [131]. Topics covered included scene examination, evidence collection and preservation, and fire chemistry, with limited discussions on laboratory analysis.

Ost-Prisco discussed important changes to the current 2021 version of NFPA 921, where the fire cause classification chapter was removed from the document [132]. The article provided the history of classifications in NFPA 921 and highlighted the challenges investigators will face going forward without this information in the latest version.

Betty and Oliva provided a critical review of the science of fire investigation and how it effects the court presentation of evidence and testimony [133]. The authors pushed for the fire investigation field to develop an error rate, use linear sequential unmasking of relevant case information, and to develop a standardized evidence quality assessment tool.

Jansen's article was based on a podcast that interviewed a variety of people, including a fire investigator, a fire research engineer, and forensic chemists [134]. The origins of typical fire myths are discussed and debunked, as well as the move towards standardization in methods at both the scene and in the laboratory.

Siegel and Mirakovits included a chapter covering fire investigations and laboratory analysis in their book on the basics of forensics science [135]. The chapter provides a foundation and background on fire chemistry, fire scene examination, and ignitable liquid analysis.

Johnson et al. explored the challenges of fire investigations in the United Kingdom [136]. The book chapter covers a variety of topics including accreditation and certification, training, general issues, and a relevant case study.

Aron discussed investigations of fire and explosion scenes [137]. The author provided procedures for securing, searching, and processing the scene with an appropriate team.

Lentini provided an overview of the history of fire investigation and recent changes that have developed regarding scene examination and standards [138]. The author discusses how the understanding of fire effects and the science of fire investigations have evolved and have increased the need for accreditation, certification, and standardization.

Claflin highlighted the need for proper documentation of the scientific method in origin and cause reports [139]. Two of the author's primary recommendations were that organizations have standard procedures for what needs to be included in these reports and that the reports be technically reviewed by someone who did not participate in the original investigation.

Alden and Dusseau provided an overview of the basics of fire investigations [140]. Various standard terms are defined, and the application of the scientific method was explained in detail. Proper documentation, expert witness testimony, and interviewing were also covered.

Vecchiolla explained the importance of the first-arriving firefighting units and the cross-over between the firefighting and fire investigator role [141]. The importance of evidence preservation and providing firsthand witness accounts was stressed as being critical to the investigation and scene processing.

Viegra discussed examining evidence collected from a fire scene not only for the presence of ignitable liquids, but also for items that may have been used to start the fire [142]. The author emphasized the need to closely sift through debris in the area of origin to find items that may have evidentiary value and to potentially separate these items for examination, if necessary.

Avato and Gundert explained the challenges fire officers might face as supervisors of fire investigation units (FIU) [143]. The authors described how fire investigations and the resulting required documentation are different from firefighting duties and how managing an FIU will necessitate a change in mindset.

Lentini presented information that litigators should be aware of when having fire investigators as expert witnesses [144]. A series of case studies on fire investigations were discussed that highlighted failures on the part of the experts during the investigation. The author also listed numerous questions that should be posed to fire investigators to challenge qualifications as an expert.

Morling and Henneberg discussed the concept of cognitive bias and its effect on the investigation of fatal fires [145]. Suggestions to limit task irrelevant data that might compromise the decision-making process included utilizing a case manager and linear sequential unmasking of information. Both approaches filter only necessary information to the forensic examiners, which includes the fire investigator and medical examiner.

Merola et al. advocated for the team approach when investigating fire fatalities [146]. In a limited ($n = 56$) study of homicides where fire was used to conceal the crime, fire investigators were involved only half of the time. Cases were primarily handled by major crime detectives who lacked knowledge and experience with the effects of fire on a body. A collaborative effort was recommended to include a homicide investigator, fire investigator, forensic anthropologist, and medical examiner with fire fatality experience.

Sara discussed the need for more cooperation between public and private sector fire investigators [147]. Various examples were mentioned where information was appropriately shared and beneficial to both parties and where better communication between the parties would have helped the case. The article highlighted the mutual benefit of public and private investigators cooperating to determine the origin and cause of a fire.

Woodman et al. collected data from 273 structural fires in Victoria, Australia, to determine the impact of forensic evidence on the criminal prosecution of arson cases [148]. While a statistical analysis of the data set was not possible, the authors did notice that forensic fire evidence, which included scene and laboratory examination, appeared to influence the judicial outcomes of suspected arson cases. More charges were brought with successful prosecutions when more evidence of arson was supported.

Harrison wrote a book chapter that recommended using archaeological techniques to process fire scenes [149]. The author drew parallels between an archaeology examination of a grave and a fire scene excavation. Archaeological techniques can be used to assist in understanding the deposition of debris in complex scenes.

Ljungkvist and Thomsen evaluated the use of ultraviolet (UV) light to assist with visualizing liquid and fire patterns [150]. Based on a combination of a literature review and current research that evaluated the effects of time and weather conditions, the authors concluded that UV light can enhance the liquid patterns and subsequent sampling of debris. UV light used in conjunction with fluorescent photography was helpful in observing the scope and dispersion of the liquid.

4.3. Electrical

Tubbs emphasized the need for fire investigators to either use a qualified electrical expert or to be properly educated and qualified in the subject when dealing with potential electrically caused fires [151]. Investigators need to be prepared for court and must have the requisite knowledge to defend their origin and cause reports when electrical ignition sources are suspected.

Parise et al. described a deductive approach to test possible hypotheses for electrically initiated fires [152]. The authors highlighted a case that illustrated their approach and ultimately recommended that electrical engineers assist with fire investigations to help rule in or rule out potential electrical sources and causes.

Novak wrote a two-part article where the first describes a methodology for examining and documenting an electrical system and the second discusses a process for identifying and interpreting electrical wiring damage [153,154]. The first article focuses primarily on arc mapping and documenting the observed damage to electrical systems. The second article provides various photos and descriptions of electrical wire damage and information on how to interpret the effects of fire on wiring.

May and Icove commented on the limitations of arc mapping as a way to determine the origin of a fire [155]. The authors explained some of the concerns regarding fire investigators claiming to be experts in electrical engineering and metallurgical analysis, which are areas of expertise needed in order to reliably perform arc mapping.

Icove and May discussed using arc mapping for determining the origin and spread of a fire [156]. Numerous articles, case studies, and recent legal decisions were presented in order to inform fire investigators on the limitations and legal issues surrounding this topic.

Franzi et al. tested how different energized cables protected by circuit breakers were affected when exposed to various heat fluxes [157]. Results were documented and compared in an effort to provide insight on the behavior of protected circuits. The most notable finding was that certain types of circuits and breakers did not always produce visible arc melting.

Rashad and Mattar studied the macroscopic, chemical, and microstructure differences between melting globules and primary and secondary arcing beads [158]. The goal of the research was to assist investigators with the evaluation of electrical wiring in fire scenes.

4.4. Case studies

Bilancia and Mann presented a case concerning a fire under a Christmas tree that was originally thought the be accidental but further investigation proved arson [159]. The authors discussed how the scientific method was used to determine the origin and cause and to prevent bias. Electrical, botanical, and chemical analyses, as well as interviews, photographs, financial audits, and full-scale test burns, were performed to properly document the scene and series of events leading up to the fire.

Ljungkvist et al. discussed a case that involved the excavation of a Viking-age (10th Century) ring fortress in Borgring, Denmark [160]. During the site excavation, evidence of a fire was uncovered, and a fire investigation team was brought in to help with the documentation and reconstruction. While the collaboration between the archaeologists and fire investigators was not able to determine the origin of the fire, the original construction of the fortress and potential fire progression were elucidated during the excavation effort.

Leshner described a case where obtaining exemplar materials was beneficial for determining the likely cause of the fire [161]. The fire was thought to have originated in an electrically powered reclining chair. Through evaluation of the power supply from old and new exemplar recliners, the wiring in the power supply proved to be the cause of the fire. The case history, subsequent testing, and dissenting opinions from the defense expert witnesses were presented.

5. Fire research

5.1. General

Baukal et al. wrote a color graphical book on fire that provides photos of various flames from combustion fundamentals to modeling to industrial flames, such as internal combustion engines [162]. Images are also included of pool fires, wildland fires, and smoldering combustion.

Scott gives an overview of fire, including topics on fire chemistry, historical perspective, uses, and effects on the environment and society [163]. While the book focuses primarily on wildland fire effects, the information provided on the elements of fire is sufficiently covered at a basic level of understanding.

The primary focus of the book by Rego et al. is on wildland fires and fire management; however, Parts I and II (of III total) are centered around fire science topics [164]. Important fire chemistry concepts on combustion, heat transfer, fuels, and fire behavior are relayed in a manner that students and practitioners can grasp and understand.

5.2. Fire modeling

Lattimer and Yang et al. presented research on a methodology to determine material properties for fire modeling data input [165–167]. The three publications covering this topic discussed an experimental process to determine thermal, physical, and combustion data for materials including fiberboard, wood, and plastics. The collected data was then input into fire modeling software and found to be within 20% of actual values; therefore, proving that the methodology would be useful for practitioners in generating accurate fire models.

Ellington provided an overview of the basics of fire dynamics and fire modeling and how they can be used in fire investigations [168]. Different types of models were discussed, along with the overall value these can bring, if applied properly, to determining the origin and cause of a fire.

Icove and May discussed how computer fire modeling is used in fire investigations and further addressed in courts [169]. Evidence admissibility, expert witness testimony, and legal challenges were presented to assist those intending to submit a fire model in court.

