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Fire Cause & Fire Debris Analysis

A Review: 1998 to 2001

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INTRODUCTION

This review paper covers advances in scientific methods applied to fire cause and fire debris analysis reported since the 12th INTERPOL Forensic Science Symposium in October 1998. Major forensic laboratories from around the world were asked to provide information on both published articles and internal research reports in this area. A literature review was also conducted, covering articles published in the principal forensic science journals over the period in question (up to May 2001). This was supplemented by an extensive search of “Chemical Abstracts” (American Chemical Society), “SciFinder Scholar” (American Chemical Society), and the Internet, for articles related to fire investigation in the forensic arena. The final report is a collation of information received from these various sources.

SCENE EXAMINATION & GENERAL FIRE INVESTIGATION

General

The National Institute of Justice (1) and the National Fire Protection Association (2) have published standard guidelines for fire scene examination and arson investigation. Book chapters on all aspects of fire investigation have also appeared (3–10). The proceedings from an international symposium on the forensic aspects of fire investigation, sponsored by the Federal Bureau of Investigation, have been published (11).

Karisson and Quintiere (12) have published a book designed to provide the reader with an academic understanding of the dominating mechanisms influencing fire development in enclosed spaces. Their book, *Enclosure Fire Dynamics*, is a valuable resource for individuals involved in fire scene investigation and reconstruction. Lilley (13) has published a review on fire dynamics, including fundamental principles on ignition, fire behaviour, and fire development.

Technical working groups have been established in Europe and North America to coordinate research efforts and develop protocols for fire and explosion investigation, including the laboratory analysis of debris. The Technical Working Group for Fire and Explosions (TWGFEX) was established in the USA during a symposium in 1997 that was attended by professionals from analytical and crime scene disciplines (14). TWGFEX, sponsored by the National Center for Forensic Sciences (NCFS), has been involved in the development of national guidelines for the collection and analysis of fire and explosion debris, as well training and research to improve the quality of fire and explosion investigations. The Fire and Explosion Investigation Working Group (FEIWG) of the European Network of Forensic Science Institutes (ENFSI) was established in 1998 and currently has members from 22 European countries (15, 16). The working group has been examining European-wide fire investigation methods and is currently establishing guidelines for fire scene and fire debris analysis, quality assurance, and training. Other issues being addressed by FEIWG includes fire debris packaging materials, accelerant databases, and computer modelling. Funding has also been obtained from the European Union to carry out a series of live test burns that will go ahead later in 2001.

In the 1993 case *Daubert v. Merrell Dow Pharmaceuticals, Inc.*, the US Supreme Court set new restrictive rules for evaluating the admissibility of scientific and expert testimony based on relevance and reliability. The *Daubert* opinion instructed trial judges to act as ‘gatekeepers’ in deciding which types of scientific evidence to allow juries to hear. The trial courts were to hold preliminary hearings under *Federal Rule of Evidence 702* at which the scientists would explain their methods and conclusions. The judge would then decide, using a series of criteria for scientific validity, whether the testimony was accurate enough for the jury to hear. The Supreme Court identified five factors to examine in relation to *Daubert* challenges: (a) whether the theory has been tested before; (b) whether the theory has been subject to peer review; (c) whether there is a known rate of error; (d) whether standards or controls exist; and, (e) whether the theory is generally accepted by the relevant scientific community. According to some courts, *Daubert* has forced a re-examination of types of evidence that had always been permitted under the old rules. The potential exclusion of previously accepted evidence may be one of *Daubert’s* most important effects. Brannigan (17) has considered the impact of *Daubert* on arson evidence, and the possibility that such evidence may end up being excluded as unscientific. In a second article, Brannigan and Torero (18) highlighted some of the special legal and technical problems with key provisions of the National Fire Protection Association’s ‘Guide for Fire and Explosion Investigations’ [NFPA 921] (2). The authors conclude that, for the admissibility of arson expertise, three critical steps are required: (a) the separation of data collection from inferences; (b) demonstration of the repeatability of the analytical methodology; and, (c) the use of full-scale burns and fire models to reconstruct fires.

A number of recent court rulings on the application and interpretation of *Federal Rule of Evidence 702* on the admissibility of scientific evidence have re-emphasised the need for expert testimony to be reliable. Stauss and Hogan (19) provided an example where the testimony of three experts in a fire case was rejected by the Court of Appeals based on a perceived lack of reliability. The authors concluded that experts need to self-limit their opinions to their areas of expertise and the actual material facts of the particular case. If the bases for an opinion cannot be supported by other evidence (such as reliable eyewitness verification, physical evidence, laboratory analysis, scientific testing, etc.), then the opinion is based on speculation and should be rejected by the court.

Lentini (20) reported on an arson investigation and subsequent trial that led to the conviction of the defendant (*Commonwealth of Pennsylvania v. Han Tak Lee*). The methodology used by the investigators was examined, as was the presentation of expert testimony in the trial. The paper illustrates the need for trained scientists to become more involved in the collection and documentation of evidence, and to testify in a manner that does not magnify the certainty or importance of otherwise inconclusive data.

Combustion Studies

DeHaan and coworkers (21) described experiments in which the combustion of animal tissue (pork) was measured under a variety of conditions that may be encountered in fire scenes. It was demonstrated that animal tissue could be burned in a hot but localised fire fuelled by rendered fat absorbed into a charred porous substrate (acting like the wick in a kerosene lamp). Extensive thermodynamic data are reported from these tests, together with implications for the consumption of human bodies in fires.

