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A NEW CLASSIFICATION SYSTEM FOR ANALYZING BURNED HUMAN REMAINS

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REMAINS

By

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Abstract

Fatal fires produce a range of physical alterations to the body that can be studied and analyzed to interpret perimortem events. Currently, the forensic community lacks a consistent, objective, and detailed scale to describe burn injuries or patterns in a variety of settings and conditions. There is a need to create a scale based on quantitative experimental data (e.g. duration and temperature of fire) that provides insight into the nature of the fire and cause of injuries contributing to the condition of the remains.

Observations from four main fire environments were used in developing a new classification system for analyzing heat related damage. This new classification system covered both soft tissue and skeletal changes and will be beneficial to the medico-legal community in standardizing the description of burned remains. It will also prove important in reconstructing events involved in fatal fires and will aid investigators building a legal case. Prior to this study, there has been no attempt to standardize the description of burned remains and quantify the amount of thermal damage observed. Previous models were constructed from specific fire environments, and therefore not widely applicable to the forensic community. This research laid the groundwork for applying a more quantitative approach to analyzing and interpreting burned human remains. The information gained from this study can be used to better predict when these physical alterations may occur on the human body, and from what fire environments the remains likely were recovered. More importantly, it enhances our understanding of the underlying processes that affect thermal alterations.

Chairperson: Dr. Meradeth Snow

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Introduction

Fatal fires involve the loss of life of one or more individuals. Most fire fatalities are either accidental in nature, or the result of suicide or homicide related events (Viklund et al. 2013, Tumer et al. 2012, Fanton et al. 2006, Bonhert and Rothschild 2003, Parks et al. 1989). Therefore, fire becomes a key component to the manner in which individuals may have died. When fire is used in homicides, the body is set on fire with the intention to either destroy evidence or to damage the body to the extent that identification of the victim is unlikely (Tumer et al. 2012, DeHaan 2008, Symes et al. 2008, Fanton et al. 2006). Fires can alter human remains in various ways; however, complete destruction of a human body by burning is impossible and skeletal remains can almost always be recovered (DeHaan 2012, Correia 1997). Thus, some evidence of human remains will always exist. Fatal fires produce a range of physical alterations to the body from blistering of soft tissue to the calcination of bones (DeHaan 1999, 2012, Pope and Smith 2004, Symes et al. 2008, Thompson and Chudek 2007). Theses physical alterations leave patterns that can be studied and analyzed to interpret perimortem events.

A variety of forensic professionals interact with and analyze these remains postmortem, which can lead to variation in how remains are described. While the medical literature tends to classify injuries by smoke inhalation (Prahlow 2010, Kawateshi et al. 2009), and categorical extent of thermal injuries to skin, i.e. first, second, or third degree burns (Giretzlehner et al. 2013, Moore et al. 2019, Mullins et al. 2009, Parks et al. 1989), forensic anthropologists tend to focus on the condition of the skeleton. The variation in the way the forensic sciences records, describes, and analyzes the same set of human remains poses challenges among forensic professionals. This dissertation aims to establish a new standardized method that would encompass all physical alterations of burned remains and be more applicable to the broader forensic community. This study utilizes experimental observations from a variety of fire environments and a subset of fatal fire cases in the creation of a new classification system for analyzing fatal fire deaths. In addition to establishing a new classification model, this research will provide a second model for estimating exposure time to a fire. The variables of temperature and time will be added into a model that can be used to estimate how long an individual may have been exposed to fire conditions. The models produced from this study will provide forensic investigators with a new tool for analyzing fatal fire cases, and aid in building a legal case.

The following chapter (Chapter 1) provides an overview of experimental fire research, methods for analyzing fatal fire injuries, and an overview of models for estimating timing of death events. Chapter 1 provides a detailed discussion on the thermal alterations known to occur on a human body, and the variables that are known to influence heat-related damage. This chapter also highlights the models that have been used to classify thermal damage and their applicability to modern day fatal fire cases. This chapter also provides a brief discussion on time since death estimates, and how it is possible to use similar variables to estimate exposure time to a fire.

The ensuing chapters will outline the methods used in establishing both models and provide a detailed discussion on the results from this study. Chapter 2 discusses the methods used in developing a new classification system and for creating a post-fire interval. Chapter 3 describes how the new classification model was developed and how it is best applied to fatal fire deaths. Chapter 4 discusses the results from these analyses and demonstrates how it is possible to model heat related environments. Chapter 5 describes the post-fire interval, and how it can be best applied to fatal fire deaths. Chapter 6 provides a detailed discussion on how well these models performed on fatal fire cases from medical examiner offices. Finally, chapter 7 offers a broader discussion on the impact this study will have on the forensic community, and outlines future research.

Chapter One

Background

This chapter provides an overview of the thermal alterations that emerge on a human body when exposed to heat and describes how to identify these changes on a human body. The following discussion also highlights the methods that have been created for analyzing burned human remains, while demonstrating the need for a more quantitative approach that can be defended in court. This chapter will also include a discussion of anthropological methods and variables used in creating post-mortem interval models (PMI) for estimating time since death. These models provide important information surrounding the timing of death events and demonstrate how this approach can be applied to other areas, including fatal fire cases. These previous studies lay the groundwork for this dissertation project by illustrating how the new model(s) were developed, and why it is possible to estimate timing of death events, even from fatal fire scenes.

Anthropological Methods for Estimating Timing of Death Events (Review of PMI)

Within anthropology, a series of methods have been developed to provide an estimate of time surrounding death events. A majority of these models are derived out of taphonomic studies (Bass 1984, Galloway et al. 1989, Komar 1998, Megeysi et al. 2005, Pokines and Baker 2014) that focused on developing a post-mortem interval (PMI). Estimating timing of death events is possible given the series of bodily changes that occur after death based on known environmental conditions. Experimental observations have found that a human body undergoes a series of physical alterations at death, making it possible to estimate time since death. These models are of interest to this research, as heat also produces a series of bodily changes that can be analyzed, and is dependent upon several environmental conditions as well. The following discussion is of models that have been created through experimental human decomposition research, and highlight how a post mortem interval (PMI) for estimating time since death was developed. This research aims to employ a similar model for estimating exposure time to a fire, which can provide additional insight and information to forensic investigators building a legal case.

Upon death, the body undergoes a series of changes that contribute to the decay of soft tissue. Observational research has found that these physical alterations (e.g. fresh, bloat, advanced decay, and mummification), can be correlated with specific time intervals (Bass 1984, Galloway et al. 1989, Komar 1998, Megeysi et al. 2005, Pokines and Baker 2014). The progression of soft tissue alterations are noted to emerge at specific times, making it possible to estimate time since death. These physical changes are dependent on environmental factors, like temperature, moisture, and insect activity that can contribute to the development of these changes. Since environmental factors are known to contribute to the decay process, geographic and environmentally specific models have been created to estimate how long it takes for a body to develop these changes after death (Bass 1984, Galloway et al. 1984, Galloway 1997, Megeysi et al. 2005). Environment can influence the rate of decay, thus, altering time since death estimates.

