



Investigation of thermal penetration from the fire scene into the deceased fire victim

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ABSTRACT

Investigating fatal fires is a complex multi-disciplinary undertaking, with victims considered to be a fundamental part of the evidence. This study investigated thermal penetration into human remains with the aim of extending the results to the assessment of the fatal fire victim. Data was collected during the burning of 15 unembalmed bodies in years 2017–2019 with the San Luis Obispo Strike Team (SLOFIST) on their annual Forensic Fire Death Investigation Course (FFDIC). Cadavers were placed within a scene of individually built compartment rooms to simulate accidental and intentional fires. Thermocouples were placed within the compartments at ceiling/mid/floor levels and within the thoracic cavity of the deceased which facilitated analysis of thermal transition through phases of fire development from ignition to suppression. Radiant heat flux data enabled investigation of the relationship of the thermal environment and internal body temperature rise in kW/m². A statistically significant relationship between ceiling radiant flux and internal body temperature was identified in the thermal penetration of the body at $p \leq 0.041$, and a highly statistically significant correlation of $p \leq 0.001$ between internal body temperature rise and the fire development phenomenon of flashover. The effect size for this relationship (88%) indicates that a large proportion of internal body temperature rise in fire victims is accounted for by exposure to the fire phenomenon of flashover.

1. Introduction

Investigating fatal fires is a complex multi-disciplinary undertaking often involving the challenging recovery of human remains. The body of the deceased may have been left within the scene until it has been forensically processed, and initial fire investigation performed. In the United Kingdom every fire fatality is treated as a victim of a crime until proven otherwise with the considered fundamental evidence [1]. An understanding of the effect of extreme heat and flame on the human body is therefore not just necessary, but paramount in order to assess and understand the thermal interaction between the scene and the deceased [2–5].

The research presented in this paper focused on investigating the complex heated fire environment and the resulting thermal penetration into human remains within a series of real fire scenes. It is anticipated that empirical data collected and analysed will enable an increased understanding of the relationship between the analysis of the scene and the deceased fire victim within.

Symes and colleagues have investigated both the recovery process of

human remains from fire scenes and thermal alteration to the human body [5]. Their recovery investigation involved the analysis of pigs as proxy for human cadavers in large scale burn scenes. Thermal destruction of the human body by fire was undertaken at a professional crematorium with data obtained by intermittently opening the crematoria retort door for undefined periods of time. This empirical monitoring identified a sequence of thermal alteration which is considered a benchmark standard in the understanding of modification and destruction of the human body by fire.

Whilst these observational qualitative studies offer an insight into the effect of fire on the human body they are limited in their diagnostic applicability to the fatal fire victim. Temperatures reached in commercial cremations range between 850°C and 1000°C [6,7] with a body exposed to flame for 1.5 to 3 h dependant on the individuals' biological demographics [7,8]. The stable and externally controlled thermal setting of a crematoria retort does not replicate the real fire environment with its fluctuating temperatures and transmission of thermal energy to a victim by radiation, convection, and conduction with variable exposure time frames [1,9,10].

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This disparity in data is slowly being addressed with experimentation undertaken with donated human cadavers burned within experimental fire scenes. Studies include the physical alteration of human remains by fire [11–13], investigation of cranial fracturing of burned cadavers [14] and a new refined classification of thermally damaged human remains [4]. These investigations are predominantly empirically based producing qualitative data, with limited quantitative discussion around thermal exposure and penetration of heat into the human body in the earlier phases of fire development through to flashover.

A fatal fire victim still present in, or recovered from, a scene is often burned and has undergone heat induced changes. Research has principally focused on understanding the end result of fire's interaction with the victim such as their final position within the scene, with minimal discussion regarding thermal penetration into the soft tissue that performs a key role in the physical alteration [11]. The investigation of thermal exposure to the human body in correlation with fire development is an area of limited study. Thermal tolerance of human tissue is primarily investigated in the medical setting focusing on burn treatment for survivors [15–19], in addition to the manufacture of protective material for professionals such as firefighters and military personnel [20–22].

Skin is a highly complex membrane that provides the body with protection from disease, trauma and extreme temperatures both hot and cold, with the ability to adapt through thermoregulation to prevent and/or limit cell damage [23–25]. The response of skin to elevated thermal exposure is vasodilation of the capillaries and blood vessels within the dermis, enabling heat dissipation. A sustained external temperature of 42°C has been identified to cause maximum dilation of skin blood vessels [26,27].

Investigations have identified and quantified cellular burn damage identified the key temperature of 44°C for skin cellular necrosis [28–30]. A base line range of temperatures for the onset of pain has been identified between 43°C and 44.8°C [25,31,32], with temperatures above 70°C requiring less than 1 s to produce *trans*-epidermal destruction [33]. Exposure to continued higher temperatures can lead to vaporisation of body fluids and the rupturing of blood vessels [34], which can disrupt the metabolic processes and can lead to tissue death [35].

Fatal fire victims are exposed to temperatures higher than the skin cell necrosis temperature of 44°C within scenes of highly fluctuating multidirectional temperatures. These are caused by the turbulent thermal coefficients of the buoyancy induced convective flows within the thermal environment. In the early developmental stages of the fire temperatures produced are <c.150–200°C [1,36,37]. Thermal energy transfers within the environment by convection to cooler surfaces, with the rate of thermal transfer to an object proportional to temperature differential between the convecting medium and the surface. Absorbance levels reduce as the temperature of the object rises, with heat transfer transitioning from convection to radiation at approximately 400°C [38].

The continuing rise in temperature and thermal transfer to objects within the fire scene results in toxic gases releasing from surfaces such as furniture and flooring, with synthetic materials producing noxious and potentially lethal gases into the environment [36,39,40]. Today, asphyxiant toxic gases such as Carbon Monoxide (CO), Hydrogen Cyanide (HCN) and Hydrogen Chloride (HCL) are the leading cause of death in fires, with between 60% and 80% of fire fatalities are attributed to these gases rather than burning [41–43]. In well ventilated compartment fires, a high enough dose can lead to death in as little as 4 min from ignition [41,44–47].

When death occurs the human heart stops pumping blood throughout skin tissue, and the thermal diffusion of heat through blood vessel dilation ceases. This makes heat burn predictions obsolete as temperatures that increase within skin with good blood circulation differ to damage to skin with no blood circulation [20,21]. As heat continues to penetrate soft tissue after death, the thermal sensitivity of tissue remains in direct relation to the rise in temperature [31,48], with

many fire-related changes occurring post-mortem in origin [49]. Investigation into the effect of the fire environment on the soft tissue of the deceased is limited, with the deficit of observational data leading to misinterpretation of the fatal fire scene [13]. Research focusing on taphonomy, trauma, and classification of thermally damaged remains recognises the correlation of human body modification with temperature and fire but does not investigate the early relationship between the thermal environment and the human body [4,11].