Cabrera and Kurzawski et al. applied a Bayesian framework to fire models to assist with fire scene reconstruction [170,171]. The papers discuss the theory behind and development of the framework, as well as the practical application that allowed for the ability to accurately determine the origin of a fire in a compartment.

Li et al. utilized the multi-fidelity Kriging algorithm in order to predict the origin of a fire based on soot deposition patterns [172]. The soot patterns were either measured in the fire scene or determined from numerical simulations; however, all experimental data generated was a result of burning propane, which is a low soot-producing fuel. The research presented a proof of concept, with further work required to validate the algorithm with heavy soot-producing materials.

5.3. Furniture

Blais et al. burned three identical rooms made up of materials to represent the different furniture fire codes in France, United Kingdom, and United States [173]. Data collected was evaluated and compared. The UK furnishings contained more fire retardant, and thus burned more slowly, producing less smoke, less toxic gases, and less overall energy. The French and US rooms utilized furniture that was not as protected from the fire, which generated more black smoke, increased levels of toxic chemicals, and higher heat release rates.

Babrauskas et al. wrote a follow-up article questioning Blais's research findings [174]. Numerous concerns were raised, including those regarding the room set-up, the experimental design, and the type of flame retardant chemicals used in the furnishings.

Gratkowski conducted 108 tests on four different bedding configurations using ignition with a matchbook [175]. Of those tested, only five did not ignite with the match, and the remaining 103 readily ignited within an average of approximately 10 s. Thermocouples were used to assess the thermal exposure of the bedding to the vertical sides of the bed, with 86 of the 96 tested exceeding ignition criteria of 6 s at 250 °C.

Morgan et al. studied the transition from smoldering to flaming using an electric spot ignition source (like a cigarette) on different fabrics, batting, and foams [176]. Results showed that materials prone to smoldering could lead to ignition, but materials that melted away from the ignition source did not transition to ignition. Flame retardants present in sufficient quantities in the fabrics and foams prevented the smoldering to flaming transition.

Sundstrom summarized the results of a comprehensive study conducted by the European Commission on the combustion behavior of upholstered furniture [177]. Test data from 72 different furniture designs helped determine how the furniture burned, how the composition affected the heat release rate, and the test procedures needed to predict room fire behavior.

Pitts et al. examined the changes in fire spread and fire growth on real-scale furniture upholstered with different materials, including barrier, fabric, sewing thread, wrap, and foam [178]. The ability to ignite the furniture was dependent on the material, with the barrier, fabric, and foam having the most statistically significant effect, and thread and wrap having the least significant effect on burning characteristics.

Hofmann et al. compared the fire behavior of synthetic polymer-based ("modern") furniture to older, cellulosic-based furniture materials [179]. Four large-scale living room tests were performed to investigate the fire development. For the rooms with modern furniture, the maximum temperatures were reached within 300 s, whereas the max temperature for the older furniture was reached after 600 s. The concentration of toxic gases in the smoke layer was also greater in the rooms with polymer-based materials.

5.4. Liquids

Guo and Tang investigated the spontaneous combustion characteristics of linseed oil, perilla seed oil, and safflower seed oil using a variety of instrumental techniques, including a microcalorimeter, thermogravimetric analysis (TGA) with differential scanning calorimetry, Raman spectroscopy, and GC-MS [180]. Results showed that the oils, especially linseed oil, were prone to self-oxidation at temperatures less than 200 °C, with initial exothermic temperatures occurring between 65 °C and 90 °C.

Huang et al. examined the fire behavior of residues from rapeseed oil, peanut oil, gingili oil, and soybean oil with elemental analysis, TGA, FTIR, and cone calorimetry [181]. Rapeseed oil proved to be the most susceptible to spontaneous ignition, based on the TGA results. However, peanut oil and soybean oil were more easily ignited by radiation from surrounding flames due to their lower critical heat flux.

Both Hu et al. and Chen et al. conducted a series of small-scale tests to characterize the flammability of corn oil [182,183]. The experiments were designed to replicate electric cooktop fires. Results showed that high heat on an electric cooktop can lead to auto-ignition of the oil, with continual heating causing vaporization and a rapidly growing fire. After auto-ignition, the oil can boil over the sides of the pan, causing ignition of nearby flammable materials.

DiDomizio et al. reviewed publications where the cone calorimeter was used to determine the ignition, burning propensity, combustion characteristics, and boiling points of liquids [184]. Guidance was given on the type of container to use with the calorimeter, but more work is needed to develop a proper liquid sample holder.

Sutarov et al. presented a case from Australia where a fire destroyed two factories as a result of water pooling on top of pallets of air conditioning "Y" splitters [185]. Investigators tested various scenarios that could cause the pallets to ignite and determined that pooled water from previous rains heated up when exposed to the sun's rays, melted the plastic wrapping the pallets, and caused the cardboard between the layers of splitters to ignite.

Okamoto et al. studied the ignition and explosion hazard resulting from spilled gasoline [186]. The research was undertaken to evaluate parameters such as volatility, flammability, and combustibility, and data collected was used to generate an evaporation and diffusion model for gasoline spills. Calculated values were compared to experimental results with good predictive qualities.

Babrauskas reviewed literature for available experimental data on ignition of ignitable liquids, vapors, and gases on a hot surface [187]. Hot surface ignition temperature was the most variable data point and must be determined experimentally. This temperature is primarily dependent on the "enclosedness" of the test conditions, with the actual ignition temperature being most affected by the volatility of the fuel.

5.5. Construction materials

Gossiaux et al. developed a small-scale single burning item test in order to evaluate the fire behavior of building materials [188]. The authors described the equipment needed, the procedure used, and the methodology for calibration. Two different types of foams, with and without flame retardants, were utilized to demonstrate the efficiency of the testing process.

McLaggan et al. used a bench-scale study to assess the fire behavior of different components of cladding materials from the Cladding Materials Library [189]. Results from heat release rate data indicated that the organic content was a poor indicator of fire performance. Differences within categories of materials was found to be significant, indicating that further work is needed to evaluate the effects in full scale testing.

Eliers demonstrated the possibility of embedding temperature sensors in wall paint so that temperatures could be measured during a fire [190]. The project involved the ability to embed and remove the sensors from the paint, calibration of the sensors for different temperatures and times, assessment of the sensor performance, and evaluation of the practicality of using the sensors routinely in construction. While the sensors were successfully embedded and could accurately measure the temperatures in test fire situations, the applicability of their use is best limited to investigator training scenarios.

5.6. Lithium-ion batteries

Nagourney et al. studied post-burn features of various lithium-ion batteries in order to assist fire investigators with origin and cause determinations [191]. The batteries were intentionally burned, and repeated testing demonstrated that physical changes previously thought to have been indications of fire cause are actually a result of being a victim of the fire, not the source.

Yan et al. tested a variety of lithium-ion battery configurations, including on composite cushions with different fabrics and in laptops, to determine if there were any post-fire signatures that could indicate if the battery was the victim or cause of the fire [192]. Results showed that measuring the mass loss of the cell can support one of these scenarios. A small mass loss suggested that the batteries could not be a competent ignition source, but the authors acknowledge further research should be conducted.

Liu et al. analyzed the combustion products produced by lithium-ion batteries to determine if they could be the cause or the victim of the fire [193]. Elemental analysis indicated that if aluminum was identified in the battery remains, this would signify thermal runaway due to overcharging. If no aluminum is identified post-fire, then the battery was not the source of the fire. These findings could be useful to fire investigators when examining scenes to rule in or out lithium-ion batteries as potential causes.

6. Canines

Abel et al. investigated the ignitable liquid limits of detection for canines using gasoline and clean, porous tile substrates [194]. Serial dilutions in dichloromethane were used to spike the substrates and provided quantitative estimates of detection limits. The two canines tested were able to detect as little as 5 pL of gasoline on the tiles; however, more complex matrices proved challenging.

O'Hagan and Ellis provide an overall review of fire, arson, scene examination, evidence packaging, and canines [195]. The authors note that the canines have increased success rates in their ability to detect ignitable liquids at fire scenes, but they think laboratories need to do more to confirm dog alerts, such as use SPME and test evidence promptly.

In an effort to explain false positive canine alerts, Leung et al. analyzed volatile organic compounds (VOCs) from burned carpet and garden hoses to see if the compounds were similar to ignitable liquids [196]. They used SPME and GC-MS/MS and were able to resolve numerous aromatic compounds from both substrates. While the compounds were not present in patterns consistent with ignitable liquids, the VOCs could be a distracting odor for canines and attempts to train the dogs off of these could lead to false negative results for some ignitable liquid residues.

Tiira et al. examined the response of accelerant detection canines (ADCs) on burned ignitable liquids [197]. The authors burned gasoline, charcoal lighter fluid, and isopropanol on wood and then used five trained Finnish ADCs to test the substrate at different time points. Positive alerts were confirmed by a laboratory. Ultimately, the ADCs correctly alerted to ignitable liquid residues when there was sufficient residue to detect. When less residue was present, false alerts increased.

In a different use of canines for fire scenes, Woods discussed using bloodhounds to track wildfire arsonists [198]. The author highlighted the successful work of the West Virginia Division of Forestry bloodhound program, that not only helps track down arsonists but also serves as a deterrent for preventing wildfire arsons.

7. Contamination

Banks et al. studied firefighter exposure to PAHs, which are known cancer-causing compounds [199]. Firefighters were exposed to simulated compartment fires containing either a diesel pan fire or particle board fire and then provided skin swabs and urine samples for testing. The concentration of PAHs recovered was higher in the particle board fires, which was evident in both swabs and urine samples. Firefighters in this study were allowed to shower 10 min after finishing the burn (for a total of 30 min for exposure), which may have reduced the overall amount of PAHs observed on skin and in urine. However, further study on mitigating practices is needed.