Decomposition can be accelerated or delayed by insect activity, temperature, moisture, soil pH, and bacterial activity (Bass 1984, Knight 1988, Micozzi 1991, Rodriguez 1997). Observational research has found that surface remains recovered in temperate climates, e.g. East Tennessee, can be fully decomposed within two weeks (Bass 1984, Rodriguez 1997, Vass et al. 1992, Vass 2001, 2011). Surface remains are exposed to insect activity, disturbances by carnivores, oxygen, and temperature changes that accelerate rates of decomposition. The human body is found to decay at faster rates when insects, such as blowflies can deposit larvae, in hot climates contribute activating bacteria, and in environments where oxygen and moisture content are high (Bass 1984, Bunch 2009, Henderson 1987, Jaggers and Rogers 2009, Knight 1995, Micozzi 1991, 1997, Vass et al. 1992, Vass 2001). Increases in temperature, oxygen, and moisture provide the appropriate environmental conditions for insects and bacterial activity to be present on a human body, contributing to accelerating decay. Additional experimental observations from cold climates, like in northeastern United States, has found a delay in the later stages of decomposition process, providing evidence that cold climates extend the decay process (Bunch 2009, Komar 1998, Micozzi 1997, Pokines and Baker 2014). The differences observed demonstrate the importance of temperature, moisture, altitude, and vegetation coverage in accelerating or delaying decomposition. Decreasing temperatures, oxygen levels, and moisture content create an environment for the body that is not conducive to bacterial growth nor insect infestation, which work to delay the decomposition process (Micozzi 1997: 1991, Rodriguez 1997, Jaggers and Rogers 2009, Ubelaker 1978, Vass et al. 1992, Vass 2001). Soft tissue can be present due to a subset of environmental conditions that contribute to preservation. In areas that receive snowfall, have fluctuating temperatures throughout the year, and are located in at high elevations, environmental conditions can work to delay decomposition. The delay in these natural responses can be explained by environmental factors that contribute to preserving soft tissue. Thus, anthropologists must carefully choose an appropriate model for constructing post-mortem interval estimates (PMI) that is more representative of their geographic area. Thus, environmentally specific models are created to account for environmental influence on the timing of these physical alterations.

Burial depths and subsurface environments also limit key variables that work to preserve soft tissue on remains. Human remains are noted to decompose slower in burials than with surface remains (Galloway et al. 1989, Galloway 1997, Henderson 1987, Jaggers and Rogers 2009, Knight 1988, Komar1998, Micozzi 1991, Pokines and Baker 2014, Rodriguez 1997, Ubelaker 1997, Vass et al. 1992, Vass 2001). Temperature, moisture, and oxygen become limited in subsurface environments making it difficult for insects and bacterial activity to be maintained, contributing to soft tissue preservation. Experimental research has also found that remains located in burials, without coffins, can be completely decomposed anywhere from one to four years, depending on grave depth (Bell et al. 1996, Rodriguez 1997). Bell and colleagues (1996) found changes in deep burials as early as two and half years and as late as five years, suggesting burial depth is a major factor in preservation. Burials at depths greater than four feet exhibit significant delays in the decomposition process. Experimental research has found that insects cannot reach depths greater than one to two meters beneath the surface, which impact their ability to deposit larvae on the body (Campbosso et al. 2001, Ubelaker 1997, Vass 2001). The deeper burial depths limit insect activity, oxygen availability, and temperature, and increases moisture, which contribute to delaying decomposition. The lack of bacterial activity on the human body can work to preserve soft tissue (Bell et al. 1996, Henderson 1987, Micozzi 1997, Pokines and Baker 2014, Vass et al. 1992, Vass 2001). Thus, post-mortem interval estimates are constructed based on environmentally specific variables, which capture the progression of physical alterations for that geographic region. Environmental variables affecting the progression of bodily changes observed, must be factored into any post-mortem estimate. Similar environmental variables, including temperature, are noted to influence thermal alterations, and need to be factored into similar models for fatal fire deaths.

The human body undergoes a series of alterations from fresh, bloating, slippage of skin, mummification, to skeletonization after death. Since environment is a major contributor to these changes, anthropologists have developed models that are region or environmental specific for constructing a time since death estimate. Environmentally specific models have been developed to estimate the timing of these changes (Bass 1984, Galloway et al. 1989, Megeysi et al. 2005). Post-mortem interval is estimated based on identified stages of change to a body after death e.g. fresh, early decomposition, advanced decomposition, and skeletonization (Galloway et al. 1989, Megeysi et al. 2005, Micozzi 1991). The fresh stage is characterized as exhibiting no evidence of maggot activity and no discoloration to the body (Bass 1984, Galloway et al. 1984, Megeysi et al. 2005). Early decomposition is described as the body exhibiting discoloration and bloating. Advanced decomposition is characterized by the presence of slippage of soft tissue, intense maggot activity, and mummification. The final stage, skeletonization, is considered present when a majority of the bones are exposed on the human body (Bass

1984, Galloway et al. 1984, Megeysi et al. 2005, Micozzi 1997: 1991). Each model scores the progression of bodily changes, then; these scores are added to together to formulate a total body score (TBS). A total body score is used in estimating time since death or accumulated degree days (ADD) based on body conditions. Each stage of change is scored based on series of changes from coloration, to insect activity, to soft tissue loss. The scores are calculated differently depending on the model used (Bass 1984, Galloway et al. 1984, Komar 1998, Megyesi et al. 2005). Unlike other models, Megyesi and colleagues (2005) scored changes based on body regions, e.g. skull, abdomen, and limbs. Each bodily region is scored independently, then the scores are combined together to calculate a TBS. This model acknowledges the body does not decompose at the same rate across all bodily regions, thus it accounts for this variability by independently scoring each region. This research will also follow the same guidelines, as Megyesi and colleagues (2005), in separating out the changes by bodily region, and summing the scores. With burned remains, we know from experimental observations that elements burn at different rates, so it is also important to separate out the regions to adequately account for this variation.

Megyesi and colleagues (2005) model attempted to increase accuracy rates and account for the role temperature played in bodily changes. Their model built upon Galloway and colleagues (1984) previous work by adjusting and modifying several aspects to make their model more broadly applicable. In addition to scoring each body region, they established a way to provide a quantitative analysis of changes they felt accumulated through time. In situations where scoring maybe ambiguous, the scholars took an average of the two ends of the spectrum. They also provided a way for temperature to be factored into the estimate of time since death. Previous models did not allow for temperature to be entered into the formula developed. Megyesi and colleagues (2005) derived temperature data from the National Weather Service, and used averages in developing their ADD formula. The use of Weather Service data allowed for this model to be applied easily and provided an accessible means to weather data for others to incorporate when applying this method. It is important to note how Megyesi and colleagues (2005) method differs from existing models, and how they incorporated temperature directly into their Accumulated Degree Day model. This dissertation project aims to incorporate a similar approach for including temperature data into a model that can be used to calculate exposure time to a fire.