DeHaan [12] investigated the role of the fire victim as a potential fuel source within the fire scene rather than a passive target of heat and flame. The experimental scenes employed in his study consisted of two three-sided box cubicles with minimal fuel loading such as a single mattress. The absence of the fourth wall facilitated constant air entrainment into the scene and impeded the accumulation of heat and smoke within the ceiling. This resulted in reduced thermal transmission via convection and radiation to the body with DeHaan identifying an internal temperature rise within the torso of the human subjects following external burning between 60 and 120 min. In contrast to the previous two tests, the third test was undertaken in a larger fully furnished compartment, with a recorded burn time of 15 min; 11 min of which the room was fully involved engulfed in flame resulting in the human remains becoming significantly charred. DeHaan proposed a heat flux of 5 kW/m² (or 54°C) was enough to facilitate the separation of the epidermis from the dermal layer of the skin, with the shrinking and splitting of dermal layers resulting in the exposure of subcutaneous fat. DeHaan also recorded radiant heat flux of <8 kW/m² was enough to sustain combustion of the human body with rendered subcutaneous fat as fuel, enabling localised burning for extended periods of time.

The aim of this study is to investigate thermal penetration beyond the skin boundary in human cadavers within a real fire environment. This was undertaken by documenting thermal development of the fire scene from ignition through to suppression by means of thermocouples both within the scene and within the body. This research provides further understanding the effect of fire dynamics on influencing heat penetration beyond the human skin boundary.

2. Material and methods

2.1. Experimental set up

Experimentation was undertaken between years 2017 and 2019 using 15 human cadavers donated through the Genesis donation programme of the Medical Education and Research Institute (MERI). Cadavers were placed within real fire scene scenarios prior to ignition, with recovery facilitated by forensic and law practitioners attending the annual Forensic Fire Death Investigation Course (FFDIC). The annual course is facilitated by the San Luis Obispo Fire Investigation Strike Team (SLOFIST) with medical ethical provision through the San Luis Obispo Sheriff-Coroner Office. Experimental ethics was also approved by Cranfield University Research Ethics System (CURES/3037/2017).

Following the classroom teaching element, attendees of the course are tasked with investigating the fatal fire scene and recovering the human remains. Further demonstration burns are undertaken to enable students to observe burns first hand, reinforcing the classroom training. Secondary to teaching, the FFDIC provides a unique environment to conduct research on fire fatalities in a real fire environment [4,11,13,14,50–53].

The donated bodies remained unembalmed to ensure a natural reaction to heat and flame. Cadavers were stored frozen until requisitioned within one year of death for experimentation. Age, sex, height, weight, Body Mass Index (BMI), were recorded for all human remains (Table 1 below).

Statistical analysis was performed using IBM SPSS 28 package to investigate the relationship between internal body temperature rise, biological demographics and fire scene temperature.

Correlation between variables was investigated using Pearson's 'r'

Table 1
Physical demographics of cadavers.

Scene code	Biological sex	Age at death	Weight Lb	Height Inches	BMI
2017/3	Female	83	180	76	22
2017/6	Male	84	138	64	24
2017/7	Male	72	83	69	12
2017/8	Male	76	144	71	21
2017/9	Female	76	134	66	22
2018/3	Female	67	125	61	24
2018/6	Female	62	144	64	25
2018/7	Male	60	96	64	16
2018/8	Female	54	111	61	21
2018/9	Female	82	125	62	23
2019/3	Male	60	143	67	23
2019/6	Female	64	193	67	31
2019/7	Male	64	178	67	29
2019/8	Male	88	106	66	18
2019/9	Female	87	90	63	16

correlation to interpret the small sample size data, with regression coefficients analysed to investigate the effect size and practical significance of results [41,44–46].

Cadavers were transported in a customised refrigerated lorry at 6.7°C (40°F), slowly rising to 12.8°C (55°F) to facilitate thawing en route to San Luis Obispo. Miras et al. investigated the effect of freezing on the human body, identifying that frozen human tissue cells do not return their former volume following thawing [47]. On the day of burning the human remains were placed within the independent fire scenes early in the morning, enabling them to acclimatise to the external temperature prior to ignition. This facilitated the closest reconstruction to an unconscious or recently deceased victim of a real fatal fire, and scenes of homicide prior to fire ignition. Based on casework undertaken by the SLOFIST staff, the individual experimental set ups were pre-determined prior to undertaking this research. FFDIC burn scenarios were diverse employing different sized isolated compartment rooms (see Fig. 1) and vehicles [51,52]. The primary author (MJH) assisted in body placement and positioning within each scene. Following experimentation, all human remains were fully recovered and transported back to MERI for final cremation.

This experimental investigation used only compartment scene data (15 Scenes) in order to establish the radiant heat flux striking the body through thermocouple data. Each compartment was constructed from timber and chipboard containing both a functioning window and door. The volume of standard room compartments was 24.07 m³ with std ± 0.37, with smaller bathroom compartments 11.87 m³ with std ± 0.31. Type K thermocouples were positioned within the compartments at ceiling/middle/floor levels to enable recording of fire development and fluctuating temperatures produced by thermal buoyancy (see Fig. 2). Thermocouples were also inserted into the thoracic cavity of cadavers by



Fig. 1. Isolated compartment scenes.



Fig. 2. Internal thermocouple placement.

MERI personnel via an intubation tube in the airway, prior to placement within the scenes. Attempts were made to mitigate ambiguity around the depth and precise location of the thermocouple by measuring and standardising the length of thermocouple inserted.

Initially a thermocouple was inserted into the subcutaneous tissue within the upper arm. Unfortunately, compromising the skin in this manner caused the skin to split through thermally induced contraction, resulting in the thermocouples falling from their positions. It was therefore considered that inserting the thermocouple directly into the thoracic cavity through the cadaver's mouth gave the greater chance to collect body temperature data without compromising the soft tissue. Recording internal thermocouple data provided a measurement of heat penetration into the human body from convected and radiated heat transfer. Using Equation 1 below the radiant heat flux transfer between the ceiling and the body (C-B Flux) was investigated, as was the radiant heat flux between the ceiling and the floor (C-F Flux). The floor temperature was analysed as a proxy for temperature at the skin surface due to the positioning of the human cadaver within the scene.

2.2. Data analysis

The Stefan-Boltzman equation (Eq. (1)) was used to calculate the heat flux within the scene, where the temperature of the target layer (the floor in this experimentation) was considered an emitter feeding back to the hot layer. The Celsius temperatures were converted to Kelvin with radiation flux proportional to the fourth power of the Kelvin temperatures.

Equation (1) Stefan-Boltzman Equation Flux Equation

$$F = Em\sigma\left[(T_{ceiling}^{+273})^4 - (T_{floor}^{+273})^4\right] \quad (1)$$

where F is the true flux, Em is emissivity which is determined by the nature of the source [54]. In this experimentation Em of the solids and droplets in the flame layer was considered to be 0.9 in the absence of

evidence to the contrary, where 1 is a true black-body emitter. k is the Stefan-Boltzmann constant of $5.67 \times 10^{-8} \text{ (W m}^{-2} \text{ K}^{-4}\text{)}$. Results are given in W/m^2 with the predetermined condition that the ceiling layer is 100% solids/droplets within the smoke. The lower layer can also act as a source of radiation to the subject in which case F depends on the temperature difference between the lower layer and the subject. Emission from the subject can occur, whereby if the subject has a surface temperature of 30°C and the flame is 500°C the effect of radiation from the subject is 2.5% that of the flame. If the flame is $>700^\circ\text{C}$ the effect is less than 1%.