In a limited number of fire death cases, the body of the victim is found with intensive fire destruction of the torso, while damage to surrounding furnishings and building is minimal. Such cases may be incorrectly described as 'spontaneous human combustion' as it is thought that a 'normal' accidental fire intense enough to consume a body would necessarily be large enough to incorporate an entire room. DeHaan and Nurbakhsh (22, 23) reported a combustion study using the same experimental protocol as before but using a larger (~100 kg) animal carcass that would more closely resemble an adult human body. Measurements were also conducted using a cone calorimeter to validate the equivalency of using pig carcasses rather than human cadavers for such tests. The data obtained from this study serve as a useful base for establishing the fire conditions produced when a body is involved in a prolonged fire of limited size.

Bohnert and coworkers (24) observed and documented the changes that occurred during the cremation of 15 undissected human bodies. It was found that the complete incineration of a human body took about 2–3 hours. The study serves to relate the destruction of a cadaver to the duration of a fire.

DeHaan (25) described a total of ten fires set by various means in furnished compartments and discussed the observed fire spread and the temperature data collected. The fires were all allowed to go to flashover and maximum temperatures in the range of 980–1040° C were measured. Such high temperatures were observed at both floor and ceiling levels regardless of whether or not flammable liquid accelerants were employed. The author hopes that the results of these tests will be kept in mind when forensic investigators are evaluating the post-fire indicators of fire behaviour. Unscientific theories about flammable liquid fires *always* being hotter than ordinary combustible fires, and floor level burning *always* being the result of flammable liquids still hold sway with some investigators.

It has been demonstrated by DeHaan and coworkers (26, 27) that vapours from flammable liquids (hexane) establish highly stratified, low-lying layers when evaporating from pools into still air, and that deflagrations of such layers produce uniform pressures throughout the compartment. Lapina and Sokalski (28) have developed a model to estimate the time period required for a propane leak to produce a volume fractional concentration equal to the lower explosion limit (LEL) of propane in air.

Paul (29) has published a review on ignition and flammability tests for plastics, rubbers and textile materials. Applicable test standards and their application are also considered for parameters such as flame spread, heat release rate (HRR), and smoke generation, as well as corrosivity and toxicity of fire gases.

Electrical Fires

A significant proportion of structure fires is attributed to ignition from electrical faults associated with wiring or with wiring devices. Despite this, the modes in which electrical faults progress to the ignition of structures have not been extensively studied. Babrauskas (30) has reviewed published information on the subject and points to areas where additional research is required. The author concludes that systematic research has been inordinately scarce, and that much of the published research that does exist is only available in Japanese.

The forensic investigation of a fire will often involve the post-fire examination of electrical panelboards and circuit breakers if such equipment survives the fire. Sometime a tripped (or untripped) circuit breaker is used to prove or disprove theories about the cause of the fire. However, the heat from a fire may be transferred to a circuit breaker and cause it to trip in the absence of an overcurrent condition. DeWitt and Adams (31) have reviewed the operating principles of thermal-magnetic circuit breakers, described a series of heat transfer tests conducted on a range of circuit breakers, and discussed the potential impact of heat transfer on circuit breaker performance during fires.

Goodson (32) has described the principles of operation of Ground Fault Interrupters (GFIs) designed to prevent deaths caused by exposure to electrical current. If a portion of the electrical current has been diverted to ground, as is the case with an electrocution, the GFI trips, cutting off the power to the circuit. The author explains how GFIs may prevent some electrical fires (such as those brought about by physical damage to energised cables) and indicates their relevance to the way in which electrical fires are investigated. VanderPas and Lewis (33) reported several fires originating from GFI receptacles located near wash basins. The fires were attributed to the corrosion of copper components within the GFIs.

Surge suppressors are devices used in electrical equipment to protect the equipment from voltage transients (spikes) that could otherwise cause damage. Most surge suppressors make use of Metal Oxide Varistors (MOVs) that are intended to minimise the effect of short-lived power disturbances. Goodson (34) has highlighted the fact that MOV's can fail under certain conditions and that this failure may initiate a fire.

Fires often result from arcing faults within electrical cords, cables and other electrical devices. Hagimoto and coworkers (35) have summarised the characteristics of such arcing and reported on experiments conducted on electrical cords and cables insulated with polyvinyl chloride (PVC). The tracking resistance of insulating materials degraded by heating in an electrical furnace has been investigated by Okamoto and coworkers (36). Ashizawa (37) has studied the processes involved in the progression from thermal degradation to ignition of an

attachment plug due to the joule heating of a defective contact between socket receptacles and plug blades. Crawford (38) has presented cases where fire has resulted from the slow deterioration of overheated electrical insulation. The cases demonstrate that carbon-based insulation can become conductive when stressed by long exposure to moderate heat.

Electrical Molten Marks (EMMs), resulting from arcing between electrical wiring, are present at nearly all structural fire scenes. A reliable technique for differentiating between primary molten marks, indicating arcing as the cause of the fire, and secondary molten marks, indicating arcing as a result of the fire, would be of particular value to the fire investigator. Lee and coworkers (39, 40) studied the crystal structure of the carbon in carbonised residue caught in artificially-prepared primary and secondary EMMs. They found that both graphite and amorphous carbon was present in the primary EMMs, while the secondary EMMs only exhibited amorphous carbon. This suggests that the presence of graphite may serve as an indicator of primary EMMs (and hence arcing that has caused the fire). In a further study, it was found that the surrounding temperature at the formation of an EMM could be estimated by measuring DAS (Dendrite Arm Spacing) and oxide concentration (41).