Environmental factors contributing to these processes are used to generate a linear regression model that predicts how long it may have taken for those bodily conditions to develop. The environmental factors, e.g. time and temperature, are used to statistically generate a model that predicts the timing and development of these bodily changes. Accumulated degree days (ADD) is calculated from a formula developed from the linear regression model. The model generates an equation from which the body score can be used to estimate time since death. The number produced from the equation is an estimate of the amount of days it approximately took for bodily changes to occur (Bass 1984, Galloway et al. 1989, Megyesi et al. 2005). The TBS scored is added into the equation to generate and estimate of time since death. The formulation of TBS in decomposition studies, in particular Megyesi and colleagues (2005), will be a guide for establishing a new method for analyzing fatal fire deaths. This research will establish a similar guideline for analyzing fatal fire deaths using an accumulated scoring system and a corresponding regression model for estimating exposure time to a fire.

Thermal damage to soft tissue

As within human decomposition, the body undergoes a series of predictable physical changes when exposed to heat that can be observed and studied. Experimental research has captured the sequence of heat-related changes to the human body, making it possible to know when these alterations emerge and when they become destroyed in the burn process (Bohnert et al. 1998, DeHaan 2008, 2012, Kirk 1967, Thompson 2004). Through various observational experiments, scholars found consistent patterns in the manner remains become damaged. Fire produces a series of physical alterations from blistering, skin splits, muscle exposure to fracturing, and fragmentation (Correia 1997, Bohnert et al. 1998, DeHaan 2008: 2012, Pope 2007, Pope and Smith 2004, Symes et al. 2008). Blistering is thought to be one of the earliest physical alterations to appear, while calcination and fragmentation of skeletal tissues are some of the last alterations to emerge (Hermann and Bennett 1999, Thompson and Chudek 2007, Thompson 2009). These thermal alterations occur in predictable intervals, making it possible to study and analyze heat-related damage.

The human body goes through a series of soft tissue alterations before bone becomes exposed to heat. Heat alters soft tissue to produce color banding, blistering, skin splits, subcutaneous fat exposure, and muscle exposure before causing damage to skeletal tissues (DeHaan 2008: 2012, Devlin and Herrmann 2013, Pope 2007, Pope and Smith 2004, Spitz 2006). The body is comprised of multiple layers, e.g. skin, fat, and muscle that become exposed to and destroyed by fire. The development of these physical alterations is correlated with their anatomical positioning within the human body. Soft tissue layers, e.g. epidermis, are exposed to heat first, thus, representing some of the earliest heat-related changes.

Soft tissue color banding, blistering, and skin splits mark the early phases of heat-related damage. These soft tissue alterations emerge due to changes in the chemical composition of the body when exposed to heat. When heat is applied to soft tissue, it removes moisture from these anatomical regions creating coloration changes to the skin, blistering, and splitting of the dermal layer (DeHaan 2012, Devlin and Herrmann 2013, Martini et al. 2015, Pope 2007, Spitz 2006). Color banding and blistering are two soft tissue changes that occur first on a human body. Color banding is identified by the presence of a light-brown to charring discoloration on soft tissue. Blistering can be identified by a bubble shaped appearance on the dermal surface. These two thermal alterations manifest due to the removal of chemical components by heat over time. As the epidermal layer becomes dehydrated, the skin splits and leaves behind a breakage pattern that can be analyzed. Once the skin splits, subcutaneous fat is exposed by the opening of the dermis layer and is marked by its distinguishable yellow coloration (DeHaan 2008, Pope personal comm. 2015).

The burning away of the fat layers exposes muscles and internal organs to heat. Internal organs protrude from the abdominal cavity, exposing intestines and other organs to heat-related damage. As underlying muscles become exposed to fire, the pugilistic posture also emerges. When muscles become exposed to heat, the fibers contract and shrink (Martini et al. 2015, Pope 2007, Symes et al. 2008). The pugilistic posture is marked by the flexation of long bones and by the curving of the hands and feet inward.

(DeHaan 2008, 2012, and Symes et al. 2008). This posture is only present as long as the muscle fibers and connective tissues are present in that region of the body. Destroying extensor and flexor muscles by heat contributes to the movement of long bones as muscles contract upon being destroyed (Bohnert et al. 1998, DeHaan 2008, Pope 2007, Thompson 2009). Once the fibers and connective tissues have been destroyed by the fire, the puglistic posture is no longer identifiable (Correia 1997, DeHaan 2008: 2012, Martini et al. 2015, Pope 2007, Symes et al. 2008). When underlying muscles, connective tissues, and subcutaneous fat layers are destroyed, skeletal tissues begin to become exposed to heat-related damage.

Fire tends to create damage on remains going from external soft tissue layers to internal surfaces, e.g. skeletal tissues, allowing for a progression of changes to be analyzed. The progression of soft tissue alterations occur as a series of correlated events due to their anatomical positioning in the human body. Physical changes on the dermal layer are noted first, followed by subcutaneous fat exposure, muscle exposure, and internal organ exposure. When heat is applied, the body burns from soft tissue layers towards skeletal tissues, making it possible to identify sequences of physical alterations (Bohnert et al. 1998, Correia 1997, Devlin and Herrmann 2013, Symes et al. 2008, Thompson 2004: 2009).

Thermal damage to bone

Thermal alterations to bone manifest due to changes in the chemical and structural composition of bone. Bone undergoes color banding, charring, calcination, fracturing, shrinkage, warping, and fragmentation when exposed to heat (Baby 1954, Devlin and

Herrmann 2008, Corriea 1997, Eckert 1981, Eckert et al. 1988, Symes et al. 2008). As with soft tissue, heat also removes moisture content from bone, contributing to the manifestation of a series of skeletal tissue alterations. The alteration of chemical components is reflected in the coloration of burnt bone. Burned bone can exhibit a variety of colors from brown, black, grey-blue, or white (calcination), which reflect the loss of these materials overtime. The transition in chemical changes can be identified on bone in four main ways: through charring, calcination, emergence of a border, and the manifestation of a heat line (Corriea 1997, Devlin and Herrmann 2013, Pope 2007, Symes et al. 2008: 2014). The presence of charring on bone represents a loss in the oxygen component, whereas calcination reflects a loss of organic material (Devlin and Herrmann 2008, Corriea 1997, Thompson 2004: 2009). Charring is distinguished by a blackened coloration, while calcination can be identified by a grey-blue or white coloration of bone. A boarder and heat line are two additional alterations that occur on burned bone, and are easily distinguishable from one another.