An additional factor to be considered is convection. In fires convected heat is the result of hot gas transferring to cooler surfaces as they impinge on them, which in this case is the human subject. The process is complex and dependent on temperature difference between the hot gases and the surface which is controlled by flow effects [42,54]. Natural convection which is a more stable linear flow is less efficient than forced convection, where turbulence can occur. In a fire with heat induced

lifting from the burning surfaces and a counter downwards flow occurring from the ceiling layer, this study considered forced convection to predominate especially once “flashover” has begun. The basic equation for analysing this process is known as Newton’s law of cooling:

Equation (2) Newton’s Law of Cooling

$$Q = A.h.(T_{hot} - T_{cold}) \quad (2)$$

where Q is the convection heat flux in Wm^{-2} and T is in Celsius or Kelvin. It has been suggested that values of h between 2.5 and 25 be given for natural cooling and 10 to $500 \text{ Wm}^{-2} \text{ K}^{-1}$ for forced convection in air [38,55]. For this study, since it was believed that a suitable volume to show how forced convection might rank alongside radiation in the post flashover environment, the mid range of $h = 100 \text{ Wm}^{-2} \text{ K}^{-1}$ was chosen for the investigation of the increase of internal subject temperature.

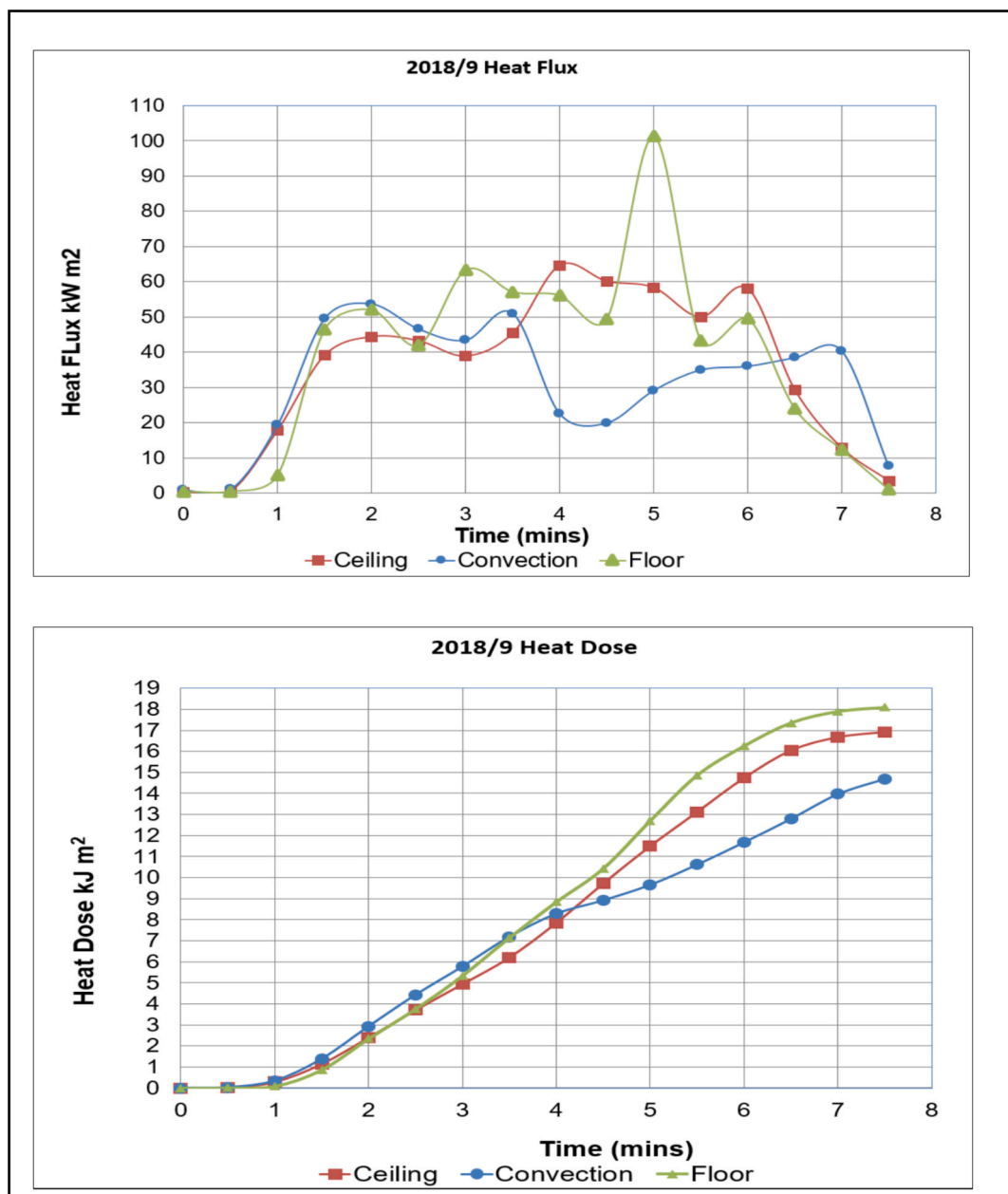


Fig. 3. Thermal heat flux and dose for scene 2018/9.

3. Results

Thermocouple results from the floor and ceiling showed the fire transferring energy through both convection and radiation. Heat flux and heat dose were calculated from thermocouple temperatures identifying a complex transition from convection to radiation as the primary form of thermal distribution during fire development. Convection was only considered with respect to the floor temperature. Heat dose was calculated as the integrated sum of heat flux with time. Numerical examples of heat flux are given for the maximum observed unless stated otherwise (Fig. 3).

3.1. Body demographics

The precise time of partial degree centigrade rise within the human subject was identified from internal thermocouple data. This is recorded as the internal Body Temperature Rise (BTR). Floor and Ceiling temperatures at BTR were extrapolated from each scene to investigate the effect of thermal transition from convection to radiation as the dominant form of heat transfer within the structure on the human subject (Table 2). The biological sex of each cadaver was identified as male (M) and female (F).

Body thermocouple temperatures did not increase beyond 20°C in 2018/6 and 2019/3 even though scene temperatures exceeded 1000°C and 650°C respectively. This lower temperature in the two scenes was considered to be the result of thermocouple failure and have not been included in the correlation analysis.

The presence of a relationship between cadaver specific demographics as shown in Table 2 and BTR was investigated using IBM SPSS 28 package, with no statistical significance identified (Table 3). Scene variable relationships were also investigated between BTR and Flashover, Ceiling-Floor Flux (C-F Flux) and Ceiling-Body Flux (C-B

Table 2
Rise in body temperature.