Goodson and coworkers (42) have reviewed a number of cases that demonstrate how electrical energy in a fault situation can travel along a gas line, creating a gas leak and a resultant fire. Of importance to the investigator in such situations is an appreciation of how gas fittings may be damaged by an electrical current. The operation of electric water heaters has also been reviewed, with a conclusion that the heaters themselves do not generally cause fires (43). Fires involving electric water heaters are most probably caused by an overheated connection, or a direct short that occurs in close proximity to combustibles. Conditions under which a fire is possible from a halogen lamp have been discussed (44). The main danger is from combustible material falling on the lamp shade, in close proximity to the halogen bulb. However, the long-term failure of a halogen lamp can sometimes result in an 'exploding light tube' that ignites any readily combustible material near the lamp (45).

Non-Electrical Fires

Lighted cigarettes can ignite materials that are capable of smouldering, whereas commonly encountered solid materials are not ignited directly by such a source. Holleyhead (46) has discussed the mechanism of ignition of solid materials by cigarettes, the smouldering process, and the transition of a smoulder to flaming combustion. In addition, the results of tests to ignite solid materials and the components used in the manufacture of furniture, especially polyurethane foam, have been reviewed.

Bishop and DeMars (47) considered how easy it was to ignite a Christmas tree using an 'accidental' source such as shorted wires, matches, or butane lighters.

Experimental results indicated that it was very difficult to get a Christmas tree to sustain a flame when ignition was by some ordinary means. The authors concluded that it was unlikely that an ordinary Christmas tree will ignite and cause a fire where the tree itself is the initial fuel.

Hagimoto and coworkers (48) reported that a significant number of fires in Japan are caused by welding and cutting sparks at construction sites. The authors investigated the generation and dispersion of particles that resulted from the use of electrical welding equipment. They found that welding particles could readily ignite many combustible materials, including combustible liquids of high flash point. The investigation of fires involving gas-fired water heaters and fuel oil furnaces has been discussed (49, 50).

Ezekoye and Martin (51) reported on a violent explosion that resulted from a metal paint thinner can being refilled with kerosene at a refuelling station. Significant static charges can build up in a petroleum-based fuel flowing through a tube. If the fuel container being filled is metal and is not grounded (as was the situation for the case in question), the charges that accumulate at the tip of the fuel nozzle can result in a spark between the nozzle and the container. Such a spark may contain sufficient energy to ignite flammable vapour in the container.

Nic Daéid and Thain (52) have indicated that many domestic fires in Scotland result from the incorrect or careless use of candles of various types. Candles known as 'night lights' or 'tea lights', very popular with consumers, are small and encased in an aluminium dish. The authors report on the temperature increase of the metal container over time, under various airflow conditions. Under certain circumstances, temperatures were reached that could result in ignition of some surfaces.

Roby and Carpenter (53) have discussed the role of carpet in determining the origin and cause of a compartment fire. The authors consider how carpet behaves with respect to compartment fires and include examples of how such information can be used to help support findings from other sources.

Vehicle Fires

Investigators are frequently presented with the problem of investigating total loss, or 'black hole', motor vehicle fires. This type of fire is characterised by the total consumption of every combustible item in the vehicle. Such vehicles are often reported stolen, with the motive for the fire being insurance fraud. Wendt (54) has considered the difficulties associated with such investigations and has emphasised the need for a 'global perspective' to conduct a thorough and complete inquiry.

Gomez (55) has conducted studies to determine if it is possible to enflame a vehicle using a portable ignition source such as matches or butane lighters. The direct ignition of a vehicle tire was unsuccessful. However, it was found that certain polymer fittings on the exterior of a vehicle could be ignited and that this could lead to a fire that readily penetrated to the interior of the vehicle.

Spontaneous Combustion

There has been debate over whether or not wood that has been exposed to long-term, low-temperature heat sources (below about 150° C) can generate char that may result in spontaneous combustion. Babrauskas (56) has questioned claims that the concepts of 'pyrophoric carbon' or 'pyrophoric char' have been disproved through scientific research. The author argues that such claims are premature and further research is required on the subject.

Sanderson and Schudel (57) have considered the possibility that the spontaneous combustion of lint may be the most common cause of residential clothes dryer fires. Oils used in cooking are somewhat subject to spontaneous heating and may cause fires associated with dryers under certain circumstances. However, the authors report that none of the results from 16 tests they conducted showed any evidence of spontaneous heating in lint samples.

Several laundry fires have been reported in the United Kingdom and Ireland where the cause is thought to be spontaneous combustion, specifically of fatty acids (such as linoleic acid) that may be present on cotton materials after the laundering process. Combustion has been known to occur amongst freshly laundered and tumble-dried clothing if the materials are heaped or stacked immediately after drying. Nic Daéid and Walker (58) found that significant levels of linoleic and oleic acids (known constituents of human sweat) were recoverable from cloth even after very hot washing cycles (90° C). It was concluded that, if such materials were then exposed to heating (during the tumble-drying process) such that auto-oxidation temperatures were reached, then spontaneous combustion was conceivable if the subsequent heat was not allowed to dissipate.

Cooper and coworkers (59) investigated the phenomenon of spontaneous combustion of common fibrous evaporative cooling filters originating from paint booth filtration systems. A modified oven test method was utilised to predict the likelihood of spontaneous ignition over a range of ambient temperatures, with specific focus on lower temperatures. The background for the study was a multimillion-dollar structural fire where the exact fire cause was undetermined, but the spontaneous combustion of paint filters could not be eliminated as a possibility.