A border is distinguishable by its white, flaky appearance located near the charred regions. Unlike a border, a heat line is identified by the formation of a line located between burned and unburned areas on bone (Symes et al. 2008: 2014). These thermal alterations mark transitions in heat-related changes on bone.

The most advanced stages of heat-related damage can be characterized by exhibiting high degrees of calcination, fracturing, shrinkage, and fragmentation. The removal of key chemical components needed in maintaining bone structure contributes to development of calcination, fracturing, and fragmentation (Baby 1954, Eckert et al. 1988, Symes et al. 2008). The bone shrinks and fragments due to loss of water and changes in the mineral composition, which contributes to making bones very fragile (Bratmiller and Buikstra 1984, Buikstra and Swegle 1989, Christensen 2002). The latter descriptions, e.g. calcination, fracturing, and fragmentation, develop in a systemic manner, making it possible for anthropologists to analyze and classify thermal alterations.

Identifying Heat Related Fracturing

Heat can also contribute to producing a series of fracture patterns, e.g. longitudinal, transverse and concentric fracturing on burned bone. The development of these fractures is key in differentiating between heat-related fracturing and other forms of trauma (Correia 1997, Galloway 1999, Pope and Smith 2004, Symes et al. 2008: 2014, Ubelaker and Adams 1995). Trauma induced prior to burning exhibits differential characteristics, e.g. thick beveling and presence of tool marks, which can be used to distinguish it from heat-related trauma or post-mortem damage. Experimental observations and cases studies also noted differences in development of fracture patterns between fresh and dry bone (Mayne 1990, Pope 2007, Pope and Smith 2004, Symes et al. 2008: 2014). When trauma occurs on bone prior to burning, bone is compromised, exposing the internal structures to heat. Thus, pre-burn trauma compromises bone structure and coloration differences (Correia 1997, Dirkmaat et al. 2012, Galloway 1999, Pope 2007, Symes et al. 2008, Ubelaker and Adams 1995). These observations have documented changes in bone, making it possible to distinguish between fractures created prior, during burn, or after.

Pre Burn Fracturing

Pre-burn fracturing, encompasses fracturing, e.g. blunt force, sharp force, gunshot trauma and healed trauma, that occur before heat is applied to bone. If a fracture occurred while living tissue was present, a bony response can be identified by the formation of a callus on the fracture surface (Galloway 1999, Gonclaves et al. 2011, Martini et al. 2015, Symes et al. 2014, Thompson 2004). The manifestation of identifiable healing on burned bone, suggests the fracture occurred before burning. However, burned bone alters bone composition and can contribute to additional breakage on the healed surface (Galloway 1999, Pope 2007, Symes et al. 2014). The presence of healing can still be identified microscopically by assessing fracture margins in bone microstructure. Heat produces additional breakage at the callus formation site, making it possible to distinguish between pre-burn and during burn fracturing.

Blunt force, sharp force, and gunshot trauma also produce characteristics that are distinguishable from heat-related fracturing (Correia 1997, Galloway et al. 1990, Pope and Smith 2004, Pope 2007). Blunt force trauma exhibits depressions, flaking, concentric fracturing, radiating fractures, and a bevel shaped appearance that distinguishes it from heat-related fracturing (Berryman and Symes 1998, Corriea 1990, 1997, Galloway 1999, Pope 2007, Symes 2014). Heat is unable to produce the crushing impact of blunt force trauma (Galloway 1999, Pope and Smith 2004, Ubelaker et al. 1995). Beveling is a distinctive characteristic associated with blunt force and gunshot traumata. Beveling often manifests as an oval to circular defect, that exposes the inner or outer table of bone. Beveling can also be found in heat-related trauma, but the exposed table of bone is often compromised and appears much thinner. Heat tends to shrink and change the chemical composition of bone, thus contributing to a reduction in the thickness of this layer.

Sharp force trauma can be distinguished based on presence of fracture lines, chipping of bone, evidence of striations on bone walls, and hinge fractures that differ from heat-related trauma (Bass 2005, Berryman and Symes 1998, Byers 2007). Gunshot trauma is also distinguishable based on the presence of an entrance or exit wound, presence of beveling, and radiating fractures that spread away from the site. In both blunt and gunshot traumata, the fractures radiate away from the site, making it possible to differentiate from heat-related fracturing. Heat does not produce radiating fractures into unburned bone (Pope 2007, Pope et al. 2004). Gunshot trauma also produces thick beveling, while heat-related fracturing produces a thin beveled appearance on some bones, making it possible to distinguish as pre-burn trauma (Byers 2007, Bass 2005, Sauer 1998). Concentric fractures also produced from blunt force and gunshot trauma are also distinguishable based on shape and direction of radiating fractures. They exhibit a perpendicular shape and tend to radiate away from the impact sites (Berryman and Symes 1998, Galloway 1999, Sauer 1998).

Any pre-burn trauma related injuries alter the burn process and fail to produce the fractures expected with soft tissue destruction, making it possible to distinguish from heat-related fracturing (Mayne 1990, Pope 2007, Symes et al. 2008). Once bone is broken prior to fire, the bone exhibits different patterns in thermal alterations. The breakage of bone causes each fractured piece to burn independently, making it possible to distinguish as occurring prior to burning. Experimental research has found that trauma that exposes bone does not exhibit the same sequence of characteristics, e.g. coloration, making it possible to distinguish before burning (Mayne 1990, Pope and Smith 2004, Pope 2007, Symes et al. 2008: 2014). If the bone was not fractured prior to burning, the bone would not exhibit differential colorations in margins. The presence of different colorations in the margins of bone, absence of fractures associated with soft tissue destruction, evidence of thick beveling, an entrance or exit wound, evidence of healing on bone are indicators trauma occurred prior to burning.

Heat-Related Fracturing (During Burn)

Heat alters bone by changing the chemical composition and structure, making it possible to distinguish between fractures that occur during fire or after. Fire contributes to the production of warping and fracturing on bone. The differences in heat-related fracturing are dependent on the state of the bone at the time of fracturing (Baby 1954, Mayne 1990, Pope 2007, Pope and Smith 2004, Symes et al. 2008: 2014). Ubelaker (2009) noted that dry bone often tends to exhibit very little warping, while fleshed remains exhibit warping, transverse cracking, and irregular longitudinal cracks (Corriea 1997, Pope and Smith 2004, Ubelaker 2009). Fresh bone tends to fracture differently than dry bone, exhibiting characteristics that make it possible to distinguish. Fresh bone exhibits splintering, irregular edges, and remains connected to existing bone structures (Mayne 1990, Sauer 1998, Symes et al. 2008, Ubelaker 2009). Dry bone exhibits a more fragile and brittle state, due to a loss in the collagen component of bone. Thus, when dry bone fractures, it fractures completely from existing bone structures into multiple pieces

(Devlin and Herrmann 2013, Galloway 1999, Mayne 1990, Pope 2007, Symes et al. 2008: 2014, and Ubelaker 1989).