Kirk and Logan examined firefighter exposure to air contaminants in compartment fires with particleboard used as fuel [200]. Numerous volatile organic compounds, as well as hydrogen cyanide and formaldehyde, were detected not only outside the firefighter gear, but also inside the protective clothing. Since protective clothing was originally designed for thermal, not chemical, protection, the potential exists for contaminants to enter the body through dermal absorption.

Kirk et al. investigated the combustion products generated in simulated industrial fires and the resulting contamination to firefighter protective gear [201]. PAHs and lighter gaseous materials, such as hydrogen cyanide, were found not only on the exterior of the clothing, but also the interior. As a result, the authors recommend that self-contained breathing apparatus (SCBA) be worn during active firefighting, overhaul, or when exposed to any smoke. Effective on-scene and post-scene decontamination procedures need to be in place to prevent further inhalation or dermal absorption of the carcinogenic combustion products.

Bakali et al. found that PAHs were more prevalent in fires fueled with biomass and wood as compared to fires burning with fuels such as propane [202]. PAH concentration was elevated not only in the “warm zone” but also in the “cold zone”, which has traditionally been thought to be a safer area with less exposure risk. The authors hope that the results of this study will help dictate best practices for first responders regarding locations of warm and cold zones, as well as possible protective equipment needed in those areas.

Horn et al. sampled air post-fire in controlled residential settings with common US-type furnishings and discovered that airborne particulates were elevated to unhealthy levels shortly after fire suppression and during shoveling or demolition [203]. Formaldehyde concentrations were also high during the earliest investigation periods. These findings highlighted the need to protect firefighters and fire investigators from particulates and vapors with appropriate personal protective equipment (PPE) and to provide post-investigation decontamination of gear.

Simms et al. fabricated a volatile organic compound air sampler that could be attached to an unmanned aerial vehicle (UAV) to collect and identify compounds given off during fires [204]. A stationary version was used during five days of the 2018 Camp Fire in Davis, California, and the mobile version was tested during a simulated fire. Compounds, including aromatics and aldehydes, were identified in air samples using GC-MS and were consistent in both the real and simulated events. The ability to use a UAV to collect the toxic gases reduces the risk on investigators monitoring the fire situations.

Pauley discussed the health hazards associated with cold fire scenes, which are scenes where the fire has been extinguished for at least 72 h [205]. The most common routes for contamination are through inhalation and skin exposure, which can affect anyone at the scene, from fire investigators to crime scene technicians, to lawyers. The author recommended that anyone entering a fire scene needs proper PPE, including coveralls, disposable gloves, steel-toe boots, respiratory protection, eye protection, and a helmet.

8. Psychology/human behavior

Behavioral profiles of potential suspects are sometimes used during the fire investigation to assist law enforcement. However, fully understanding the motives behind those that set fires is usually done in retrospect by examining groups of individuals and looking for trends in behavior and motivation. As a result, instead of summarizing each paper separately here, they will be primarily grouped and referenced by topic.

Arson, arson-associated homicides, and adult firesetters are the focus of book chapters by Fritzon et al.; Morewitz; Tilt; and Tyler and Barnoux [206–209].

The classification of firesetters is discussed by Nanayakkara; Allely; Nanayakkara et al.; Parker; and Tyler and Gannon [210–214].

Several authors (Gunther et al.; Collins et al.; Loewenstein; Allely; Holst et al.; and Nanayakkara et al.) have examined firesetting among people with mental disorders and intellectual disabilities [215–220].

The topic of youth firesetting is covered by Ruben; Persson and Unhoo; Breteton et al.; Berger; Perks et al.; Dadswell et al.; and Rickett [221–227].

Horsely explores the relationship between humans and fire in four separate publications that focus on different aspects of the role of fire in human life [228–231].

Ellis-Smith et al. and Hall analyzed trends in arsonists and fire clusters, respectively [232,233].

Arson recidivism was examined by Edwards and Sambrooks et al. [234,235].

Self-immolation was discussed in a case study above and in work presented by Irie et al. and Byard and Health [236,237].

Other general topics regarding the psychology and behavior of firesetters are covered by Butler and Gannon; Barrowcliffe et al.; Nanayakkara et al.; and Hewitt et al. [238–241].

Acknowledgments

The author would like to thank Logan Tapscott for assistance with searching for and acquiring the articles referenced in the review.

References

[1] E. Stauffer, Fire investigation, in: M. Houck (Ed.), 19th Interpol International Forensic Science Managers Symposium Review Papers, Interpol, Lyon, 2019, pp. 156–193.
[2] ASTM International, ASTM E2451-21: Standard Practice for Preserving Ignitable Liquids and Ignitable Liquid Residue Extracts from Fire Debris Samples, 2021.
[3] ASTM International, ASTM E3245-20e1: Standard guide for systematic approach to the extraction, analysis, and classification of ignitable liquids and ignitable liquid residues in fire debris samples, 2020.
[4] ASTM International, ASTM E3197-20: Standard Terminology Relating to Examination of Fire Debris, 2020.
[5] ASTM International, ASTM E1412-19: Standard Practice for Separation of Ignitable Liquid Residues from Fire Debris Samples by Passive Headspace Concentration with Activated Charcoal, 2019.
[6] ASTM International, ASTM E1413-19: Standard Practice for Separation of Ignitable Liquid Residues from Fire Debris Samples by Dynamic Headspace Concentration onto an Adsorbent Tube, 2019.
[7] ASTM International, ASTM E1618-19: Standard Test Method for Ignitable Liquid Residues in Extracts from Fire Debris Samples by Gas-Chromatography-Mass Spectrometry, 2019.
[8] K. Evans-Nguygen, K. Hutches (Eds.), Forensic Analysis of Fire Debris and Explosives, Springer, 2019.
[9] K. Evans-Nguyen, Forensic Chemistry, American Chemical Society, 2021.
[10] K. Mirakovits, G. Londino-Smolar, The Basics of Investigating Forensic Science: a Laboratory Manual, CRC Press, 2021.
[11] R. Wolstenholme, S. Jickells, S. Forbes (Eds.), Analytical Techniques in Forensic Science, John Wiley & Sons, 2021.
[12] L.H.P. Bueno Carmona, E.G. Campos, V.L. Caleffo, P. Bigao, A.L.C. Pereira, F. Duate Maia, L. Silva Telles, B.S. De Martinis, Activated charcoal pellets as an innovate method for forensic analysis of ignitable liquid residues from fire debris by GC-MS, Braz. J. Anal. Chem. 9 (34) (2022) 198–209.
[13] J. Baerncopf, K. Hutches, Evaluation of long-term preservation of ignitable liquids adsorbed onto charcoal strips: 0 to 2 years, Foren. Chem. 18 (2020). Article 100234.
[14] M.J. Swierczynski, K. Grau, M. Schmitz, J. Kim, Detection of gasoline residues present in household materials via headspace-solid phase microextraction and gas chromatography-mass spectrometry, J. Anal. Chem. 75 (1) (2020) 44–55.
[15] L. Buchler, D. Werner, O. Delemont, Detection of gasoline on suspects' hands: study of different sampling alternatives, Forensic Sci. Int. 318 (2021). Article 110590.
[16] V. Totten, J. Willis, The use of hydrophobic pads to recover ignitable liquids from water, Forensic Sci. Int. 312 (2020). Article 110309.
[17] J.N. Carlotti, Absorbent Household Materials for the Collection of Ignitable Liquid Residues from Surfaces of Varying Porosity (Publication No. 28491625), Master's Thesis, Eastern Kentucky University, 2021 (ProQuest Dissertations and Theses Global).
[18] J. Baerncopf, Prevalence of ignitable liquids in clothing with printing, Forensic Sci. Int. 312 (2020). Article 110312.
[19] A.M. Dhabbah, Detection of petrol residues in natural and synthetic textiles before and after burning using SPME and GC-MS, Aust. J. Forensic Sci. 52 (2) (2020) 194–207.

[20] G. Guerrera, E. Chen, R. Powers, B.W. Kammrath, The potential interference of body products and substrates to the identification of ignitable liquid residues on worn clothing, Foren. Chem. 12 (2019) 46–57.

[21] K. Hutches, N. Stevens, L. Milleville, Inherent ignitable liquids in new/lightly used shoes, Foren. Chem. 18 (2020). Article 100211.

[22] R.K. Whitney, Effective Laundering Conditions for Ignitable Liquid Decontamination of Fire Scene Clothing Used by the Bureau of Alcohol, Tobacco, Firearms, and Explosives, Master's thesis, Virginia Commonwealth University, 2020 (VCU Scholars Compass).

[23] A.L. Jess, D.P. Land, M. Hengel, B. Lasater, Qualitatively analyzing QuEChERS' ability to extract ignitable liquid residues (ILRs) from cotton-based fire debris, Fire & Arson Investig. 72 (2) (2021) 14–19.

[24] P.C. Hsieh, R.Y. Lin, K.Y. Cheng, Research on adapting pyrolysis GC-MS to analyze spontaneous ignition in vegetable oil, Fire & Arson Investig. 72 (3) (2022) 24–35.

[25] C.M. Bryant, J.M. Warnica, R. Chen, C. Shepard, Identification of triglycerides in liquid and fire debris samples by triple quadrupole liquid chromatography-mass spectrometry, J. Forensic Sci. 66 (2) (2021) 534–546.