Accelerant Detection Canines

Accelerant detection canines (ADCs) have assisted fire investigators at fire scenes since the early 1980s. The use of ADCs, trained to specifically locate trace amounts of ignitable liquids, has proliferated at a significant rate. Roberts and Roberts (60) have argued that the olfactory capability of canines should not be used in fire investigations for three reasons: (a) there are significant hazards for the dog at a fire scene (toxic fumes, sharp objects, unstable surfaces, etc.); (b) there is a common problem of assigning dogs capabilities that they do not possess (for example, dogs cannot determine intent and have no sense for the issue of cross-contamination); and, (c) the use, even presence, of an 'arson dog' at a fire scene can be an influence, direct or subconscious, that destroys objectivity.

Lynch and Sawyer (61) discussed a California arson trial where results from the analysis of fire debris samples were challenged based on an allegation that cross-contamination may have occurred at the scene by the actions of an ADC. The authors recommend that ADC organisations test such propositions through a series of controlled experiments. Unless it is scientifically proven that cross-contamination by ADCs does not occur, such allegations are likely to persist.

Sample Collection & Packaging

Containers for the collection and storage of fire debris samples should be durable, inert, impermeable to volatile materials, and devoid of any residues that may interfere with test results. Unused lined or unlined paint cans, glass jars, and special-purpose polymer bags have traditionally been used for this purpose. Mann (62) has published results from a study designed to test and compare these containers. Issues addressed included background volatiles, permeation of the container seals by hydrocarbon-based volatiles, irreversible adsorption of hydrocarbon-based volatiles by the container membrane, effects of temperature on storage, and sample cross-contamination. The data indicated that the cleanest and most leak-free container for storage and analysis of fire debris samples is a well-sealed specialty polymer bag. Care must be exercised, however, with the packaging of debris with sharp edges. A metal can with a friction-fit lid provided the least protection from sample loss and cross-contamination. Accelerant leakage from metal paint cans was confirmed in experiments reported by Birchall (63).

Delémont and Wistedt (64) have surveyed the packaging devices (metal cans, glass jars, plastic bags) used by ENFSI forensic laboratories for the sampling of fire debris. Extensive studies are currently under way to evaluate the permeability of different polymer bags to gasoline vapours. Cryovac and Globus brand polyethylene/polyvinylidene dichloride bags have been tested by Kocisko (65) for their suitability in storing ignitable liquid evidence. The bags were found to absorb components of diesel, kerosene, and gasoline, and were also found to produce interfering by-products that complicated the interpretation of chromatographic profiles. The unsuitability of these bags as a means of packaging fire debris highlights the need to test evidence containers to ensure that analytical results are not compromised.

A survey was reported by Lang (66) where stocks of glass mason jars used for fire debris collection were analysed by headspace gas chromatography for possible background contaminants. The majority of mason jars exhibited no appreciable contamination that would interfere with typical fire debris analyses. Approximately one-third of the jars showed trace level contaminant peaks in the range of C8 to C18. Such contaminants would not be incorrectly identified as an ignitable liquid and would potentially interfere with the analysis of only trace level accelerants. Procedures were subsequently developed to prevent container contamination and ensure consistency in container handling.

The possibility of cross-contamination between packaged liquid gasoline and other samples, in simulation of a casework submission, was evaluated by MacManus (67). Glass mason jars and glass vials, combined with nylon bags, were tested as containers for liquid gasoline by packaging them together with empty mason jars for one month. The indications of gasoline detected in several of the empty glass jars by headspace gas chromatography were not considered sufficient to definitively show that cross-contamination would occur under such circumstances. However, care must still be taken when packaging suspected volatile ignitable liquids with fire debris samples for laboratory analysis.

Doyle (68) has evaluated the use of a 3M brand high capacity hydrophobic sorbent as a sampling medium for liquid accelerant residues at fire scenes. The product is designed for commercial applications such as adsorbing organics (oil and petrol) from factory floors. It was found that the 3M sorbent is extremely sensitive to gasoline vapour and will still render an identifiable chromatogram when there is as little as 5 ppm of gasoline in air.

Training & Research

Berrett and Candy (69) have summarised the current situation with respect to the training of fire investigators in the United Kingdom. While there has been a significant lack of such training in the past, a number of new initiatives have given rise to optimism. Courses with a strong practical element have proven to be the most successful.

An interactive, CD-ROM-based training package for fire investigators has been developed in the USA by a public-private partnership comprising the Bureau of Alcohol, Tobacco and Firearms (ATF), the US Fire Administration (USFA), private industry (American Re-Insurance Company), and a host of professional organisations [including the National Fire Protection Association (NFPA) and the International Association of Arson Investigators (IAAI)] (70-73). The training program, known as 'interFIRE VR', uses the latest in photo-realistic virtual-reality technology to present lessons on best practice in fire investigation. The software has three working sections that include a series of video-clip-based tutorials, a reference file, and a casework scenario that allows the user to 'respond to a call' and conduct an investigation from start to finish.

With the increasing complexity of fire investigations and the courts demanding that only 'valid scientific methods' be used to evaluate fire scenes, technical assistance for investigators is becoming more important. Tontarski (74) has presented the concept and operation of the ATF's Fire Research Laboratory (FRL) and Fire Research Center (FRC). The FRL, a partnership between law enforcement, fire services, public safety agencies, industry and academia, is designed to promote and support the greater use of fire science in fire origin and cause determinations. The facility provides a controlled environment where fire investigation theories can be investigated and fire propagation scenarios reconstructed on a large scale.