Experimental studies have found that longitudinal, transverse, pina, curved fractures, and delamination manifest due to heat (Baby 1954, Mayne 1990, Shipman et al. 1984, Pope 2007, Pope et al. 2004, Symes et al. 2008). Curved transverse fractures manifest on bone as a circular concentric pattern that reflects the contraction of soft tissues, suggesting it can be an indicator of fracturing during burn. Pina fractures are also found to occur during burning due to the contraction of soft tissue, suggesting this is another fracture pattern directly associated with burn processes (Mayne 1990, Pope 2007). Other fractures patterns occur to both fresh and dry bone, but timing can still be determined based on the directionality of radiating fracture patterns and charring of margins. Soft tissue also contributes to the formation of identifiable fracture patterns, like curved transverse fractures, pina fractures, or radiating fractures into other burned areas (Baby 1954, Mayne 1990, Shipman et al. 1984, Pope 2007, Pope et al. 2004). During burning, tissues pull away from bone compromising the periosteal layer of bone, producing a curved concentric fracture pattern. This type of fracture pattern is associated with the retraction of soft tissues and muscles when exposed to heat, and is distinguishable from other type of fracture patterns. Differences in coloration between layers can also be used to suggest fracturing occurred during burn. Experimental observations have found that fractures produced during fire are going to radiate into other burned areas of bone, unlike with fractures produced after (Dirkmaat et al. 2012, Pope 2007, Symes et al. 2008: 2014). The presence of radiating fractures into burned areas, charring in margins of bone, and presence of curved transverse and pina fractures provide evidence for distinguishing between during burn or after fracturing.

Postmortem Fracturing (After Burn)

Fracturing can also occur after burning and exhibit identifiable patterns that can be analyzed. Postmorterm fracturing is characterized as fracturing that occurs to dry bone (Corriea 1997, Buikstra and Swegle 1989, Devlin and Herrmann 2008, Mayne 1990, Pope 2007, Symes et al. 2008: 2014, Ubelaker 2009). Heat changes the bone composition, making bone fragile and more susceptible to fracturing and fragmentation. Postmorterm fracturing can be the result of handling processes, suppression efforts, or recovery (DeHaan 1999, Galloway 1999, Symes et al. 2008). The water and pressure from fire hoses can create additional damage to already fragile bones. The breakage of bone after burn is distinguishable from heat-related fracturing due to the absence of charring in the margins. If the margins do not exhibit a different coloration, then it is likely the bone was fractured postmortem and post-fire. When bone exhibits equal coloration on both pieces, it infers the bone burned first before being fractured (Dirkmaat et al. 2012, Buikstra and Swegle 1989, Symes et al. 2008). The main identifiable difference is the lack of radiating fractures in unburned regions and the lack of differential charring found in the margins of bone. Heat produces observable changes on the human body from soft tissue to skeletal alterations that make it possible to analyze.

Variables Influencing Thermal Alterations

Heat produces a series of soft tissue and skeletal changes on a human body that often occur in a sequenced order. There are several key variables, including time and temperature that contribute to factoring into which end of the thermal spectrum one might observe in a set of remains. Ventilation, one's body mass index, presence or absence of clothing, and use of an accelerant have all been observed to influence burn patterns (Dehann 2008, 2009, 2012; Kirk 1967; Thompson 2009). Clothing can work as a protective barrier to the human body, limiting the amount of thermal damaged received (Dehann 2008, 2012, Keyes 2019, Imaizum 2018). An individual's body fat can also work to help sustain a fire, even at low intensity, contributing to the thermal alterations observed. Body mass index also becomes an important variable as it may alter timing of alterations, as some individuals may have higher BMI, and thus fat, influencing burn patterns. The use of an accelerant can also influence thermal alterations, if directly applied to the body. When an accelerant is applied, it tends to burn off quickly, thus resulting in concentrated areas of thermal damage (DeHaan 1999, Kirk 1967). Accelerants, BMI, clothing, and ventilation all work to either speed up the burn process or hinder the development of thermal alterations. This literature review will primarily focus on the influence of ventilation, time and temperature, as these become key factors that are often omitted in classification methods, but play a large role in the alterations observed. It is through experimental observations that we begin to gain a deeper understanding of how time, temperature, and ventilation contribute to the emergence of these thermal alterations.

Experimental observations have described the relationship between duration of fire, temperature, and the thermal alteration observed. Time and temperature are two variables that have been studied and noted to contribute to whether soft tissue may be present, or contribute to remains in a highly fragmented or calcined state. It has been noted that low intensity fires create greater soft tissue damage, and if exposed over a longer period of time can damage the bone (Bohnert et al. 1998, DeHaan 1999, 2012). Field research has also found that high intensity fires that are short lived will create a greater degree of damage to the external surface with little to no damage to the internal body (Bohnert et al. 1998, DeHaan 2008, 2012). In fire environments where remains have been exposed to prolonged higher temperatures, the remains often exhibit some of the highest degrees of thermal alterations, including fragmentation and calcination. In fire environments, where remains have been exposed to high temperatures for shorter periods of time, remains often exhibit many of these soft-tissue alterations, including skin splitting, subcutaneous fat exposure, or muscle exposure. Experimental observations demonstrate the wide range of thermal alterations that can be produced, and the importance of evaluating changes per fire environment, e.g vehicle, structure, or outdoor. Each fire environment is going to produce conditions that are going to increase or decrease ventilation or temperature, which come to affect the thermal alterations observed.

Through these various field experiments, scholars have also been able to identify key physical alterations and correlate them with specific times and temperatures. The pugilistic posture has been found to emerge around 670-810 degrees Celsius; while the exposure of internal organs has been noted to occur approximately 30 minutes after a burn begins (Bohnert et al. 1998). The hands and feet and frontal portion of skull were also found to be some of the first elements to burn, thus exhibiting charring, bone exposure, and calcination much earlier than other skeletal elements. (Symes et al. 2008, Thompson 2004, 2009). Experimental observations have demonstrated how temperature and duration are going to influence the amount of thermal alterations that are present on a set of remains, and need to be factored into classification models. Given different bodily regions are found to burn at different rates, classification models need to encompass methods that account for this variability.

Forensic professionals maybe presented with fatal fire cases that range from a variety of environments, including vehicle, structure, or outdoor fires. Each of these fire environments produce varying temperatures, times, and ventilation patterns that can work to affect the degree of thermal alternations observed. Thus, forensic cases involving a short exposure time, lower temperatures, and limited physical changes illustrate the challenges in applying many classification methods to analyzing burned human remains. The amount of variability in heat-related damage leaves professionals with a range of variation in physical alterations that either can be scored between levels or not at all on some models.