[26] H. Letendre, K. Seguin, A. Grenier, B. Mousseau, L. Cadola, F. Crispino, First lessons regarding the data analysis of physicochemical traces at activity level in TTADB, J. Can. Soc. Forensic. Sci. 54 (3) (2021) 139–156.

[27] J. Jin, K. Li, J. Chi, s. Li, J. Zhang, L. Lu, The most remarkable interference to gasoline identification from polystyrene-co-butadiene and the corresponding cause, J. Chromatogr. A 1654 (2021). Article 462462.

[28] J. Jin, J. Chi, T. Xue, L. Liu, Y. Li, L. Deng, J. Zhang, Influence of thermal environment in fire on the identification of gasoline combustion residues, Forensic Sci. Int. 315 (2020). Article 110430.

[29] I. Barnett, F.C. Bailey, M. Zhang, Detection and classification of ignitable liquid residues in the presence of matrix interferences by using direct analysis in real time mass spectrometry, J. Forensic Sci. 64 (5) (2019) 1486–1494.

[30] V.K. Yadav, T. Das, A. Harshey, M.M. Yadav, K. Nigam, A. Srivastava, A forensic approach to evaluate the effect of different matrices and extraction solvents for the identification of diesel residue in simulated arson by GC-MS, Chromatographia 84 (5) (2021) 413–423.

[31] M.M. Bordbar, J. Tashkhourian, B. Hemmateenejad, Paper-based optical nose made with bimetallic nanoparticles for monitoring ignitable liquids in gasoline, ACS Appl. Mater. Interfaces 14 (2022) 8333–8342.

[32] M.E. Harries, S.S. Wasserman, J.L. Berry, K.M. Jeerage, Characterization of a headspace sampling method with a five-component diesel fuel surrogate, Foren. Chem. 22 (2021). Article 100301.

[33] Y. Zhang, X. Zhu, C. Zhao, B. Peng, S. Yang, L. Xie, Study of diesel residues from fire debris in a bus arson experiment [Conference presentation], October 18-20, in: 2019 9th International Conference on Fire Science and Fire Protection Engineering, 2019 (Chengdu, China).

[34] Z.R. Roberson, Advances in Gas Chromatography and Vacuum UV Spectroscopy: Applications to Fire Debris Analysis & Drugs of Abuse, Doctoral dissertation, Purdue University, 2020 (IUPUI ScholarWorks Repository).

[35] Z.R. Roberson, J.V. Goodpaster, Preparation and characterization of micro-bore wall-coated open-tubular capillaries with low phase ratios for fast-gas chromatography–mass spectrometry: application to ignitable liquids and fire debris, Sci. Justice 59 (6) (2019) 630–634.

[36] A.S. Rael, C.A. Cruse, M. Rydberg, J.V. Goodpaster, A critical comparison of vacuum UV (VUV) spectrometer and electron ionization single quadrupole mass spectrometer detectors for the analysis of alkylbenzenes in gasoline by gas chromatography: experimental and statistical aspects, Talanta 225 (2021). Article 122081.

[37] M.N. Torres, N.B. Valdes, J.R. Almirall, Comparison of portable and benchtop GC–MS coupled to capillary microextraction of volatiles (CMV) for the extraction and analysis of ignitable liquid residues, Foren. Chem. 19 (2020). Article 100240.

[38] M.N. Torres, J.R. Almirall, Evaluation of capillary microextraction of volatiles (CMV) coupled to a person-portable gas chromatograph mass spectrometer (GC–MS) for the analysis of gasoline residues, Foren. Chem. 27 (2022). Article 100397.

[39] M.K. Nims, A.M. Melville, J.J. Moran, K.H. Jarman, B.W. Wright, Compound specific stable isotope analysis of aromatics in diesel fuel to identify potential cocktailing, Forensic Sci. Int. 334 (2022). Article 111244.

[40] L.M. DuBois, G. O'Sullivan, P. Steganuto, C.D. Sandau, J. Focant, Use of GCXGC for the characterization of odours in forensic applications, in: C.E.I. Cordero (Ed.), Comprehensive Analytical Chemistry, vol. 96, Elsevier, 2022, pp. 335–365.

[41] J. Pandohee, J.G. Hughes, J.R. Pearson, O.A.H. Jones, Chemical fingerprinting of petrochemicals for arson investigations using two-dimensional gas chromatography - flame ionisation detection and multivariate analysis, Sci. Justice 60 (4) (2020) 381–387.

[42] N. Boegelsack, K. Hayes, C. Sandau, J.M. Withey, D.W. McMartin, G. O'Sullivan, Method development for optimizing analysis of ignitable liquid residues using flow-modulated comprehensive two-dimensional gas chromatography, J. Chromatogr. A 1656 (2021). Article 462495.

[43] N. Boegelsack, C. Sandau, D.W. McMartin, J.M. Withey, G. O'Sullivan, Development of retention time indices for comprehensive multidimensional gas chromatography and application to ignitable liquid residue mapping in wildfire investigations, J. Chromatogr. A 1635 (2021). Article 461717.

[44] L.N. Kates, P.I. Richards, C.D. Sandau, The application of comprehensive two-dimensional gas chromatography to the analysis of wildfire debris for ignitable liquid residue, Forensic Sci. Int. 310 (2020). Article 110256.

[45] G.M. Young, I.S. Lurie, Recent forensic applications of enhanced chromatographic separation methods, J. Separ. Sci. 45 (1) (2022) 369–381.

[46] Crocombe, R., Leary, P., & Kammrath, B. (Eds.). Portable Spectroscopy and Spectrometry (Vols. vols. 1–2). John Wiley & Sons.

[47] E. Sisco, T.P. Forbes, Forensic applications of DART-MS: a review of recent literature, Foren. Chem. 22 (2021). Article 100294.

[48] S.V. Patel, I.S. Lurie, The use of portable separation devices for forensic analysis: a review of recent literature, Foren. Chem. 26 (2021). Article 100365.

[49] J.D. DeHaan, Enhancing fire scene investigations through new technologies, Fire & Arson Investig. 71 (3) (2021) 28–35.

[50] G. Sauzier, W. van Bronswijk, S.W. Lewis, Chemometrics in forensic science: approaches and applications, Analyst 146 (8) (2021) 2415–2448.

[51] M.E. Sigman, M.R. Williams, Chemometric applications in fire debris, WIREs: Forensic Sci. 2 (5) (2020). Article e1368.

[52] A.G. Akmeemana, Chemometric Applications in Fire Debris Analysis: Likelihood Ratios from Naïve Bayes and Frequency of Component and Pyrolysis Product Occurrence, Doctoral dissertation, University of Central Florida, 2019 (University of Central Florida STARS).

[53] C. Bogdal, R. Schellenberg, O. Hopli, M. Bovens, M. Lory, Recognition of gasoline in fire debris using machine learning: part I, application of random forest, gradient boosting, support vector machine, and naïve bayes, Forensic Sci. Int. 331 (2022). Article 111146.

[54] C. Bogdal, R. Schellenberg, M. Lory, M. Bovens, O. Hopli, Recognition of gasoline in fire debris using machine learning: part II, application of a neural network, Forensic Sci. Int. 332 (2022). Article 111177.

[55] C. Park, W. Park, S. Jeon, S. Lee, J. Lee, Application and evaluation of machine-learning model for fire accelerant classification from GC-MS data of fire residue, Analy. Sci. Technol. 34 (5) (2021) 231–239.

[56] S. Korver, E. Schouten, P. Moultos, P. Vergeer, M.M.P. Grutters, L.J.C. Peschier, T. J.H. Vlught, M. Ramdin, Artificial intelligence and thermodynamics help solving arson cases, Sci. Rep. 10 (2020). Article 20502.

[57] M. de Figueiredo, C.B.Y. Cordella, D.J. Bouveresse, X. Archer, J. Begue, D. N. Ruteldge, Evaluation of an untargeted chemometric approach for the source inference of ignitable liquids in forensic science, Forensic Sci. Int. 295 (2019) 8–18.

[58] A. Allen, The Evaluation of Classifier Performance on the Forensic Analysis of Fire Debris and the Expansion of the Substrate Database, Doctoral dissertation, University of Central Florida, 2019 (University of Central Florida STARS).

[59] A. Allen, M.R. Williams, M.E. Sigman, Application of likelihood ratios and optimal decision thresholds in fire debris analysis based on a partial least square's discriminant analysis (PLS-DA) model, Foren. Chem. 16 (2019). Article 100188.

[60] N.A. Thurn, T. Wood, M.R. Williams, M.E. Sigman, Classification of ground-truth fire debris samples using artificial neural networks, Foren. Chem. 23 (2021), 100313.

[61] M.E. Sigman, M.R. Williams, N. Thurn, T. Wood, Validation of ground truth fire debris classification by supervised machine learning, Foren. Chem. 26 (2021). Article 100358.

[62] N.K. Eklund, Further Investigation of a Kinetic Model to Accurately Predict Evaporation of Gasoline (Publication No. 13897508), Master's Thesis, Michigan State University, 2019 (ProQuest Dissertations & Theses Global).

[63] N.K. Eklund, B.A. Capistran, V.L. McGuffin, R.W. Smith, Improvements in a kinetic-based model to predict evaporation of gasoline, Foren. Chem. 17 (2020). Article 100194.

[64] B.A. Capistran, Kinetically Modelling Total Ion Chromatograms and Extracted Ion Profiles to Identify Ignitable Liquids for Fire Debris Applications (Publication No. 28031746), Master's Thesis, Michigan State University, 2020 (ProQuest Dissertations & Theses Global).