The future of fire investigation has been considered by Madrzykowski (73). The use of digital imaging, virtual fire scene reconstruction, mathematical fire simulations, and remote computer modelling, is expected to increase significantly over the next decade. Such technology is being actively researched within the National Institute of Standards and Technology (NIST) Building and Fire Research Laboratory. The author provides an overview of where the state-of-the-art research is at and where it is heading.

Internet Resources

The Internet explosion has continued over the last three years, with most agencies and organisations involved in fire investigation now hosting web sites to support investigators (75-84). Information contained on these sites, including links to other sites of potential interest, provides a wealth of material to assist the fire investigator. Easy access to such information is complimented by the increasing use of electronic mail (e-mail) as the communication tool of choice for contacting interstate and international colleagues. It is expected that, as network capabilities and computer technologies improve, more advanced applications to assist the fire investigator will become available.

LABORATORY ANALYSIS OF FIRE DEBRIS SAMPLES

General

Bertsch and Ren (85) have written an extensive chapter on the detection and identification of ignitable liquid residues in fire debris samples. Modern sampling techniques are detailed, together with advances in gas chromatography (GC) and gas chromatography/mass spectrometry (GC/MS). The authors have included comprehensive sections on data analysis and interpretation, including automated data processing, and a review of current practices in forensic laboratories around the world. The possibility of taking the laboratory to the scene has also been considered, with compact 'electronic nose' sensors and portable gas chromatographs having potential application for the field testing of fire debris. One of the authors [Ren (86)] has also completed a university dissertation on sample preparation and data interpretation for the analysis of accelerants.

Lentini (87) has commented on the relative performance of laboratories, over the last three years, with respect to proficiency tests prepared and circulated by Collaborative Testing Services (CTS). In comparing the performance of laboratories that use GC as their only instrumental technique, versus those who use GC/MS, it is clear that those using GC/MS have a significantly higher probability of reporting results consistent with the manufacturer's specifications. Inconsistent answers given by some laboratories may be the result of confusion over the ASTM (American Society for Testing and Materials) classification system. In response to this problem, ASTM is discontinuing the use of class numbers for ignitable liquids, opting for the more descriptive class name.

Sampling and Sample Preparation Techniques

Sample preparation methods for the analysis of ignitable liquid residues in fire debris samples have been reviewed by Bertsch and Ren (88). A study representing a critical comparison of adsorbent-based heated headspace methods for the enrichment of volatile materials from fire debris has been published by the same authors (89). A dynamic and a static method, based on charcoal adsorption, and solvent extraction were compared to solid phase microextraction (SPME) procedures. Ren and Bertsch (90) have also evaluated currently available analytical methodologies for the chemical analysis of water-soluble accelerants such as ethanol and acetone. A micro-distillation procedure, used in conjunction with SPME methodology, appeared to be particularly simple and effective.

Furton and coworkers (91-93) have published several studies on the application of SPME for the recovery and analysis of accelerant residues. In one study, SPME/GC was found to be a simple, fast, inexpensive, and sensitive technique for the detection and identification of flammable liquid residues on the skin of arson suspects (93). The use of SPME as a sampling technique for volatile flammable liquids has also been investigated by a number of other authors (94-96).

Passive headspace adsorption onto activated charcoal strips is a common sampling technique for volatile accelerants in fire debris. Carbon disulfide is widely used as an extraction solvent for the recovery of volatile organics from activated charcoal strips. The popularity of carbon disulfide is due to its superior desorption of most accelerant types, its high volatility, and its low detector response when extracts are analysed by GC using a flame ionisation detector (FID). However, carbon disulfide has a strong, unpleasant odour, is highly flammable, and represents a significant health hazard to laboratory personnel. Several studies have looked at finding a safer alternative to this solvent for the preparation of fire debris samples (97-99). Birrer and coworkers (97, 98) concluded that dichloromethane was a better eluting solvent than diethyl ether for alkanes and aromatics, but was less efficient than carbon disulfide. Massey (99) recommended the replacement of carbon disulfide with a solution of 10% iso-propanol in dichloromethane for the desorption of all accelerant classes from activated charcoal devices. While carbon disulfide remains the best solvent for desorbing alkanes and aromatics, the consistently high degree of desorption offered by 10% iso-propanol in dichloromethane for all accelerant classes (including alcohol) was unsurpassed.

Chromatographic Analysis & Data Interpretation

Gasoline is the most commonly encountered flammable liquid in fire debris analysis. A study has been reported by van Bebbber (100) that sought to determine detection limits and characteristics target compounds for gasoline identification, using a number of sampling methods and GC/FID analysis. Touron and coworkers (101) have detailed an analytical strategy for the semi-automatic analysis of fire debris samples. The first step in the protocol involves the use of a portable photoionisation analyser to detect and pre-estimate the amount of accelerant in a given sample. Results from this initial screen are then used to determine what subsequent chromatographic analyses are to be conducted.

Lewis and coworkers (102) have described a simple procedure for the identification of propan-2-ol (iso-propanol) in fire debris. Heated headspace vapours are collected from the sample and discharged into distilled water in a sealed vial. Subsequent analysis of the aqueous solution is then performed by headspace GC/FID.