Scene	Time BTR (Mins)	CeilingTemp °C at BTR	FloorTemp °C at BTR	Body position	Sex	BMI
2017/3	5.3	715.59	372.3	Supine(on back)	F	22
2017/6	3.54	599.94	463.61	Prone (face down)	M	24
2017/7	3.04	554.21	748.75	Supine	M	12
2017/8	1.28	757.52	450.85	Sitting	M	21
2017/9	5.0	523.33	283.33	Supine	F	22
2018/3	25.3	695.75	96.15	Supine under furniture	F	24
2018/6	Failure	—	—	Supine	F	25
2018/7	7.47	697.75	487.11	Sitting	M	16
2018/8	10.27	784.35	440.66	Supine	F	21
2018/9	0.53	129.5	46.3	Supine	F	23
2019/3	Failure	—	—	Prone	M	23
2019/6	5.41	724.98	124.20	Prone	F	31
2019/7	1.19	598.16	560.84	Sitting	M	29
2019/8	2.4	658.67	144.75	Sitting	M	18
2019/9	4	386.84	67.91	Supine	F	16

Table 3

Correlation analysis between body temperature rise (BTR) and variables.

Time of BTR	Variable	Pearson's 'r' correlation	Two-tailed significance	Statistical significance
BTR	BMI	−0.008	0.977	—
BTR	Sex	0.368	0.177	—
BTR	Age	−0.275	0.321	—
BTR	Body Position	−0.245	0.375	—
BTR	Flashover	0.937	0<.001**	**significant at 0.001 level
BTR	C-F Flux	0.623	0.023*	* significant at 0.05 level
BTR	C-B Flux	0.571	0.041*	* significant at 0.05 level

Flux) $n = 13$. Pearson's 'r' correlation analysis was undertaken in addition to two-tailed significance test.

Results identified both the C-B Flux and the C-F Flux were significant in their relationship with BTR with significance $p \leq 0.05$ (Table 3). Correlation between BTR and Flashover revealed a statistical significance at the higher level of $p \leq 0.001$.

3.2. Thermal environment

Scene 2018/3 was subject to slow fire development with the temperatures gradually increasing through to flashover at 25 min 21 s. However, the time elapsed between flashover and BTR was 9 seconds making this comparable with other scene data. This result when plotted was identified as an outlier due to the extended fire development time (see data point 6 in Fig. 4) and was subsequently winsorised. Winsorising is a process that reduces an extreme outlier data point to the next observation data point down [56]; in this case reducing the extended fire burn time to the next plotted time of 10 mins 28 s (a reduction of 15 mins 7 s). This did not affect the times between BTR and flashover but enabled a more accurate analysis to be conducted without time frames skewed by delayed fire progression.

Linear regression analysis was performed to investigate the relation of BTR with flashover $n = 13$ (Fig. 5). The regression equation for predicting BTR from flashover was $y = 0.94 + 0.91 \cdot x$, with the r^2 for this equation at 0.879, producing an effect size of 88%. This result indicates that the variance in BTR can be predicted by flashover time in 87.9% of cases.

Maximum temperature in compartments at point of flashover ranged from 535°C to 830°C. In accordance with these temperatures, radiant heat flux temperatures at flashover were recorded ranging from -26.2 Kw/m^2 to 72 kW/m^2 (Fig. 6). Negative flux was recorded where the floor temperature exceeded the ceiling temperature.

The relationship between BTR and both C-B Flux and C-F Flux (Fig. 7) were both found to be statistically significant at the <0.005 level.

Linear regression was performed to investigate the relationship for variance in BTR, predicted from C-F flux provided an r^2 of 0.328 (32.8%) with a moderate effect size of 33%. The relationship variance in BTR and C-B flux produced the r^2 of 0.388 (38.8%), with the moderate effect size of 39%.

Internal body temperatures continued to be documented post BTR, evidencing an internal temperature increase with maintained thermal exposure. The maximum internal temperature was identified for each cadaver, in addition to the length of time the remains were exposed to the post flashover environment (Table 4).

Statistical analysis of the relationship between post flashover exposure time and maximum internal body temperature identified a strong linear association producing the regression equation $y = 5.05E2 + 90.58 \cdot x$, with r^2 of 0.354 (Fig. 8).

A Pearson's 'r' correlation was performed for this relationship producing a two tailed statistical significance of 0.041, which is significant

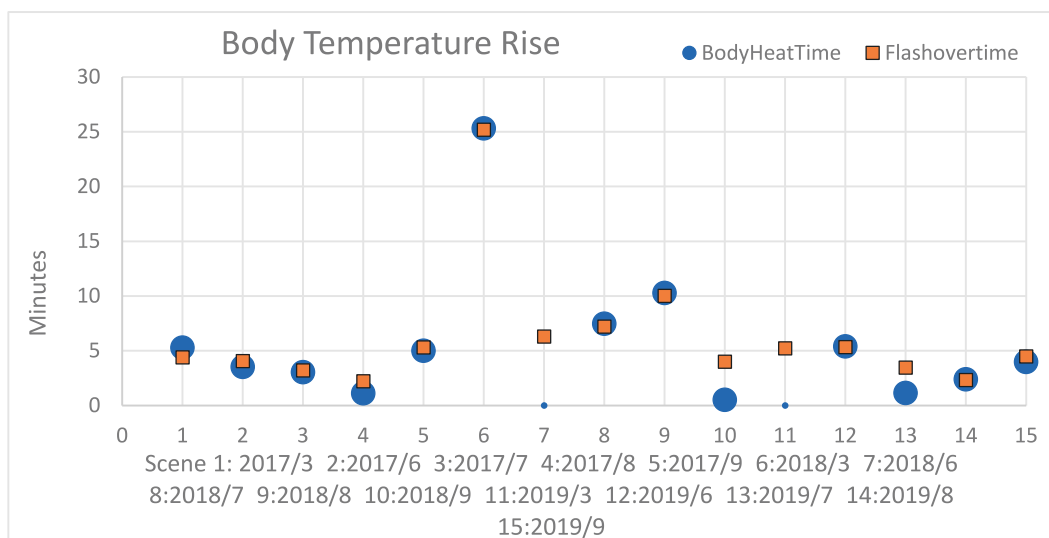


Fig. 4. Body Temperature Rise time and corresponding Flashover time for each scene. NB: no body data available for 7:2018/6 or 11: 2019/3 due to thermocouple failure.