[65] B.A. Capistran, V.L. McGuffin, R.W. Smith, Application of a kinetic model to predict extracted ion profiles for the identification of evaporated ignitable liquids, Foren. Chem. 24 (2021). Article 100340.

[66] A.L. Burkhart, Measuring Evaporation Rate Constants of Highly Volatile Compounds and Investigating the Effect of Interface on a Kinetic Model Applied to Forensic Fire Debris (Publication No. 28549232), Doctoral Dissertation, Michigan State University, 2021 (ProQuest Dissertations & Thesis Global).

[67] V.L. McGuffin, R.W. Smith, A unified kinetic and thermodynamic model of evaporation for forensic applications, Foren. Chem. 23 (2021). Article 100304.

[68] A.L. Burkhart, R.W. Smith, V.L. McGuffin, Measuring evaporation rate constants of highly volatile compounds for use in predictive kinetic models, Anal. Chim. Acta 1182 (2021). Article 338932.

[69] B. Christy, K. Winters, A. Rossheim, R. Newman, L. Tang, A foundational study of fire debris interpretation using quantitative measures of chromatographic features in gasoline and the use of graphical display to demonstrate data sufficiency, Foren. Chem. 24 (2021). Article 100337.

[70] P. Vergeer, J.N. Hendrikse, M.M.P. Grutters, L.J.C. Peschier, A method for forensic gasoline comparison in fire debris samples: a numerical likelihood ratio system, Sci. Justice 60 (5) (2020) 438–450.

[71] B. Falatova, M. Ferreiro-Gonzalez, D. Kacikova, S. Galla, M. Palma, C.G. Barroso, Chemometric tools used in the process of fire investigation, Acta Facultatix Xylolgiae Zvolen 61 (1) (2019) 111–119.

[72] P.E. Sudol, K.M. Pierce, S.E. Prebihalo, K.J. Skogerboe, B.W. Wright, R. E. Synovec, Development of gas chromatographic pattern recognition and classification tools for compliance and forensic analyses of fuels: a review, Anal. Chim. Acta 1132 (2020) 157–186.

[73] J. Deng, H. Lu, Y. Li, W. Wang, Y. Xiao, L. Bai, C. Shu, Mathematical method for polymerised styrene butadiene rubber 1502 pyrolysis residue and gasoline differentiation, J. Therm. Anal. Calorim. 142 (2) (2020) 685–694.

[74] M. de Figeiredo, D.J. Bouveresse, C.B.Y. Cordella, X. Archer, J. Begue, D. N. Rutledge, Exploratory study on the possibility to link gasoline samples sharing

a common source after alteration by evaporation or combustion, Forensic Sci. Int. 301 (2019) 190–201.
[75] I.C. Willis, Z. Fan, J.T. Davidson, G.P. Jackson, Weathering of ignitable liquids at elevated temperatures: a thermodynamic model, based on laws of ideal solutions, to predict weathering in structure fires, Foren. Chem. 18 (2020). Article 100215.
[76] C. Wensel, The Effects of Household Substrates on the Evaporation of Ignitable Liquids at Temperatures up to 210°C, Master's thesis, Wester Virginia University, 2020 (Research Repository at West Virginia University).
[77] V.K. Yadav, K. Nigman, A. Srivastava, Forensic investigation of arson residue by infrared and Raman spectroscopy: from conventional to non-destructive techniques, Med. Sci. Law 60 (3) (2020) 206–215.
[78] Y. Huang, J.C.C. Yu, Development of crime scene intelligence using a hand-held Raman spectrometer and transfer learning, Anal. Chem. 93 (25) (2021) 8889–8896.
[79] M.J. Aliano-Gonzalez, M. Ferreiro-Gonzalez, G.F. Barbero, M. Plama, Novel method based on ion mobility spectrometry sum spectrum for the characterization of ignitable liquids in fire debris, Talanta 199 (2019) 189–194.
[80] Y.Y. Aviassar, I. Hefetz, A. Grafit, S. Kimchi, D. Muller, The effect of ignitable liquid analysis on latent fingermark development, J. Forensic Ident. 69 (2) (2019) 83–97.
[81] B. Bastide, G. Porter, A. Renshaw, Detection of latent bloodstains at fire scenes using reflected infrared photography, Forensic Sci. Int. 302 (2019). Article 109874.
[82] B. Bastide, G. Porter, A. Renshaw, The effects of heat on the physical and spectral properties of bloodstains at arson scenes, Forensic Sci. Int. 325 (2021). Article 110891.
[83] A. O'Hagan, R. Calder, DNA and fingerprint recovery from an arson scene, Foren. Res. Criminol. Int. J. 8 (1) (2020) 15–29.
[84] C. McGann, Evaluating the Recovery of DNA after Heated Passive Headspace Concentration, Master's thesis, Boston University, Open BU, 2021.
[85] R.H.A. Hady, H.Z. Thabet, N.E. Ebrahem, H.A. Yassa, Thermal effects on DNA degradation in blood and seminal stains: forensic view, Foren. Res. Criminol. Int. J. 11 (1) (2021) 7–23.
[86] A. Klein, O. Krebs, A. Gehl, J. Morgner, L. Reeger, C. Augustin, C. Edler, The use of liquid latex for detecting traces of blood following thermal exposure, Int. J. Leg. Med. 133 (5) (2019) 1567–1574.
[87] H. Bourn, Thermal Trauma and the Effect of Temperature and Time on the Morphology and DNA of Dentition, Master's thesis, University of Western Australia, 2020 (UWA Profiles and Research Repository).
[88] T.J. Federchook, J.T. Pokines, K. Crowley, C.M. Grgicak, Recovery of DNA from teeth exposed to variable temperatures, Forensic Anthropol. 2 (3) (2019) 143–151.
[89] M. McKinnon, M. Henneberg, D. Higgins, A review of the current understanding of burned bone as a source of DNA for human identification, Sci. Justice 61 (4) (2021) 332–338.
[90] D. Solodov, I. Solodov, Data recovery in a case of fire-damaged hard disk drives and solid-state drives, Forensic Sci. Int.: Report 3 (2021). Article 100199.
[91] M. Constantine, S. Mooney, B. Hibbert, C. Marjo, M. Bird, T. Cohen, M. Forbes, A. McBeath, A. Rich, J. Stride, Using charcoal, ATR FTIR and chemometrics to model the intensity of pyrolysis: exploratory steps towards characterising fire events, Sci. Total Environ. 783 (2021). Article 147052.
[92] B.K. Sharma, D. Chand, V.K. Shukla, A.A. Thomas, E. Jeridi, Decipherment of the written and printed matter on the charred document using UV and IR under different wavelengths [Paper presentation], January 9-10, in: 2020 International Conference on Computation Automation and Knowledge Management, 2020 (Dubai, United Arab Emirates).
[93] V.J.M. DiMaio, D.K. Molina, DiMaio's Forensic Pathology, CRC Press, 2021.
[94] W.U. Spitz, F.J. Diaz, Fire and scalding injuries, in: Spitz and Fisher's Medicolegal Investigation of Death: Guidelines for the Application of Pathology to Crime Investigation, fifth ed., Charles C. Thomas Publisher, 2020, pp. 551–580 (EBSCOhost eBook Collection).
[95] A. McGarry, B. Floyd, J. Littleton, Using portable X-ray fluorescence (pXRF) spectrometry to discriminate burned skeletal fragments, Archaeol. Anthropol. Sci. 13 (6) (2021). Article 117.
[96] R.A. Rahmat, M.A. Humphries, J.J. Austin, A.M.T. Linacre, M. Raven, P. Self, Integrating spectrophotometric and XRD analyses in the investigation of burned dental remains, Forensic Sci. Int. 310 (2020). Article 110236.
[97] R.A. Rahmat, M.A. Humphries, J.J. Austin, A.M.T. Linacre, P. Self, The development of a tool to predict temperature-exposure of incinerated teeth using colourimetric and hydroxyapatite crystal size data, Int. J. Leg. Med. 135 (5) (2021) 2045–2053.