The technical aspects of GC/FID and GC/MS analysis of fire debris samples have been presented by Bertsch and Ren (103). The general move within criminalistics laboratories from the use of a general response type detector (FID) to mass spectrometry (MS) is discussed. The trend towards more routine use of GC/MS techniques for fire investigation will continue as bench top instruments become more affordable and more user-friendly.

Ohtsuji and coworkers (104) have discussed the analysis of volatile hydrocarbons by GC/MS in burned body autopsies and its usefulness in fire investigations. In all of twenty cases examined, where GC/MS analysis was conducted on intratracheal gas, blood, and the victim's clothing, the analytical findings were consistent with accelerant identification by other means. Sturaro and coworkers (105) reported casework data obtained by GC/MS analysis of residual cloth and soil samples from a burned body, which identified the accelerant together with some unrelated compounds originating from the container used to carry the flammable liquid. Identification of these compounds (that included a mixture of dichlorotoluene isomers) and nomination of a possible source had a significant effect on the course of the investigation.

Mass chromatography is being adapted by many forensic laboratories as the preferred method for interpreting GC/MS data from fire debris samples. Wallace (106) has described software approaches for minimising interferences and for facilitating the identification of flammable liquid residues. Guidelines have been developed for recognising chromatographic distortions that often occur when adsorption/elution sampling techniques are employed. The author illustrates the application of these software tools and guidelines through case examples.

GC/MS analysis along with the use of extracted ion profiling can be a useful tool for the fire debris analyst, particularly in distinguishing an ignitable liquid from interference due to pyrolysis products or other contaminants. An example of the use of individual ion profiles versus summed ion profiles to identify an ignitable liquid in an actual case has been presented by Gilbert (107).

While the characterisation of pure flammable liquids is a relatively simple task, real-world samples are generally complex mixtures comprising both artefacts and pyrolysis products in addition to the masked accelerant. Bukowski and coworkers (108, 109) have described the use of pattern-matching software to assist the analyst with the interpretation of complex GC/MS chromatograms. The software automatically performs target compound identification after GC/MS data acquisition, and proceeds to compare the resultant pattern of target compounds with the contents of a standards library. A list of the most probable matches is then presented to the analyst.

A computer database of GC/FID profiles for a range of flammable liquids and interfering matrices (such as wood, carpet, polymers, etc.) has been developed by Calderara and coworkers (110) using Filemaker Pro software (Claris Corporation). This system makes standard chromatographic profiles more easily accessible. Comment and Martin (111) have investigated the potential of neural networks to assist the analyst with the interpretation of GC/MS results. Data on sixty target compounds is subjected to neural network treatment to characterise the type of accelerant present.

The application of GC/MS and multivariate pattern recognition techniques for petroleum-based accelerant detection and classification has been presented by Tan and coworkers (112). Method feasibility and matrix effects on accelerant classification were studied using principal component analysis (PCA). A soft independent model classification analogy (SIMCA) model was then developed to evaluate evaporation, sample size, and sample charring. Depending on the sample class, the detection limits for correct classification were in the range of 5-50 μm .

Rodgers and coworkers (113) have reported that the elemental compositions of each of 100 to 500 different constituents of lighter fluid, kerosene, mineral turpentine, gasoline, diesel fuel, and two brands of mineral spirits (and their weathered analogues) make possible direct identification of each accelerant in an experimental fire, based on electron ionisation Fourier transform ion cyclotron resonance (EI FT-ICR) ultrahigh resolution mass spectrometry. Extraction and EI FT-ICR mass analysis of fire debris from the controlled burn of a couch with simple (lighter fluid) and complex (mineral turpentine) ignitable liquid yielded dozens of elemental compositions serving as a unique 'fingerprint' for each petroleum product, despite the presence of up to 249 additional extracted matrix and pyrolysis components.

The value of gas chromatography coupled with tandem mass spectrometry (GC/MS/MS), as a confirmatory analysis after conventional GC/MS processing of fire debris samples, has been reported by Sutherland and coworkers (114, 115). A study was conducted on squares of new carpet that were spiked with a small amount of gasoline, severely burnt, soaked with water, and left exposed outdoors (115). The samples were then periodically analysed by GC/MS. After several days, the gasoline residues could no longer be positively identified based solely on GC/MS. Samples were then reanalysed using the more specific and more sensitive method of GC/MS/MS. The GC/MS/MS analyses gave definitive positive results for samples left an extra 14 days beyond the point where GC/MS analysis alone failed to confirm the presence of an accelerant.

The application of GC/MS/MS to fire debris analysis has also been investigated by Zeng and Zhang (116). Residues of gasoline, kerosene and diesel in soil and on burned polypropylene and carpet were analysed by GC/MS/MS using the parent ions m/z 91, 106, 120 and 142. It was determined that the 106 m/z ion was the optimal parent ion for the analysis and that the interference of pyrolysis products from the burned samples was overcome.

MISCELLANEOUS STUDIES

Accelerant Transfer & Persistence

Coulson and Morgan-Smith (117) conducted a study aimed at measuring the approximate amount of gasoline transferred on to the clothing and shoes of a person during the action of pouring petrol around a room. Two different heights of pouring and two different types of floor surface (carpet and concrete) were investigated. The results showed that, for all of the combinations examined, gasoline was always transferred to the shoes and often transferred to the upper and lower clothing. The information obtained illustrated the necessity of analysing the clothing, and particularly the shoes, of any suspected arsonists for the presence of flammable liquid residues.