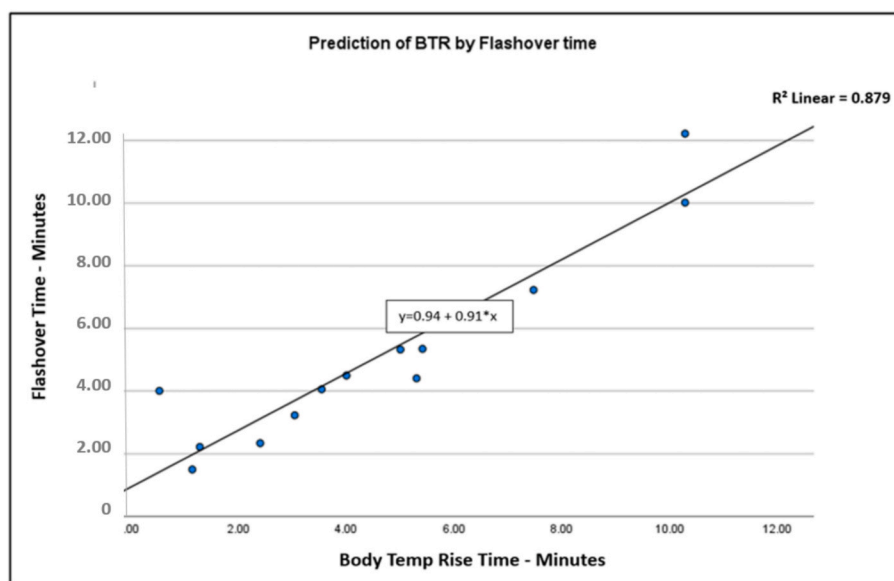


Fig. 5. Linear regression of relationship predicting BTR time with Flashover time.

at the $p < 0.05$ level. The effect size ($r^2 = 0.354$) indicates that maximum recorded internal body temperature is 35% correlated with length of exposure.

4. Discussion

The investigation of the effect of heat transfer in fires to human victims has been principally undertaken through laboratory experimentation and crematoria observations, with a lack of empirical data on the effect of the thermal environment on human remains in a real fire scene [13]. In fatal fires it is necessary to understand fire as a taphonomic agent [57], and the literature has identified that investigation and experimentation in this field would enhance forensic investigation of fatal fires [5,58,59].

The use of human cadavers in this experimentation has facilitated the collection of internal body temperature data throughout fire development. It may be argued that a 'real' fatal fire victim would have been alive at the start of the fire and this would question the applicability of

this study. However, not all fire victims are alive at the point of fire ignition, with fire used as a mechanism to disguise crime such as homicide [60–63]. Such criminal or intentional cases contribute a proportion of the fatal fire investigations. Furthermore, inhalation of toxic gases from the fire environment can cause incapacitation and death within minutes from ignition.

As fire develops thermal transfer to objects within the fire scene results in toxic gases releasing from surfaces such as furniture and flooring, with synthetic materials producing noxious and potentially lethal gases into the environment [36,40]. When organic materials burn the incomplete combustion of hydrocarbons, this results in the release of Carbon Monoxide (CO) [43]. When inhaled, CO binds with the haemoglobin molecule in the bloodstream creating Carboxyhaemoglobin (CHOb). This binding has 200–250 more affinity than the binding of the oxygen molecule, effectively reducing the level of oxygen within the blood resulting in hypoxia [40,64,65]. Since CHOb is stable within the bloodstream postmortem sampling can identify the level present which would be lethal above 50% and enough to incapacitate victims as low as

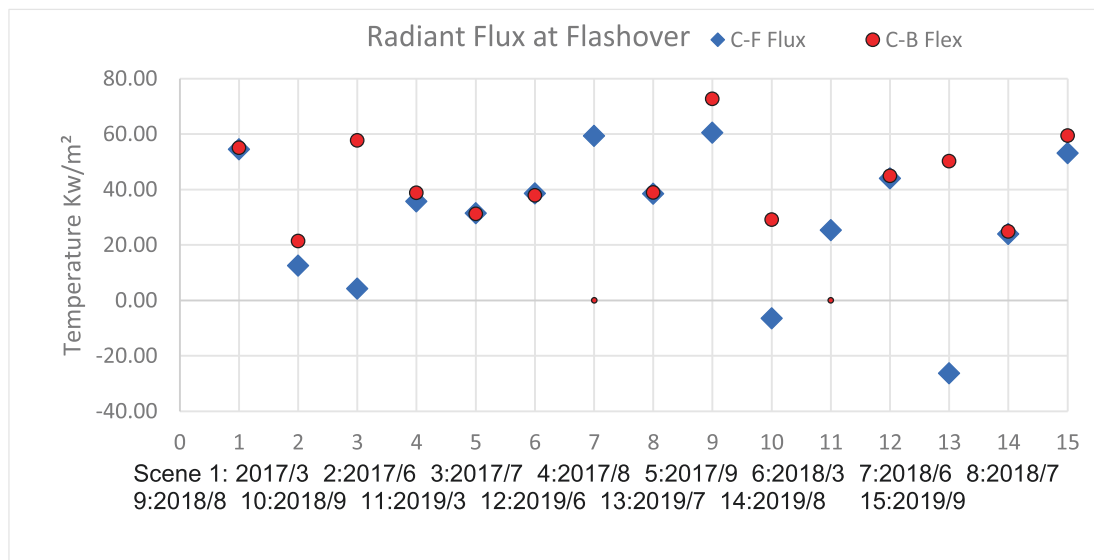


Fig. 6. Heat flux at point of fire flashover.

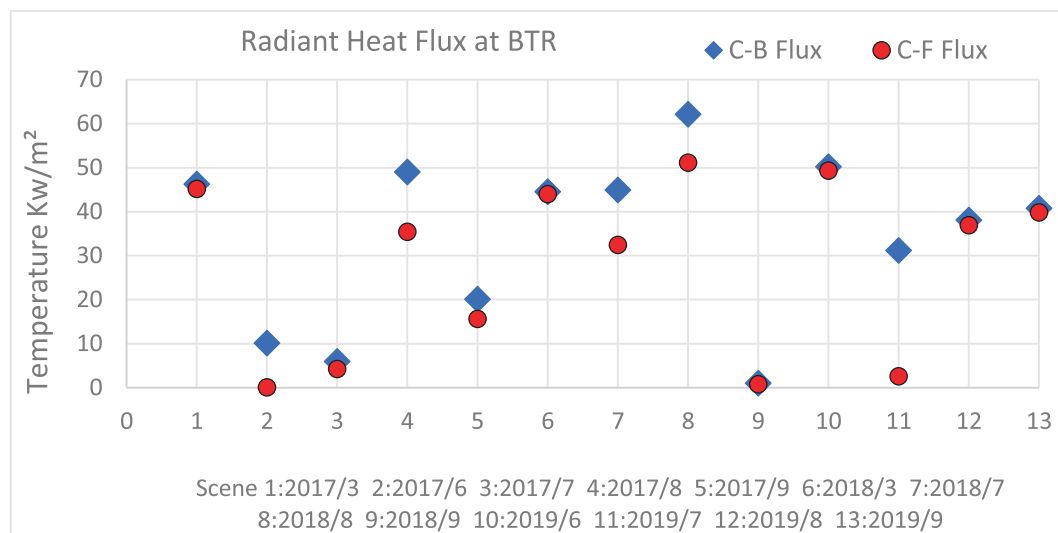


Fig. 7. Heat flux at time of body temperature rise.