[98] T. Krap, J.M. Ruijter, K. Nota, J. Karel, A.L. Burgers, M.C.G. Aalders, R. Oostra, W. Duijst, Colourimetric analysis of thermally altered human bone samples, Sci. Rep. 9 (2019). Article 8923.
[99] M. McKinnon, M. Hennberg, E. Simpson, D. Higgins, A comparison of crystal structure in fresh, burned and archaic bone – implications for forensic sampling, Forensic Sci. Int. 313 (2020). Article 110328.
[100] A.N. Williams, A New Classification System for Analyzing Burned Human Remains (Publication No. 27998511), Doctoral dissertation, University of Montana, 2020 (ProQuest Dissertations and Theses Global).
[101] I. Galtes, S. Scheiers, Differentiation between perimortem trauma and heat-induced damage: the use of perimortem traits on burnt long bones. Forensic Science, Med. Pathol. 15 (3) (2019) 453–457.
[102] S.L. Malainey, G.S. Anderson, Effect of arson fires on survivability of entomological evidence on carcasses inside vehicle trunks, Forensic Sci. Int. 306 (2020), 110033.
[103] K.S. Conway, C.J. Schmidt, T.T. Brown, Medical examiner review of the characteristics of fire-related homicides, Foren. Res. Criminol. Int. J. 10 (2) (2020) 87–93.
[104] F. Simonit, U. Da Broi, L. Desinan, The role of self-immolation in complex suicides: a neglected topic in current literature, Forensic Sci. Int. 306 (2020). Article 110073.
[105] H.M. de Bakker, G.H.J. Roelandt, V. Soerdjbalie-Maikoe, R.R. van Rijn, B.S. de Bakker, The value of post-mortem computed tomography of burned victims in a forensic setting, Eur. Radiol. 29 (4) (2019) 1912–1921.
[106] E.F. Kranioti, D. Nathena, K. Spanakis, A. Karantanas, R. Bouhaidar, S. McLaughlin, M.J. Thali, G. Ampanozi, Unenhanced PMCT in the diagnosis of fatal traumatic brain injury in a charred body, J. Forensic Legal Med. 77 (2021). Article 102093.
[107] K. Mahe, J. Cappy, R. Carlier, J. Alvarez, G. Lorin de la Grandmaison, Distinctions between peri and postmortem bone lesions on a burnt body in the aftermath of a road accident, Clin. Case Rep. Int. 5 (2021). Article 1240.
[108] S. Hammarlebiod, A. Farrugia, G. Bierry, J. Raul, T. Willaume, Thermal bone injuries: postmortem computed tomography findings in 25 cases, Int. J. Leg. Med. 136 (1) (2022) 219–227.
[109] P.M. Tutor, N. Marquez-Grant, C.V. Rojas, A.M. Garcia, I.P. Guzman, M. B. Sanchez, Through fire and flames: post-burning survival and detection of dismemberment-related toolmarks in cremated cadavers, Int. J. Leg. Med. 135 (3) (2021) 801–815.
[110] P.M. Tutor, M.B. Sanchez, C.V. Rojas, A.M. Garcia, I.P. Guzman, N. Marquez-Grant, Cut or burnt? – categorizing morphological characteristics of heat-induced fractures and sharp force trauma, Leg. Med. 50 (2021). Article 101868.
[111] V. Vachirawongsakorn, J. Painter, N. Marquez-Grant, Knife cut marks inflicted by different blade types and the changes induced by heat: a dimensional and morphological study, Int. J. Leg. Med. 136 (1) (2022) 329–342.
[112] C.C. Siegert, M.D. Hamilton, E.M. Erhart, J.B. Devlin, A comparative assessment of consolidation materials applied to burned bone, Forensic Sci. Int. 310 (2020). Article 110224.
[113] K. Salesse, E. Stamataki, I. Kontopoulos, G. Verly, R. Annaert, M. Boudin, G. Capuzzo, P. Claeys, S. Dalle, M. Hlad, G. de Mulder, C. Sabux, A. Sengelov, B. Veselka, E. Warmenbol, M. Vercauteren, C. Snoeck, These boots are made for burnin': inferring the position of the corpse and the presence of leather footwears during cremation through isotope (δ13C, δ18O) and infrared (FTIR) analyses of experimentally burnt skeletal remains, PLoS One 16 (10) (2021). Article e0257199.
[114] C.A. Keyes, How reliable is the charred body scale? An interobserver reliability study on scoring burned remains, Burns 45 (7) (2019) 1673–1679.
[115] C.A. Juarez, E. Pope, A. Galloway, Refined classification system for thermally damaged human remains by body segment, Forensic Anthropol. 5 (1) (2022) 57–72.
[116] L. Labuschagne, The Use of Histological Examination Methods to Distinguish between the Burnt Remains of Human and Non-human Bones, Master's thesis, University of Cape Town, 2020 (OpenUCT).
[117] T. Krap, L. Busscher, R. Oostra, M.C.B. Aalders, W. Duijst, Phosphorescence of thermally altered human bone, Int. J. Leg. Med. 135 (3) (2021) 1025–1034.
[118] A. Ost, D. Messer, D. Dirkmaat, The role of forensic anthropologist at the fatal fire recovery: a retrospective study of cases from 1983-2020, Forensic Anthropol. 5 (1) (2022) 46–52.
[119] A. Wegner, E. Doberentz, B. Madea, Fire exposure after lethal hypothermia. Forensic Science, Med. Pathol. 16 (4) (2020) 728–731.
[120] P. Hehna, M. Bohnert, M. Janik, Unique thermal destruction of the body following suicidal burning, Forensic Sci. Med. Pathol. 15 (2) (2019) 262–266.
[121] F. Simonit, U. Da Broi, C. Furioso, L. Desinan, A burned body with a gunshot wound in the mouth and a suicide note: a complex or complicated suicide? J. Forensic. Legal. Med. 72 (2020). Article 101958.
[122] L. Monetti, M. Voulgari, I. Karagiorgou, K. Moraitis, Macroscopic determination of the pre-burning condition of human remains recovered from an unusual forensic context: a case report, J. Forensic. Legal. Med. 78 (2021). Article 102115.
[123] M. Alexandri, A. Koukoulis, M. Tsellou, S. Papdodima, A burned body with a shotgun head injury found on an "altar" made of banknotes: a case report from Greece and brief review of the literature, Leg. Med. 51 (2021). Article 101882.
[124] S. Nath, R. Majumder, H.K. Pratiharti, Mystery of a burnt body, Foren. Res. Criminol. Int. J. 8 (6) (2020) 215–218.
[125] A. Ishigami, S. Hata, Y. Ishida, M. Nosaka, Y. Kuninaka, H. Yamamoto, E. Shimada, Y. Hashizume, T. Takayasu, A. Kimura, F. Furukawa, T. Kondo, Complete decapitation by a self-constructed guillotine in a burned body - complex suicide or postmortem burning? Int. J. Leg. Med. 135 (1) (2021) 301–305.
[126] National Fire Protection Association, NFPA 921: Guide for Fire and Explosion Investigations, 2021, 2021.
[127] National Fire Protection Association, NFPA 1033: Standard for Professional Qualifications for Fire Investigator, 2022, 2022.
[128] National Fire Protection Association, NFPA 1321: Standard for Fire Investigation Units (Proposed Standard), 2022.
[129] European Network of Forensic Science Institutes Fire and Explosion Investigation Working Group, Best Practice Manual for the Investigation of Fires and Explosions (ENFSI-BPM-FEI-01), European Network of Forensic Science Institutes, 2021.
[130] H.A. Harris, H.C. Lee, Arson and explosives, in: H.A. Harris, H.C. Lee (Eds.), Introduction to Forensic Science and Criminalistics, second ed., CRC Press, 2019, pp. 289–325.
[131] S. Kumar, A. Singlua, R.R. Vidwans, Fire investigation and ignitable liquid residue analysis, in: C. Chen, W. Yang, L. Chen (Eds.), Technologies to Advance