Anthropological Methods for Classifying Burned Remains

Thermal alterations have been used in developing classification systems for burned human remains. Three primary classification methods, Raymond Baby's (1954) model, Eckert's (1988) classification system for cremated remains, and the Crow-Glassman Scale (CGS) (Glassman and Crow 1996), have been used by anthropologists. The classification models were primarily created from descriptions of physical alterations, e.g. soft tissue loss, bone exposure, and fragmentation, observed on the human body. The design and development of the classification models contributes to their usage or applicability to the broader anthropological and forensic community. The earlier two methods, e.g. Baby (1954) and Eckert (1988), developed classification systems based on cremated remains. Thus, the classification systems progress quickly through the burn process, capturing only the advanced stages of heat-related damage, and therefore are not widely used today. The third model does include additional thermal alterations, however, it still only captures a subset of the possible conditions that can be found, thus limiting its applicability and use today.

Baby (1954) devised a three stage scale based on remains recovered from Hopewell burials; emphasis was placed on coloration, fragmentation, and fracturing. No other heat-related alterations were included in this system. The three stages include:

complete incineration, incomplete incineration, and non-incinerated remains (Baby 1954). Baby (1954) differentiated between levels by placing emphasis on differences in coloration and degree of fragmentation of remains. Burned remains that exhibited a grey-blue coloration, warping, and fracturing were classified as complete. Remains that exhibited charring and a blackened coloration were classified as incomplete (Baby 1954). A final and third stage in the system was created for non-incinerated remains, which described remains unaffected by the heat-related process (Baby 1954). The three stage model encompasses a range of variation from no alterations to fragmentation and warping, limiting the applicability of this model to broader fire cases. Given the context of how this model was constructed, the stages are representative of advanced heat-related damage, e.g. bone exposure, fracturing, warping, and fragmentation. Thus, this model cannot be applied to remains where soft tissue, subcutaneous fat exposure, and muscle exposure may be present.

Eckert's (1988) classification model is derived from forensic case studies of remains with advanced stages of heat-related damage. The forensic cases used in developing this model exhibited high percentage of fragmentation and calcination with little to no soft tissue present (Eckert et al. 1988). Eckert (1988) observed charring, fragmentation, soft tissue loss, and internal organ exposure. A four stage model was developed for describing the severely burned remains. The four stages include: complete, incomplete, partial, and charred (Eckert et al. 1988). The first two stages, e.g. complete and incomplete, are based on the degree of fragmentation present. The remains are considered complete if no bone fragments are present and considered incomplete if bone fragments can be found (Eckert et al.1988). The latter two stages, e.g. partial and charred, assess physical alterations that occur in the earlier stages of the burn process. The partial stage assesses presence of soft tissue, while the charred stage refers to presence of internal organ exposure (Eckert et al. 1988). A majority of the cases used in constructing this system exhibited incomplete fragmentation and charring. Thus, there were limited cases containing internal organ exposure or presence of soft tissue, creating limitations to its utility (Eckert et al. 1988).

A third model, the Crow Glassman Scale (CGS) was developed to analyze burned remains from the Branch Davidian Conflict in Waco, TX (Glassman and Crow 1996). This scale was developed two decades ago to standardize the language used by forensic professionals charged with recovering and identifying burned remains from the Branch Davidian conflict in Waco, TX. This system was created *post hoc* based on a specific set of conditions and represents only a subset of the possible range of fire-related conditions (Department of Treasury 1993). The CGS consists of the following five stages:

CGS Level #1: blistering on body, some burning to head, body is still identifiable.

CGS Level#2: body begins to exhibit various charring over total body surface area (TBSA), hands and feet begin to be severely damaged.

CGS Level#3: Severe damage to arms or legs, soft tissue loss, in some instances limbs are missing.

CGS Level#4: Severe charring to body, severe damage to skull, small portions of the arms and legs maybe present.

CGS Level#5: no soft tissue remains, remains are almost in a cremated state, very fragmented, and identification is very difficult.

In its current form, the CGS is overly general, as it progresses quickly from blistering to fragmentation in only 5 stages, with no descriptions of times or temperatures that could have contributed to this process. The scale can also be fairly subjective as it does not quantify surface area or percentage of body affected. The CGS describes additional soft tissue variables, e.g. blistering, charring, and soft tissue loss, making this model more applicable to the forensic community than previous models. However, the scale progresses quickly from 1 to 5, without adequately capturing the earlier stages of the burn process, (e.g. soft tissue color banding, subcutaneous fat exposure, muscle exposure, or presence of the pugilistic posture). The scale was created from a specific scenario in Waco, Texas where the majority of remains were found in a highly fragmented state with limited soft tissue present, contributing to the development of the highly advanced stages found in the CGS (Department of Treasury1993). Thus, the scale fails to adequately capture the earlier stages of the burn process.

The lack of description of these earlier stages creates challenges for the applications of the CGS to a wide range of fire conditions, thereby limiting its use within the forensic community today. The limited inclusion of soft tissue physical alterations creates challenges for the application of the CGS to a wide range of fire conditions, thereby limiting its use in the broader forensic community. The classification models created capture a subset of the range of physical alterations that can be present on a set of remains. However, previous models failed to adequately encompass soft tissue alterations, creating limitations to applying these methods to forensic cases where soft tissue may be present. There is a need to develop an anthropological based method that encompasses all thermal alterations, and can be more broadly applied to a range of fire environments.

Medico-legal Classification Methods

There are also inconsistencies among forensic professionals in how to describe and quantify the amount of heat-related damage. As such, descriptions of burned bodies from pathologists and medical examiners are often inconsistent with those provided by forensic anthropologists in the bodily elements described, in the assessment of total body surface area affected, and in employing a variety of criteria to classify the burn injuries (Amhed et al. 2009, Fracasso et al. 2009, Martin-de las Heras et al. 1999, Moore et al. 2019, Dunne et al. 1977). For example, total body surface area (TBSA) is not analyzed in similar manners between disciplines. Pathologists follow the "rule of nines" when recording TBSA on human remains. The "Rule of Nine/Wallace Rule of Nines" is derived from the medical field and often used to classify burn injuries. Even though this method was created as a way for medical professionals to assess a patient's injuries, it is borrowed by pathologists and applied to fatal fire cases. The method was derived as a way to provide medical professionals with a means to calculate the percentage of surface area burned on an individual, so they could in turn prescribe the proper treatment. Based on the "Rule of Nines," TBSA is calculated from nine pre-defined regions of the body. Each of the nine regions are given percentages based on proportionment of surface area to body size (Fracasso et al. 2009, Giretzlenhner et al. 2013, Martin-de las Heras et al. 1999, Moore et al. 2019). Within this model, percentages are assigned based on soft tissue injuries to the body. The model assesses burned injuries to the head, trunk, upper and lower extremities. Within each region, the percentages are broken down even further to account for differences between anterior and posterior, and within the chest and abdomen areas of the trunk. The "Rule of Nines" was created to help medical professionals make a quick assessment, however there are some limitations. This model can be inaccurate in producing up to a 20% inter-observer error, as a large portion of the assessment is based on subjectivity and one's experience in handling these types of cases