30% [40,64,66]. Prahlow states that the physical appearance of individuals who died in the fire, and those who were deceased prior to ignition, are observationally undistinguishable at autopsy [67]. In fact, autopsy reports indicate that approximately 80% of fatal fire deaths are attributed to toxic inhalation rather than flames [36,40,68].

Further toxic gases such as Hydrogen Cyanide (HCN) and Hydrogen Chloride (HCL) can be identified within the victim's bloodstream. HCN is the by-product of heating combustible materials such as paper, nylon, and products made from polymers and polyurethanes such as carpets and furniture and is considered to be an important contributor as a cause of death in fire victims due to its incapacitating effect. Inhalation of HCN causes neurological, respiratory and cardiovascular depression by paralysing the respiratory centre in the brain leading to loss of consciousness and potentially respiratory and cardiac arrest [40,68–71].

The highly toxic and irritant gas Hydrogen Chloride (HCL) is released as a by-product of heated cellulose materials such as Polyvinyl Chlorides (PVC), found in a high percentage of modern furniture and commonly present within the highly noxious fire scene environment [36,72,73]. HCL is an irritant to the mucous membrane in the nose throat and respiratory tract, which when inhaled in high enough doses can cause

pulmonary edema [74,75]. It has been identified that the combustion of a polyurethane plastic mattress cushion produces HCN of 200 ppm, enough to incapacitate an individual within 2 min. Inhalation of CO at a concentration of 12,000–16,000 ppm, and HCN 250–400 ppm is enough to cause death at 5 min [36]. This chemical and heat release rate is autonomous to materials within the fire scene, with the potential of producing asphyxiant critical fatal levels of HCN before the higher incapacitating saturation of >50% CHOb is reached [65,76].

Postmortem analysis of burned human remains is challenging, with thermal degradation and consumption of soft tissue varied [63,77]. Morling and Henneburg state that 'Autopsy and injury data from a fire victim is inherently linked not only to the development and behaviour of the fire, but also to how the victim interacted with it' [78]. The raising of internal body temperature following death accelerates the decomposition process. Zhou and Byard state that autolysis and putrefaction may accelerate if the internal body temperature was elevated at the time of, and following death [79].

It is therefore imperative that thermally induced alteration is understood in order to undertake comprehensive examination and analysis of the body [35,80–82]. The results of this study provide insight into

Table 4
Maximum body temperature and fire environment.

Scene	BTR time (Mins)	Max body temp °C	Time max temp (Mins)	Post flashover exposure time (Mins)	Max C-B flux post flashover
2017/3	5.3	633.29	9.05	4.24	61 kW/m ²
2017/6	3.54	760.43	7.25	3.31	155 kW/m ²
2017/7	3.04	1044.21	6.21	3.02	192 kW/m ²
2017/8	1.28	1066.7	6.31	4.09	225 kW/m ²
2017/9	5	67.22	7.02	1.29	57 kW/m ²
2018/3	25.3	838.18	27.27	2.06	42 kW/m ²
2018/7	7.47	1052.79	15.18	7.56	122 kW/m ²
2018/8	10.27	1129.04	14.30	4.28	66 kW/m ²
2018/9	0.53	622.53	5.03	0.58	50 kW/m ²
2019/6	5.41	751.56	6.47	1.12	63 kW/m ²
2019/7	1.19	103.44	2.27	—	43 kW/m ²
2019/8	2.40	647.66	2.34	1.24	98 kW/m ²
2019/9	4.00	920.85	4.50	1.08	52 kW/m ²

thermal penetration of the deceased from the fire environment when undertaking the analysis of a fatal fire victim. Fundamentally, accurate analysis requires examination of all data concerning both the victim and the fire environment is reliant on a multi-disciplinary approach to include fire investigators [63,83]. It is suggested by Pope that awareness of post mortem thermal exposure and alteration can improve forensic analysis [53]. Forensic medical examination of fatal fire victims encompasses toxicology, postmortem computed tomography (PMCT) and autopsy. These techniques are not mutually exclusive, with PMCT providing good diagnostic images of foreign bodies, bone fractures and severe organ damage [84,85]. This non-invasive method does have limitations, with thermal soft tissue organ damage difficult to identify

[86,87]. Traditional autopsy remains the predominant method of observation for vitality indicators such as soot in the oesophagus and trachea, and bronchial thermal damage [85].

Symes and colleagues [6] proposed that the overall degree of heat alteration to the human body can be more accurately predicted from tissue thickness, rather than the extent of fire exposure. Additionally, they suggested that weight, compositional fat and body muscle need to be considered when assessing burn patterns on human remains. This current study analysed biological variables (biological sex, age at death, weight and BMI) with heat penetration into the human body and found no statistical difference (see Table 3). The dataset used in this study produced a BMI range of 16–31, mean 24.18 with Std $\pm$ 4.75 in conjunction with an age at death range 54–88 years, a mean of 72 years and Std $\pm$ 10.77.

Moreover, the age range of the human subjects in this experimentation is relevant to fatal fire investigations. Analysis of UK Government Fatal Fire statistics accessed through NOMIS (Office for National Statistics) for the years 2013–2020 [88] record that persons over 50 years of age account for 73.6% $\pm$ 4.9% of fatal fire deaths. Studies have also identified that adults over 60 years are at highest risk of dying in a fatal fire [89–91], with the risk doubled in those over 65 years and quadrupled in over 75 year olds [92]. It is considered that this age demographic presents a higher risk due to frailty and lower mobility as a predominant factor [93], in addition to hearing impairment affecting the recognition of smoke alarms [94].

DeHaan's work proposed time frames for the internal body temperature rise between 60–120 min, with the suggestion that bodies with large masses of flesh require considerable time for core temperature to rise [12], the results of this work disputes this statement. The experimentation undertaken by DeHaan used a 'moderately thin' elderly male, a male of 'average build', and 'a torso of an adult male' with no further biological data presented. The thermocouple temperatures recorded for DeHaan's study as well as the heat flux data were reported with no reference to the absence of a wall for observation enhancing the development of the fire by the continuous oxygen entrainment. The absence of the wall may have additionally limited penetration of heat into the body as the heat was not contained in a thermally focused environment. The findings in our study propose caution in applying the conclusion that 'finding a body in a recent fire with a low internal temperature [is] an indicator that the person was dead some time before