Automation in Forensic Science and Criminal Investigation, IGIG Global, 2022, pp. 91–118.
[132] T. Ost-Prisco, Fire cause classification: how the proposed changes to NFPA 921 may impact your courtroom testimony, Fire & Arson Investig. 71 (1) (2020) 16–20.
[133] V.E. Betty, J.D. Oliva, Evidence on fire, N. C. Law Rev. 97 (3) (2019) 483–528 (HeinOnline).
[134] K. Jansen, Extinguishing subjectivity in fire investigations, C&EN 97 (26) (2019) 6.
[135] J.A. Siegel, K. Mirakovits, Forensic Science: the Basics, fourth ed., CRC Press, 2021.
[136] S. Johnson, K. Harrison, J. Dean, Challenges in fire investigation, in: L. Dennany (Ed.), Challenges in Detection Approaches for Forensic Science, Royal Society of Chemistry, 2021, pp. 139–152.
[137] I. Aron, Forensic investigation of fire and explosions, Bulletin of the Transilvania University of Brasov. Series VII: Social Sciences. Law 14 (63) (2021) 144–148.
[138] J.J. Lentini, Fire investigation: historical perspectives and recent developments, Forensic Sci. Rev. 31 (1) (2019) 37–44.
[139] P. Clafin, Documenting the use of the scientific method in an origin and cause report, Fire & Arson Investig. 70 (2) (2019) 16–20.
[140] J.R. Alden, B. Dusseau, Fire investigation basics, Fire Eng. 174 (1) (2021, January) 48–56.
[141] D. Vecchiolla, Fire investigation and the first-arriving company, Fire Eng. 175 (1) (2022) 48–50.
[142] J. Viegra, Analyses of your fire debris, Fire & Arson Investig. 70 (2) (2019) 24–26.
[143] S.J. Avato, R.D. Gundert, Supervising fire investigation units, Fire Eng. 175 (1) (2022) 28–33.
[144] J.J. Lentini, A model for confronting fire investigation errors, Lincoln Memorial Univ. Law Rev. 7 (2) (2020) 1–36 (HeinOnline).
[145] N.R. Morling, M.L. Henneberg, Contextual information and cognitive bias in the forensic investigation of fatal fires: do these incidents present an increased risk of flawed decision-making? Int. J. Law, Crime. Just. 62 (2020). Article 100406.
[146] M.A. Merola, S.W. Craun, L.B. Schlesinger, Homicides with crime concealment arson: implications for investigation & apprehension, Fire & Arson Investig. 72 (2) (2021) 34–39.
[147] G. Sara, Cooperation between public & private sector fire investigators–always room for improvement, Fire & Arson Investig. 71 (2) (2020) 22–27.
[148] P.A. Woodman, K.N. Ballantyne, R. Julian, C. Spiranovic, The Forensic Examination of Structural Fires in Victoria, Australia: Decision-Making Processes and Impact on Judicial Outcomes, 2021.
[149] K. Harrison, The application of archaeological techniques to forensic fire scenes, in: K.S. Moran, C.L. Gold (Eds.), Forensic Archaeology: Multidisciplinary Perspectives, Springer, 2019, pp. 153–162.
[150] E. Ljungkvist, B. Thomsen, Interpretation of a fire scene with ultraviolet light: an assessment of the possible utilisation of ultraviolet light at fire scenes and subsequent recommendations for procedures, Forensic Sci. Int. 297 (2019) 284–292.
[151] S. Tubbs, Electrically caused fire and the expert, Fire & Arson Investig. 70 (3) (2020) 26–27.
[152] G. Parise, L. Parise, G. Mazzau, Investigations to identify electrical ignitions of fires: the sleuth engineering can draw from an array of tools, IEEE Ind. Appl. Mag. 25 (3) (2019) 54–59.
[153] C. Novak, A methodology for the examination of an electrical system by fire investigators and engineers, Fire & Arson Investig. 70 (4) (2020) 30–37.
[154] C. Novak, A methodology for the identification and interpretation of damage on electrical wiring, Fire & Arson Investig. 71 (1) (2020) 22–30.
[155] T.R. May, D.J. Icove, Arc mapping methodologies and the pursuit of magical globules, notches, and beads: a bridge too far to establish fire origin? Lincoln Memorial Univ. Law Rev. 7 (2) (2020) 37–77 (HeinOnline).
[156] D.J. Icove, T.R. May, State of the arc (mapping), J. Natl. Acad. Forensic Eng. 38 (1) (2021) 63–75.
[157] K. Franzi, C. Novak, M. Keller, Comparison of heat impinged conductors, Fire & Arson Investig. 71 (4) (2021) 12–18.
[158] M.M. Rashad, T. Mattar, Microscopic and metallurgical studies as a function on forensic investigation of electrical fires, Key Eng. Mater. 835 (2020) 135–140.
[159] L.F. Bilancia, D.C. Mann, Arson under the Christmas tree [paper presentation], May 6-8, in: 2019 IEEE International Symposium on Product Compliance Engineering, 2019 (San Jose, California, United States).
[160] E. Ljungkvist, B. Thomsen, S.M. Sindebaek, J. Christensen, N. Holm, M.K. Schultz, J. Ulriksen, 'The coldest case of all.' Fire investigation at the Viking Age ring fortress of Borgring, Denmark, Danish J. Archaeol. 10 (2021) 1–12.
[161] M.D. Leshner, Pinched power cord is latent defect causing fire when appliance is not is use, J. Natl. Acad. Forensic Eng. 38 (1) (2021) 45–50.
[162] C.E. Baukal, A.K. Agarwal, S. Olson, M.J. Gollner, T.J. Jacobs, M. Vaccarti, A Gallery of Combustion and Fire, Cambridge University Press, 2020.
[163] A.C. Scott, Fire: a Very Short Introduction, Oxford University Press, 2020.
[164] F.C. Rego, P. Morgan, P. Fernandes, C. Hoffman, Fire Science: from Chemistry to Landscape Management, Springer, 2021.
[165] Lattimer, B.Y. (Principal investigator) (2017-2019). Determination of Material Property Input Data for Fire Modelling (Grant No. 2016-DN-BX-0185) [Grant]. National Institute of Justice.
[166] F. Yang, J.L. Hodges, C.L. Rippe, B.Y. Lattimer, Methodology for material property determination, Fire Mater. 43 (69) (2019) 684–706.
[167] F. Yang, J.L. Hodges, B.Y. Lattimer, Material Burning Property Estimation Methodology and Validation, Interflam 2019, London, UK, 2019.
[168] J.M. Ellington, Forensic fire dynamics analysis & fire modeling, Fire & Arson Investig. 70 (3) (2020) 18–23.
[169] D.J. Icove, T.R. May, Computer fire modeling and the law: application to forensic fire engineering investigations, J. Natl. Acad. Forensic Eng. 38 (1) (2021) 77–90.
[170] J. Cabrera, Towards a Bayesian Framework for Fire Origin and Evolution in Fire Forensics, Doctoral dissertation, University of Texas at Austin, 2020 (Texas ScholarWorks).
[171] A. Kurzawski, J. Cabrera, O.A. Ezekoye, Model considerations for fire scene reconstruction using a Bayesian framework, Fire Technol. 56 (2) (2020) 445–467.
[172] N. Li, E.W.M. Lee, S.C.P. Cheung, J. Tu, Multi-fidelity surrogate algorithm for fire origin determination in compartment fires, Eng. Comput. 36 (3) (2020) 897–914.
[173] M.S. Blais, K. Carpenter, K. Fernandez, Comparative room burn study of furnished rooms from the United Kingdom, France, and the United States, Fire Technol. 56 (2) (2020) 489–514.
[174] V. Babrauskas, K.M. Rodgers, D. Lucas, R. Fuoco, Questions and comments about the methodology and conclusions in 'Comparative room burn study of furnished rooms from the United Kingdom, France, and the United States by Blais et al. 2019, Fire Technol. 57 (2) (2021) 497–502.
[175] M.T. Gratkowski, Bedding ignition, vertical flame spread and subsequent thermal impact on underlying mattress, Fire Mater. 45 (1) (2021) 28–36.
[176] A.B. Morgan, G. Knapp, S.I. Stoliarov, S.V. Levchik, Studying smoldering to flaming transition in polyurethane furniture subassemblies: effects of fabrics, flame retardants, and material type, Fire Mater. 45 (1) (2021) 56–67.
[177] B. Sundstrom, Combustion behavior of upholstered furniture. Important findings, practical use, and implications, Fire Mater. 45 (1) (2021) 97–113.
[178] W.M. Pitts, M. Werrel, M. Fernandez, M.A. Long, E.A. Eisenberg, J. Filliben, C. D. Runyon, Effects of upholstery materials on the burning behavior of real-scale upholstered furniture mock-ups, Fire Mater. 45 (1) (2021) 127–154.
[179] A. Hofmann, A. Klippel, T. Gnutzmann, S. Kaudelka, F. Rabe, Influence of modern plastic furniture on the fire development in fires in homes: large-scale fire tests in living rooms, Fire Mater. 45 (1) (2021) 155–166.
[180] Q. Guo, Y. Tang, Laboratory investigation of the spontaneous combustion characteristics and mechanisms of typical vegetable oils, Energy 241 (2022). Article 122887.
[181] S. Huang, R. Wei, T. Xie, J. Wang, Evaluation of fire hazards in typical vegetable oil residues, Process Saf. Environ. Protect. 154 (2021) 223–235.
[182] Y. Hu, J. Chen, M. Bundy, A. Hamins, The character of residential cooktop fires, J. Fire Sci. 39 (2) (2021) 142–163.
[183] J. Chen, Y. Hu, Z. Wang, K.Y. Lee, S.C. Kim, M. Bundy, M. Fernandez, A. Hamins, Why are cooktop fires so hazardous? Fire Saf. J. 120 (2021). Article 103070.
[184] M.J. DiDomizio, V. Ibrahimli, E.J. Weckman, Testing of liquids with the cone calorimeter, Fire Saf. J. 126 (2021). Article 103449.
[185] N. Sutarov, M. Forbes, J. Mundy, Fire created from water—a natural fire cause, Fire & Arson Investig. 71 (4) (2021) 32–39.
[186] K. Okamoto, M. Nakagawa, T. Ichikawa, T. Hagiwara, M. Honma, Induced fire hazards by gasoline spills, Fire Saf. J. 120 (2021). Article 103112.
[187] V. Babrauskas, Ignition of gases, vapors, and liquids on hot surfaces, Fire Technol. 58 (1) (2022) 281–310.
[188] A. Gossiaux, P. Bachelet, S. Bellayer, S. Ortgies, A. Konig, S. Duquesne, Small-scale single burning item test for the study of the fire behavior of building materials, Fire Saf. J. 125 (2021). Article 103429.
[189] M.S. McLaggan, J.P. Hidalgo, J. Carrascal, M.T. Heitzmann, A.F. Osorio, J. L. Torero, Fire Saf. J. 120 (2021). Article 103133.
[190] H. Eilers, Temperature Sensors Embedded in Paint for Fire Debris Analysis and Arson Scene Investigations (Project No. 2015-DN-BX-K073) [Grant], National Institute of Justice, 2019.
[191] T. Nagourney, J. Jordan, L. Marsh, D. Scardino, B.M. May, The implications of post-fire physical features of cylindrical 18650 lithium-ion battery cells, Fire Technol. 57 (4) (2021) 1707–1722.
[192] H. Yan, K.C. Marr, O.A. Ezekoye, Towards fire forensic characteristics of failed cylindrical format lithium-ion cells and batteries, Fire Technol. 57 (4) (2021) 1723–1752.
[193] W. Liu, F. Zhao, S. Liu, W. Mi, Chemical analysis of the cause of thermal runaway of lithium-ion iron phosphate batteries, J. Electrochem. Soc. 168 (6) (2021). Article 060507.
[194] R.J. Abel, J.L. Lunder, J.J. Harynuk, A novel protocol for producing low-abundance targets to characterize the sensitivity limits of ignitable liquid detection canines, Foren. Chem. 18 (2020). Article 100230.
[195] A. O'Hagan, H. Ellis, A critical review of canines used to detect accelerants within an arson crime scene, Foren. Res. Criminol. Int. J. 9 (2) (2021) 65–72.
[196] D. Leung, S. Forbes, P. Maynard, Volatile organic compound analysis of accelerant detection canine distractor odours, Forensic Sci. Int. 303 (2019). Article 109953.
[197] K. Tiira, N. Viitala, T. Turunen, T. Salonen, Accelerant Detection Canines' Ability to Detect Ignitable Liquids, Police University of Applied Sciences, 2019.
[198] R. Woods, Tracking the wildfire arsonist bloodhounds on the trail in West Virginia, Fire & Arson Investig. 72 (3) (2022) 16–21.
[199] A.P.W. Banks, P. Thai, M. Engelsman, X. Wang, A.F. Osorio, J.F. Mueller, Characterising the exposure of Australian firefighters to polycyclic aromatic hydrocarbons generated in simulated compartment fires, Int. J. Hyg Environ. Health 231 (2021). Article 113637.
[200] K.M. Kirk, M.B. Logan, Exposures to air contaminants in compartment fire behavior training (CFBT) using particleboard fuel, J. Occup. Environ. Hyg. 7 (16) (2019) 432–439.
[201] K.M. Kirk, Z. Splawinski, R.C. Bott, M.B. Logan, Combustion products generated in simulated industrial fires, J. Occup. Environ. Hyg. 18 (10–11) (2021) 510–521.