Taylor (118) looked at the approximate rate of evaporation of gasoline from sports shoes. Experiments conducted by the author involved the application of 1 to 5 mL of unleaded gasoline to the toe area of the shoes. With the shoes stored at 20° C, gasoline residues were detectable for up to four hours only. The findings highlighted the fact that the collection and correct packaging of an arson suspect's shoes should be performed as soon as possible.

The persistence and sampling of gasoline residues on hands has been investigated by Darrer and coworkers (119). Four different sampling media were evaluated: polyethylene (PE) gloves, latex gloves, polyvinyl chloride (PVC) gloves containing talcum powder, and humidified filter paper. Of these collection methods, PVC gloves containing talcum powder were the most effective. The gloves are worn by the suspect for approximately 20 minutes, and then the gloves packaged and analysed as for a normal fire debris sample. This technique permitted the successful identification of gasoline residues on hands up to 2 hours after the initial application of 0.5 to 1.0 mL. Detection of gasoline residues was still possible, in some cases, after 4 hours. A similar study was conducted by Rolph (120), who investigated sampling techniques that included cotton swabs, cotton gloves, nitrile gloves, vinyl gloves, and a combination of cotton gloves under nitrile gloves. Of the techniques evaluated, nitrile gloves were subsequently chosen as the sampling method of choice. It was determined that, in order to identify all gasoline target compounds, the nitrile gloves had to be applied for ten minutes. Heavier target compounds could be identified by heating the gloves (via a hair dryer) during the initial two minutes of glove application.

Sester and coworkers (121, 122) investigated the potential transfer of gasoline onto hands during the normal process of refuelling a vehicle. The aim of the study was to assess the possibility that gasoline residues detected on hands may be due to this activity. The hands of fourteen volunteers were sampled, using the protocol recommended by Darrer and coworkers (119), immediately after refuelling a vehicle with gasoline. While some target compounds were detected, none of the samples gave chromatographic profiles that could be conclusively identified as gasoline. The results indicated that no significant transfer of gasoline onto hands arises through the normal refuelling process.

Contamination & Background Interference

Using passive headspace concentration and GC/MS, Lentini and coworkers (123) have studied the volatile components detectable in a range of otherwise uncontaminated substrates, including clothing, shoes, household products, building materials, paper products, cardboard, and adhesives. Due to the use of petroleum-derived liquids in the manufacture of such materials, it is frequently possible to detect volatile petroleum products, even when the substrates are several years old. The results emphasise the need to analyse comparison samples whenever possible to determine if detectable volatiles may be from the substrate itself rather than attributed to the presence of an accelerant.

Chanson and coworkers (124, 125) have analysed the volatile components present in eight different types of wood and compared these with the principal components found in seven different brands of turpentine. GC/MS analysis indicated that a range of monoterpenes were present in both the wood samples and the turpentine products. On the other hand, sesquiterpenes were only identified in the turpentine samples. The results highlight the potential difficulty that may arise if turpentine is suspected of being used as an accelerant in the presence of wood that may contain the same natural products.

A study conducted by Cavanagh (126) aimed to determine both the natural occurrence of gasoline residues on motor vehicle carpet or carpet mats, and the level of background interference from the carpet matrix when analysing for accelerants. In addition, the persistence of unleaded gasoline on carpet was evaluated. It was determined that gasoline residues will generally not be detected on previously uncontaminated carpet samples after a six-week period of use in a vehicle. However, a significant proportion of the carpet samples analysed exhibited a high background of volatile compounds, including some of the compounds that are diagnostic for gasoline, which could complicate the interpretation of chromatographic profiles. Results indicated that small volumes of gasoline (less than 100 μL) are unlikely to be detected on car carpet mats 24 hours after application. A volume of 100 μL could be detected after 24 hours, but not after seven days. The findings from this study reinforce the evidential value of finding significant quantities of gasoline on carpet products in motor vehicles. The importance of collecting unburned carpet samples for comparison purposes is also emphasised.

In 1998/99, the New Zealand Fire Service implemented compressed air foam (CAF) delivery systems for the suppression of fires in rural areas. The purpose of the foam (Phos-Chek WD881; Monsanto) is to reduce the amount of water needed to extinguish a fire by reducing the surface tension of the water. A study by Coulson and coworkers (127) investigated whether the introduction of the foam to the seat of the fire interfered with the subsequent detection of hydrocarbon fuels in fire debris samples. No significant interferences from the foam were found when the samples were analysed by direct headspace enrichment using activated charcoal strips. The only foam component detected was limonene.

A product described as a 'micelle encapsulator fire suppression agent' (F-500; Hazard Control Technologies) is finding use in Canada due to its claim of overall speed and effectiveness of fire suppression, its cooling properties, its low toxicity, and its ability to reduce the likelihood of re-ignition. McGee and Lang (128) have studied the effects of this fire suppression agent on the analysis of fire debris samples by dynamic headspace sampling and gas chromatography/ion trap mass spectrometry. It was determined that, when samples were heated to 130° C during routine analysis, strong peaks from the F-500 were observed in the chromatograms at retention times that interfere with the patterns from common volatile ignitable liquids. A number of ways of addressing this problem using the ion trap mass spectrometer were explored.