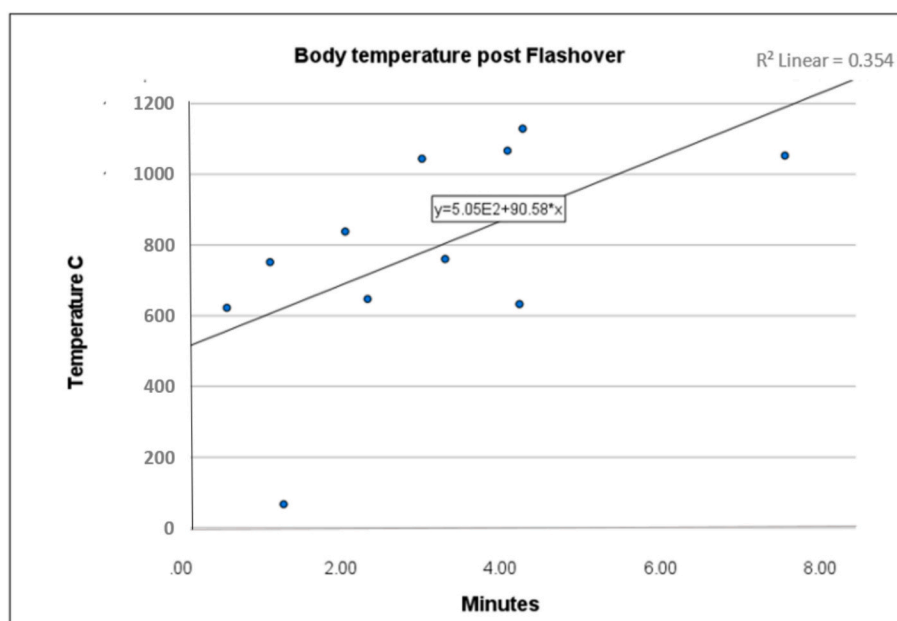


Fig. 8. Linear regression of relationship between post flashover exposure and maximum internal temperature rise.

the fire' [12].

Results produced through the burning of 15 scenes in this current work identified that internal Body Temperature Rise (BTR) can occur in as little as under a minute (scene 2018/9) given the right conditions, with temperatures rising above the temperature of flashover instigation of 600°C in 11 of the scenes. In two scenes the BTR of cadavers recorded significantly lower maximum temperatures of 67°C (2017/9) and 103°C (2019/7). Whilst these temperatures are extremely low in comparison to other body temperature data recorded they are high enough to have induced *trans*-epidermal necrosis at $\sim 44^{\circ}\text{C}$ [28–30,95]. Furthermore, it is reported that if the core temperature of the fire victim exceeds 43°C , death is likely to occur [36].

In reviewing the data, scene temperatures were in excess of 500°C at the point of BTR with both development heat flux and heat dose comparable to the remaining scenes. Post flashover heat flux was recorded at 57 kW/m^2 and 43 kW/m^2 respectively for the scenes, and individual body demographics documented BMI as healthy for 2017/9 at 22, and overweight at 29 for 2019/7. This higher BMI in addition to the body positioned sitting within a bath of water are potential factors contributing to the reduced internal body temperature. In scene 2017/9 the individual was exposed to extreme temperatures in excess of 700°C , with floor temperature near the body reaching 300°C with BTR at 5 min reaching 67°C and then plateauing out until suppression in 1 min 40 s later.

This study has identified the association of BTR with radiant heat as the predominant form of thermal transfer within the fire scene. Convective temperatures produced as the fire developed beyond ignition were recorded in excess of those required to initiate cellular necrosis at the sub dermal juncture, but did not penetrate deep enough to instigate internal temperature rise of the cadaver. This highlights an area for further research.

The radiant heat flux between the ceiling level and the floor level (C-F Flux), and the ceiling level and the body (C-B Flux) enabled investigation of the relationship of the thermal environment and body temperature in kW/m^2 . Previous experimentation recorded heat flux from air temperatures in the range 60°C – 300°C producing 1.26 to 8.37 kW/m^2 , with temperatures of 175°C at floor level able to produce a short term heat flux of 30 kW/m^2 [96]. Nichols [3] suggests that as little as 4 kW/m^2 is enough to burn the skin of an individual, although no exposure time is provided. Fairgrieve [97] does however provide a time frame of 30 s exposure at 4 kW/m^2 to produce second degree blistering and pain. Fires routinely reach temperatures of 900°C – 1000°C throughout the compartment producing a radiant heat intensity in the order of 150 kW/m^2 or more [12,13,36], with the maximum post flashover heat flux proposed at 170 kW/m^2 [97]. Thermocouple results from this experimentation support these temperatures, with $n = 15$, temperature range >900 evidenced in 13 burns, 86.67% of our data set. Results of radiant thermal flux analysis with BTR identified the statistically significant relationship at $p \leq 0.005$ in the thermal penetration of the body, with $p = 0.023$ for ceiling and floor flux (C-F), and $p = 0.041$ for the ceiling and body flux (C-B). It is reported in the literature that internal body temperatures do not reach 100°C until the room temperature rises to around 500 – 600°C [5] which are consistent with the phenomenon of flashover.

In order for a room to reach flashover gases held within the turbulent thermal environment at ceiling level reach their ignition point resulting in the ceiling gas/smoke layer igniting. This further increases radiant heat transfer to the objects within the room below the ceiling layer, promoting 'flashover' ignition of all exposed surfaces within the scene [36,98–100]. Flashover is primarily a compartment fire phenomenon which occurs at approximately 600°C , heat flux $\sim 20\text{ kW/m}^2$ [38,100,101]. Temperature in the post flashover environment can continue to rise reaching over 1000°C , with maximum post flashover radiant flux measuring 170 kW/m^2 [36,73]. These high temperatures can last for several minutes making the post flashover environment untenable for survival [102,103]. This study's results have identified a highly significant correlation at $p \leq 0.001$, with Pearson's regression

coefficient of $r^2 = 87.9\%$ between BTR time and flashover producing a prediction equation of $y = 0.94 + 0.91 \cdot x$. The effect size for this relationship (88%) indicates that a large proportion of internal body temperature rise in fire victims is accounted for by exposure to the fire phenomenon of flashover, and in the developmental stages of the fire, thermal penetration into the core of the human body is limited.

The cyclic nature of turbulent thermal flow in fire development leading to flashover can be reflected in fluctuating temperatures, especially at floor level due to air entrainment. It is recognised that flux data prior to flashover is the result of thermocouples recording fluctuating mixing temperatures of the pre flashover environment (see Fig. 9), which is reflected in the lower significance of C-F Flux sig 0.023, and C-B Flux sig 0.041 with BTR.

Once flashover has taken place the C-F Flux data can record as negative or close to 0. This is the direct result of the fluctuating turbulent dynamics of air circulation within the compartment, which at the point of flashover experienced higher temperatures at floor level than in the ceiling.

Offiah states that fire damage may not correlate directly to cause of death but is dependent on temperature around the body and duration of thermal exposure [49]. This correlation was investigated post flashover for both fluctuating scene temperatures and internal body temperatures through to fire suppression. Post flashover exposure timings were variable ranging from 0.58 s through to 7.56 min with maximum internal body temperatures recorded identifying a statistically significant relationship of 0.041 at the $p \leq 0.005$ level with exposure time. Pearson r^2 correlation produced a coefficient of $r^2 = 0.354$. Whilst the effect size at 35% is lower than that of the relationship between flashover and BTR, it is still considered to be a strong relationship, above the 0.25 medium range [46]. Where the effect of heat on human remains is considered to be time and temperature related, this study provides quantitative results of the correlative effect and effect size of the post flashover environment on continued internal temperature rise within the fire victims.