[202] U. Bakali, J.L.R. Baum, C. Killawala, E.N. Kobetz, N. Solle, S.K. Deo, A.J. Caban-Martinez, L.G. Bachas, S. Daunert, Mapping carcinogen exposure across urban fire incident response arenas using passive silicone-based samplers, Ecotoxicol. Environ. Saf. 228 (2021). Article 112929.
[203] G.P. Horn, D. Madrzykowski, D.L. Neumann, A.C. Mayer, K.W. Fent, Airborne contamination during post-fire investigations: hot, warm and cold scenes, J. Occup. Environ. Hyg. 19 (1) (2022) 35–49.
[204] L.A. Simms, E. Borras, B.S. Chew, B. Matsui, M.M. McCartney, S.K. Robinson, N. Kenyon, C.E. Davis, Environmental sampling of volatile organic compounds during the 2018 Camp Fire in Northern California, J. Environ. Sci. 103 (2021) 135–147.
[205] J.L. Pauley, Cold fire scene health hazards: recognizing the hidden dangers, Prof. Saf. 66 (8) (2021) 20–24.
[206] K. Fritzon, S. Miller, D. Perks, Arson, in: J.M. Brown, M.A.H. Horvath (Eds.), The Cambridge Handbook of Forensic Psychology, second ed., Cambridge University Press, 2021, pp. 296–316.
[207] S.J. Morewitz, Arson and arson-associated homicides, in: S.J. Morewitz (Ed.), Clinical Psychological Perspectives on Foul Play, Springer, 2019, pp. 171–196.
[208] S. Tilt, Deliberate fire-setting, in: N. Gredecki, P. Turner (Eds.), Forensic Psychology, Routledge, 2022, pp. 123–135.
[209] N. Tyler, M. Barnoux, Adult perpetrated firesetting, in: C. Garofalo, J.J. Sijtsema (Eds.), Clinical Forensic Psychology: Introductory Perspectives on Offending, Springer, 2022, pp. 397–413.
[210] V. Nanayakkara, Classifying Subgroups of Firesetters: Exploring Differences in Individual, Clinical and Contextual Variables, Doctoral dissertation, Swinburne University of Technology, 2020 (Swinburne Research Bank).
[211] C.S. Allely, Fire-setting and psychopathology: a brief overview of prevalence, pathways and assessment, J. Crim. Psychol. 9 (4) (2019) 149–154.
[212] V. Nanayakkara, J.R.P. Ogloff, T.E. McEwan, M.R. Davis, Applying classification methodology to high-consequence firesetting, Psychol. Crime Law 26 (7) (2020) 710–732.
[213] V.J. Parker, Deliberate Firesetting: Exploring Crime Scene Behaviours and Developing Firesetter Types, Doctoral dissertation, University of Birmingham, 2020 (UBIRA ETHESES).
[214] N. Tyler, T.A. Gannon, The classification of deliberate firesetting. The classification of deliberate firesetting, Aggress. Violent Behav. 59 (2021). Article 101458.
[215] M.P. Gunther, J. Kirchebner, S. Lau, Arsonists suffering from schizophrenia—a description in comparison with other offenders with a similar diagnosis, J. Forensic Sci. 65 (3) (2020) 882–887.
[216] J. Collins, M. Barnoux, P.E. Langdon, Adults with intellectual disabilities and/or autism who deliberately set fires: a systematic review, Aggress. Violent Behav. 56 (2021). Article 1010545.
[217] R.J. Loewenstein, Firebug! Dissociative identity disorder? Malingering? Or ? An intensive case study of an arsonist, Psychol. Injury. Law. 13 (2) (2020) 187–224.
[218] C.S. Allely, Firesetting and arson in individuals with autism spectrum disorder: a systematic PRISMA review, J. Intellect. Disabil. Offending Behav. 10 (4) (2019) 89–101.
[219] S. Holst, D. Lystrup, J.L. Taylor, Firesetters with intellectual disabilities in Denmark, J. Intellect. Disabil. Offending Behav. 10 (4) (2019) 72–81.
[220] V. Nanayakkara, J.R.P. Ogloff, T.E. McEwan, L. Ducat, Firesetting among People with Mental Disorders: differences in diagnosis, motives and behaviour, Int. J. Forensic Ment. Health 20 (2) (2021) 118–132.
[221] D.H. Ruben, Avoidance/escape (operant) conditioning and respondent biophysical arousal in the behavioral forensic assessment of an adolescent arsonist, in: Behavioral Forensics: Using Applied Behavior Analysis in Psychological Court Evaluations, Academic Press, 2020, pp. 253–264.
[222] S. Persson, S. Unhoo, Deliberate firesetting: hotspot schools as arenas and preventive actors, Nordic J. Criminol. 20 (2) (2019) 176–195.
[223] A.L. Breteton, R.V. Lamade, A.F. Lee, A. Schuler, R.A. Prentky, Retrospective study of fire setting among boys in a child welfare sample, Youth Violence Juv. Justice 18 (3) (2020) 256–273.
[224] J.J. Berger, Understanding Youth Firesetting Behaviors, Master's thesis, Bethel University, 2020 (Bethel University Spark).
[225] D.L.C. Perks, B.D. Watt, K. Fritzon, R.M. Doley, Juvenile firesetters as multiple problem youth with particular interests in fire: a meta-analysis, Aggress. Violent Behav. 47 (2019) 189–203.
[226] K. Dadswell, E. Kurt, M. Ball, D. Bruck, Prevalence and profiles of persistent firesetters following a targeted fire safety intervention program, J. Forensic Psychiatr. Psychol. 32 (6) (2021) 967–984.
[227] A.L. Rickett, Aggression, Anxiety, and Fire Setting Behaviors in Adolescent Males: a Comparative Analysis (Publication No. 27961278), Doctoral dissertation, William James College, 2020 (ProQuest Dissertations & Theses Global).
[228] F.K. Horsley, Arson Reconceptualized: the Continuum of Fire Use, Doctoral dissertation, Durham University, 2020 (Durham e-Theses).
[229] F.K. Horsely, New Perspectives on Arson and Firesetting: the Human-Fire Relationship, Routledge, 2021.
[230] F.K. Horsley, The fire-fire user relationship: a grounded theory of criminalized fire users' experiences, J. Forensic Psychiatr. Psychol. 32 (6) (2021) 902–916.
[231] F.K. Horsley, The positive aspects of fire use: a grounded theory of the experiences of non-criminalised fire users, J. Forensic Pract. 23 (4) (2021) 317–331.
[232] T. Ellis-Smith, B.D. Watt, R.M. Doley, Australian arsonists: an analysis of trends between 1990 and 2015, Psychiatr. Psychol. Law 26 (4) (2019) 593–613.
[233] T.R. Hall, An Analysis of Selected Clusters of Fires in Florida (1996-2018), Doctoral dissertation, NOVA Southeastern University, 2019 (NSUWorks).
[234] M.J. Edwards, Arson Risk Assessment; the Development of an Actuarial Model for Arson Recidivism, Doctoral thesis, University of Canterbury, 2020 (UC Research Repository).
[235] K. Sambrooks, M.E. Olver, T.E. Page, T.A. Gannon, Firesetting reoffending: a meta-analysis, Crim. Justice Behav. 48 (11) (2021) 1634–1651.
[236] Y. Irie, T. Nara, K. Satoh, K. Kameyama, T. Kitamura, M. Okuyama, H. Nakae, Survey on the current status of self-immolation attempts in Akita Prefecture: a cross-sectional survey, Burns Open 5 (4) (2021) 29–35.
[237] R.W. Byard, K.J. Health, Delayed familial self-immolation: a rare memorial event, Leg. Med. 50 (2021). Article 101865.
[238] H. Butler, T.A. Gannon, Do deliberate firesetters hold fire-related scripts and expertise? A quantitative investigation using fire service personnel as comparisons, Psychol. Crime Law 27 (4) (2021) 383–403.
[239] E.R. Barrowcliffe, T.A. Gannon, N. Tyler, Measuring the cognition of firesetting individuals using explicit and implicit measures, Psychiatr. Interpers. Biol. Process. 82 (4) (2019) 368–371.
[240] V. Nanayakkara, J.R.P. Ogloff, M.R. Davis, T.E. McEwan, Gender-based types of firesetting: clinical, behavioural and motivational differences among female and male firesetters, J. Forensic Psychiatr. Psychol. 31 (2) (2020) 273–291.
[241] A.N. Hewitt, E. Beauregard, J. Sea, Motivation and crime scene behavior in Korean fire setting: a new typology, Policing: Int. J. 44 (5) (2021) 756–771.