(Arora et al. 2010, Byard 2018, Giretzlenhner et al. 2013, Moore et al. 2019). Giretzlehner and colleagues (2013) found that in contexts where burn injuries comprised less than 20% of the surface area, there was an increase in observer error, with a trend towards overestimating total body surface area. Additionally, the model does not account for soft tissues changes in the hands or feet when deriving Total Body Surface Area. The lack of including these elements has also been noted to have contributed to some of the inaccuracies in assessing TBSA.

Another method often called the "Rule of Palms" is also sometimes referenced when calculating total body surface area. This method was implemented as a means to better guide an observer in making an assessment (Arora et al. 2010, Byard 2018, Giretzlenhner et al. 2013 Moore et al. 2019). The "Rule of Palms" is another tool within the medical field that maybe relied upon to estimate total body surface area. This method often provides the observer with a bench marker for what one should consider a minimum of one percent surface area coverage. If the burned area covers about the same surface area of one's palm, then it is marked at one percent. Overall, there have been recent advancements within the medical community to reduce this error by creating computer based models that provide a better visual representation of each region. However, it should be noted these models are best applied to soft tissue changes, and are not applicable, even to the hands/feet, once bone is exposed.

The forensic sciences lack a consistent, objective, and detailed scale to describe burn injuries or patterns in a variety of settings and conditions. Forensic anthropologists also analyze TBSA but not according to the same the guidelines. Instead, they calculate TBSA much more broadly and also include the hands and feet in their analysis. There is a need to create a scale based on quantitative experimental data (e.g. duration and temperature of fire) that provides insight into the nature of the fire and cause of injuries contributing to the condition of the remains. The challenge at hand is to create a means to bridge the work between the forensic sciences, all of whom may handle and examine the same cases. Therefore, this research aims to develop a method applicable to remains encountered in fatal fires that can be broadly used across the forensic disciplines to describe remains and predict fire conditions. This new method can aid investigators by providing additional information on the fire environment contributing to the bodily alterations observed and timing of injuries. This research would provide investigators with a tool for developing a more precise timeline of death events and aid in narrowing down a perpetrator.

Forensic Significance of Quantitative Methods

Experimental research has provided valuable descriptive information on the formation of thermal alterations. However, anthropological based methods include little to no quantitative description of the accuracy of classifying damage. The lack of a way to quantify heat related patterns with some degree of accuracy makes interpretations weak when taken to court. *Daubert vs. Merrell Dow Pharmaceuticals, Inc*. (1993) identified a set of criteria for admissibility of evidence in court, which called for providing error rates and standardized descriptions (Bohen and Heels 1995). Observational research does not include the likelihood of misclassifying patterns. Most interpretations are provided by the anthropologist, who is viewed as the expert (Bohen and Heels 1995, Devlin and Herrmann 2013, Galloway et al. 1990). The anthropologist gains expertise from experience working with and analyzing remains. Thus, a majority of their interpretations are based subjectively on past experiences, skill and observational research. The lack of a standardized method demonstrating replicability and validity creates challenges for assessments brought to court. There is a need to create a scale based on quantitative experimental data that provides insight into likelihood of misclassifying patterns. This research would develop a quantitative model for analyzing burned human remains, which has yet to be created and applied to this area. This dissertation work would provide investigators with a tool for developing a more precise timeline of death events and aid in building a legal case.

Summary

This chapter reviewed key experimental research that laid the foundation for this study. From these observational experiments, we gain a better understanding of what thermal alterations emerge and when they are likely to occur, making it possible to analyze heat-related damage. This review also examined previous classification systems and noted the limitations to their applicability to modern day fatal fire cases. A review of these models demonstrates there is a need to establish a more standardized model that encompasses all thermal alterations. Many of the classification methods established do not adequately capture all the changes that are noted to occur, thus limiting their use today. This chapter also described existing models on estimating timing of death events, and the variables that must be taken in consideration when constructing time since death estimates. These experimental studies lay the groundwork for this research, by demonstrating it is possible to use these same variables to estimate exposure time to a fire. Observational research demonstrates that there is a sequenced order of thermal alterations that occur to a body, once exposed to fire. Existing models do not adequately capture the range of physical alterations that can occur, thus demonstrating a need for a more standardized classification system. These physical changes can be altered based on similar variables examined in decomposition studies, illustrating it is possible to model heat related damage.

Chapter Two

Methods

This research aims to develop a quantifiable scale to describe fire-related damage on human remains, and a model for estimating exposure time to a fire. The following chapter outlines the hypotheses that underlie this research, and describes the methods used in developing each new model. The following discussion explains how data was generated for this research, what soft tissue and skeletal variables were used in analysis, and what statistical approaches were used in drawing conclusions. Additionally, this chapter provides a detailed description of the experimental observations that were made, and describes how the new models were created and validated. A detailed discussion of the methods utilized and developed is provided, as to make it possible for others to replicate or expand upon this work in the future. The following discussion outlines the hypotheses tested, the methodical approaches used, and the statistical analyses applied in developing error/misclassification rates for each model. The models developed are based on experimental burning of human remains and center on the following hypotheses:

Hypotheses

Hypothesis I: Burn patterns can be described based on visual interpretations of the body and be quantified using a scale that can be consistently applied based on fire conditions.

Currently, there is not a widely applicable method for describing burned human remains. Experimental research demonstrates there is a sequenced pattern to the way a body burns, making it possible to analyze (DeHaan 2008, Symes et al. 2008, Thompson and Chudek 2007, Pope & Smith 2004). Previous models describe visual interpretations of burned remains and demonstrate there is a general pattern present in burn cases, but they do very little to quantify the physical alterations observed. These models primarily account for charring of tissues, bone exposure, calcination, and fragmentation of remains. Previous models exclude descriptions of subcutaneous fat exposure, muscle exposure, or presence or absence of the pugilistic posture limiting their applicability. Therefore, the current study hypothesizes that additional variables can be added and scored based on percentage of body/region affected, and presence or absence of features from burning that demonstrates a correlation between time and temperature intervals. The inclusion of these additional variables aid in producing a model that is more broadly applicable to all fatal fire cases.

Hypothesis II: A formula can be modeled to estimate fire exposure time and temperature based on defined variables.