Positive pressure ventilation (PPV) fans have application at fire scenes as a means of clearing smoke, toxic gases, heat and steam to reveal the seat of the fire, increase the chances of victim survival and rescue, permit faster fire extinguishment, and improve overall firefighter safety. Lang and Dixon (129) have undertaken experiments to explore the possibility of scene contamination by a gasoline-powered PPV fan under optimised operating conditions and when no other source of gasoline was present. Clean pieces of wet and dry fabric were suspended in an uncontaminated structure at various distances from the front door. A properly tuned gasoline PPV fan was then operated outside the door as per normal procedures. Fabric samples, collected from interior locations at intervals of 15, 30, and 45 minutes after the fan was started, were subjected to dynamic headspace sampling and gas chromatography. Traces of gasoline were identified in 3 of 39 samples, in no predictable pattern with respect to time, location, or substrate type (wet or dry). The authors recommend that the use of PPV fans be documented by the fire investigator and communicated to the laboratory personnel.

The natural release of pyrolysis products from burning substrates can produce a background of volatile components that can significantly complicate the detection and identification of ignitable liquid residues in fire debris samples. A comprehensive characterisation of pyrolysis products formed under controlled laboratory conditions has been conducted by Stauffer and Almirall (130). A wide variety of materials commonly present in a house fire were analysed by pyrolysis GC/MS. In addition, pyrolysis products were generated in a muffle furnace and the samples analysed by passive headspace concentration (activated charcoal strips) and GC/MS. The data generated from these experiments has permitted a better understanding of the range of interfering compounds that may be generated in the course of a fire.

CONCLUSIONS

A review of the relevant forensic literature published over the last three years (1998 to May 2001), covering areas related to fire cause and fire debris analysis, has highlighted the following:

- 4# Several agencies have published standard guidelines for fire scene examination and arson investigation. In addition, technical working groups have been established in Europe and North America to coordinate research efforts and develop protocols for fire and explosion investigation, including the laboratory analysis of debris.
- 4# Several court rulings in the USA have led to new requirements for evaluating the admissibility of scientific and expert testimony based on relevance and reliability. The implications of these rulings on the admissibility of fire and arson expertise have been considered by a number of authors.
- 4# Several combustion studies, some conducted on animal carcasses, have led to a better understanding of how human bodies are consumed in fires.

- 4# The study of electrical causes continues to be an area of research activity, with several reports being published that may provide assistance to fire examiners. However, further research is still required to gain a better understanding of the modes in which electrical faults progress to the ignition of structures.
- 4# Research reports have been presented on fire cause by non-electrical means including lighted cigarettes, welding sparks, and candles. The possibility of spontaneous combustion has been considered in cases involving charred wood, clothes dryer lint, and tumble-dried clothing.
- 4# The use of accelerant detection canines to provide assistance to scene examiners when selecting fire debris samples for accelerant analysis has been questioned by a number of authors. Issues including hazards to the dog and possible scene contamination have been raised.
- 4# Containers for the collection and storage of fire debris have been evaluated in a number of studies. A range of different packaging materials (including unused paint tins, glass jars, and polymer bags) continue to be used.
- 4# CD-ROM-based virtual reality software has been developed as a training and reference resource for fire scene examiners. This form of training package is likely to become more common in the future, across all forensic science disciplines.
- 4# The use of digital imaging, virtual fire scene reconstruction, mathematical fire simulations, and remote computer modelling, is expected to increase significantly over the next decade.
- 4# The Internet explosion has continued over the last three years, with most agencies and organisations involved in fire investigation now hosting web sites to support investigators. Information contained on these sites, including links to other sites of potential interest, provides a wealth of material to assist the fire investigator. It is expected that, as network capabilities and computer technologies improve, more advanced forensic applications will become available.
- 4# Extensive reviews have been written on the detection and identification of ignitable liquid residues in fire debris samples. A range of different sampling methods are now available to the laboratory analyst, including the use of activated charcoal strips and solid phase microextraction (SPME) fibres for static headspace enrichment. Studies aimed at optimising such procedures have been published.
- 4# The trend towards the more routine use of gas chromatography-mass spectrometry (GC/MS) for fire debris analysis has continued as bench-top instruments improve in performance and cost-effectiveness.
- 4# While gas chromatographic techniques have not changed significantly over the last three years, improvements have been made in the areas of data handling and data interpretation. Pattern matching software and systems based on neural networks have been evaluated for the interpretation of complex GC/MS chromatograms. The use of automatic data processing for the interpretation of chromatographic profiles is likely to become more widespread over the next few years.

- 4# A number of authors have highlighted the advantages of tandem mass spectrometry (GC/MS/MS) as a more specific and more sensitive method for ignitable liquid analysis in comparison to conventional GC/MS. Unfortunately, this technique is not widespread and is generally inaccessible to most operational forensic laboratories.
- 4# A number of transfer and persistence studies have been undertaken to ascertain the evidential value of ignitable liquid residues on substrates such as clothing, shoes, vehicle carpet, and the hands of arson suspects.
- 4# The occurrence of petroleum-derived liquids in otherwise uncontaminated substrates has been documented, emphasising the need to analyse comparison samples whenever possible to determine if detectable volatiles may be from the substrate itself rather than attributed to the presence of an accelerant.
- 4# A number of authors have investigated whether the use of particular fire suppression agents can interfere with the subsequent detection of hydrocarbon fuels in fire debris samples. As new fire suppression agents become available, their possible interference with accelerant detection techniques must be taken into consideration.
- 4# The advent of compact, high-performance 'electronic nose' sensors, as well as portable GC and GC/MS equipment, brings with it the possibility of taking the forensic laboratory to the scene. A move towards field-based testing of fire debris is likely as such instrumentation becomes more accessible and more widespread.

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