Fire suppression was undertaken whilst the scenes were fully involved in order to preserve them for educational purposes. Therefore, thermocouple data to investigate the relationship between the thermal environment and the human body in the decay stage of the fire was unable to be undertaken, again highlighting an additional aspect of fatal fire victim study that would benefit from investigation.

5. Conclusion

The work presented here provides a unique insight into the thermal penetration of deceased human cadavers in a real fire environment. Thermocouple data from within the scene and the human remains facilitated analysis of thermal transition through phases of fire development from ignition through to suppression. Results identified that an individual's biological demographics do not independently influence internal body temperature rise. Nevertheless, it should be noted that none of the cadavers were morbidly obese, and this may have an influence.

This body of work has identified that a deceased human body exposed to a flashover environment is statistically likely to have experienced an increase in internal body temperature rise. Analysis revealed a highly statistically significant relationship of $p \leq 0.001$ between the phenomenon of flashover and internal body temperature rise. Linear regression analysis indicated that internal temperature rise can be predicted in 87.9% scenes, with effect size analysis identifying a strong coefficient of determination; this highlights the significance of flashover phenomenon and internal body temperature. In the post flashover environment, exposure time and maximum internal body temperature was found to be significant at $p \leq 0.041$, with effect size still considered to be significant in the analysis of maximum internal temperatures reached in a post flashover environment.

It is proposed by the authors that the results of this study have forensic value, in particular on scene analysis by forensic practitioners

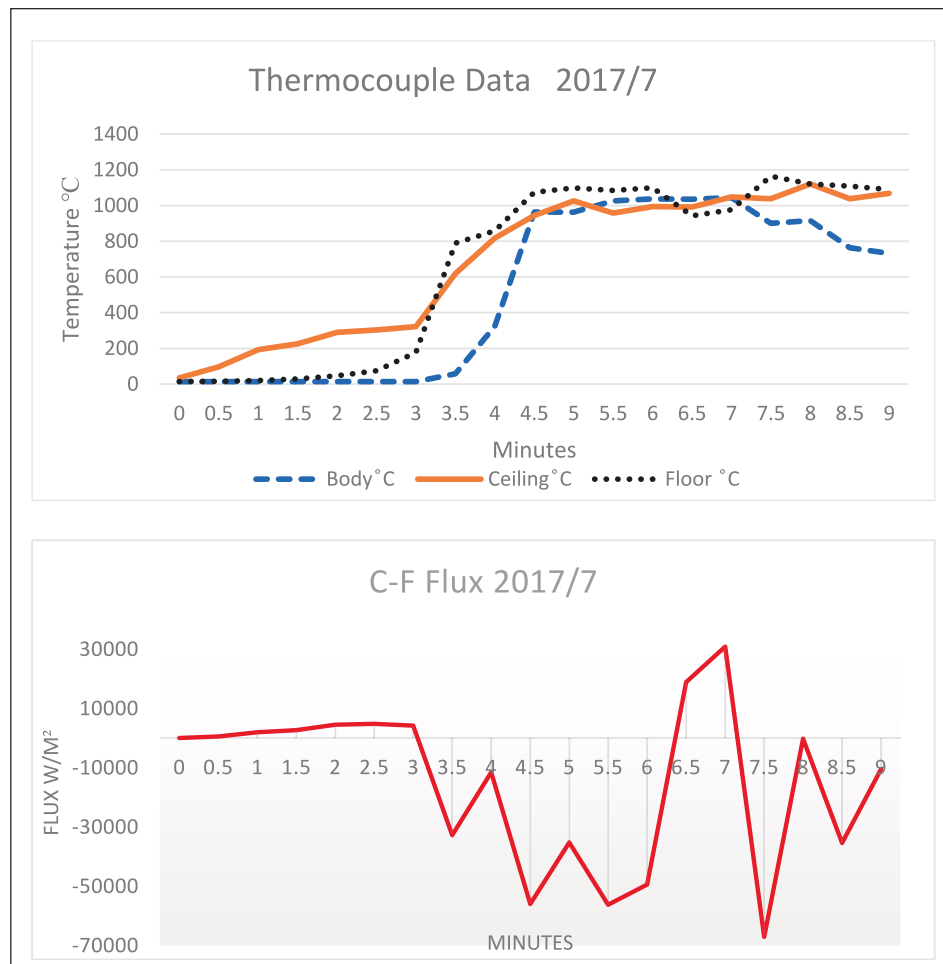


Fig. 9. Thermocouple temperatures and resulting heat flux for Scene 2017/7.

and the postmortem examination of fatal fire victims. Fatal fire investigations are a complex multi-disciplinary forensically processed scenes. Therefore, understanding the effect of a developing fire on the deceased within the scene is fundamental to an investigation. It is a requirement of the Fire Investigator to record the body in situ and document any thermal alteration to the deceased in direct correlation with the scene. The results of this research provide investigators with the insight that internal body temperature rise is statistically highly significant with the phenomenon of flashover, and if fire indicators identify that the scene has undergone this transition; Investigators are able to document the deceased with this correlation.

External and internal postmortem findings are considered dependent on both temperature and duration of heat to the body. The research presented here has quantified that thermal penetration into the human torso is contextual to the developing fire environment. Whilst we do not propose the findings are used as a diagnostic tool in pathological investigation, we believe that the quantitative results of the relationship between the deceased and the fire environment may aid in the evaluation of histology through understanding the influence of the external thermal environment. This highly statical correlation provides an indication for the pathologist of internal body temperature rise when potentially external thermal damage appears to be contained to the dermal layer of the skin. Where the deceased remains within the fire scene for a period of time before recovery, knowledge of the relationship between flashover and internal temperature rise may also assist in the assessment of accelerated decomposition should it be present.

6. Limitations

A major limitation of this study was the small dataset ($n = 15$) which become further limited due to thermocouple failure ($n = 13$). The inability to rerun additional experimentation and the provision of experimentation on an annual basis inhibited further data collection.

Whilst the results of this research suggest casework application in the assessment of the deceased fire victim, further data collection and analysis would be beneficial in investigating thermal penetration to the deceased human body.

It is acknowledged that frozen and thawed human tissue cells do not return to their initial volume, identifying an area that would benefit from investigation as research utilising human cadavers continues. We would advocate investigations using appropriate human analogues into the effect that freezing and thawing of body tissue has on thermal reaction in the fire environment.

Ethics statement

This experimentation utilised donated human cadavers donated through the Genesis donation programme of the Medical Education and Research Institute (MERI) USA. All data regarding individual donors has been anonymised.

Medical ethical approved through the San Luis Obispo Sheriff-Coroner Office, California, USA. Institutional experimental ethics was also approved by Cranfield University Research Ethics System (CURES/3037/2017).

CRediT authorship contribution statement

Mary-Jane Harding: Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nicholas Márquez-Grant:** Writing – review & editing, Supervision. **Mike Williams:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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