Experimental observations have found patterns between the emergence of physical alterations and time and temperature data, making it possible to estimate exposure time (Bohnert et al. 1998, DeHaan 1999, 2008, 2012, Thompson and Chudek 2007). Similar formulas are used to estimate a post-mortem interval in decomposition studies. These models use the condition of the remains to estimate time since death (Bass 1997, Galloway et al. 1989, Magyesi et al. 2005). It is hypothesized that a similar approach can be applied to burned human remains. A model similar to Accumulated Degree Days (ADD) can be used to estimate exposure time to a fire. The formulas generated will be specific to each environment and can be used to estimate how long a body may have been exposed to specific fire conditions.

Materials and Methods

To test these hypotheses, observational experiments were conducted that involve the burning of donated human cadavers as part of the San Luis Obispo Fire Investigation Strike Team (SLOFIST) training course. The SLOFIST program provides hands-on training to forensic professionals in the recovery of fatal fire scenes. San Luis Obispo Fire Investigation Strike Team offers a variety of training courses for forensic professionals from vehicle fires scenes to training in fatal fire deaths. Therefore, to best test each hypothesis, an experimental data set that covers a wide range of fire environments and conditions is needed. All the data collected as a part of this project was collected from the forensic fire death investigation course (FFDIC) at SLOFIST. The SLOFIST board of directors approved this research and granted access to data from 60 individuals over four field seasons (2014 through 2017).

The first hypothesis implies that not only visual analyses can be made from a set of burned remains, but that it is possible to quantify the amount of thermal damage. Therefore, this study engaged in SLOFIST's observational experiments where temperature data, time, and physical alterations could be observed and recorded. The data generated from the training courses were used to capture the soft and skeletal tissue components of the burning process. Observations from these experiments were used in documenting the burn process, and identifying key thermal alterations to be used in the new classification system.

The observational experiments consisted of 11 or 12 different scenarios covering a wide range of fire environments. Each scenario was similar to the season before, so replication of types of fires was possible from one field season to the next. The scenarios included but were not limited to: vehicle fires, structural fires, garage fires, burial/trench, tent/outdoor fire, RV fire, burn barrel, and an opened structure fire. The range of fire environments provided through the training course, made it possible to collect a wide range of data on a variety of scenarios that may be more representative of burned forensic cases. Remains were scored using the new model, and fire environment was also recorded to examine the relationship between fire environment, and degree of thermal damage on a set of remains. The individuals in this study were categorized based on type of fire environment into four broad categories: vehicle, structure, outdoor, and confined space fires. Vehicle fires included any individual placed in either the trunk or compartment seats. Structure fires included any individual placed in a RV, shed, on a mattress, couch, or on the floor. Outdoor fires included scenarios where individuals were buried in a trench, or placed in a tent. The confined space fires were characterized as any individual who was placed in a dumpster or environment with limited ventilation. Confined space fires differ slightly from a trunk fire in the amount of ventilation present in each fire environment. Trunk fires produce environments with closed ventilation, as long as the trunk is completely closed; whereas in confined spaces fires ventilation is still present, but it is restricted.

All physical alterations to both soft and skeletal tissues were documented with photography and thermocouples. Fire temperature data was collected through use of thermocouples and thermal imaging devices placed on multiple locations and depths directly on the human remains. Thermocouples were placed at varying depths and locations on the body. The thermocouples recorded the data via a data logger, where the temperatures were documented every minute. Thermocouples were also placed on the floor/lowest point within each fire environment and on the ceiling/highest point within each fire environment, to record the temperatures surrounding the body. Weather conditions were also recorded with meteorological instruments and documented during the experiment. Exposure time was recorded for the entire burn process using the time stamp from both the photography and videography devices. Time was also recorded manually while each temperature was being read from the data logger. These observational experiments were used to test both hypotheses, as each scenario produced a range of thermal alterations. The remains from each fire environment were evaluated based on the new classification model. The time and temperature data were used in developing a formula for estimating exposure time to a fire.

Data Variables

A database was created to record the multiple factors that will be used in developing the new models. Data collected and recorded include: fire temperature, fire exposure time, and visual changes to the body. In addition to these main factors, the weather conditions (e.g. humidity, wind speed, and wind direction) on the day of burn, the presence or absence of clothing, material composition of external items, distance to ignition source, use and type of accelerant, body position and body size were also recorded. The age, sex, weight, height, and body mass index; were also noted for each individual. In addition to both extrinsic and intrinsic variables, additional soft tissues variables identified and defined by Dr. Elayne Pope were added to the analysis. Skin splits, subcutaneous fat exposure, muscle exposure, and soft tissue color banding are important variables that should not be excluded from the analysis (Pope 2015, pers. comm.). The addition of these variables is vital to creating a broader model that can be more consistently applied to a wide range of fire environments.

In addition to soft tissue variables, skeletal variables were also analyzed to capture a broad range of physical alterations. These skeletal variables include: limb disarticulation, percent of bone fragmented, percent charring, percent calcined, and percent fracturing. The skeletal fragmentation, charring, and fracturing are all variables identified, defined, and analyzed by others who have studied burned human remains (Bennett 1999, Corriea 1997, Symes et al. 2008, Ubelaker 2009). Previous scholars have primarily described each of the aforementioned variables, with limited quantitative analyses. Thus, both the soft and skeletal tissue variables identified were analyzed quantitatively using a pre-defined scoring system. The quantification of visual data makes it possible to model heat-related damage.

Visual Analysis

The visual assessment of the burned bodies was guided by previous models, like the Crow Glassman Scale, while adding additional descriptions of temperature and time to the analysis. Previous models provided a foundation from which this study expanded on by including more soft tissue variables, and by assessing each bodily region independently. Experimental research has demonstrated the body does not burn equally in all regions, due to differences in body fat and varying tissue depths, to name a few. Therefore, all variables were recorded based on the affected body region (i.e., skull, upper and lower limbs, thorax, and hands/feet). Unlike previous models, the visual analysis was recorded as an accumulated score or total body score (TBS), as it better reflects the accumulation of thermal damage across all regions. Similar approaches have been applied to remains going through the decomposition process. Therefore, a similar approach was applied in this study. Each individual was scored based on a Total Body Score (TBS) of the progression of thermal alterations to the body. Each region was scored based on a point system, e.g. 1-7 or 1-9. The skull and thorax were scored on a scale from 1-7, with one being a fresh body and seven exhibiting calcination and fragmentation. The limbs and hands/feet were scored on a scale from 1-9, as they exhibit additional alterations, like the puglistic posture that must be taken into consideration. Remains were assessed by analyzing the alterations per region using the scoring model below.

Categories/Scoring for Head and Neck =__________

1= no charring, fresh body
2= blistering and partial skin splitting is present
3= skin splitting is widespread across head and neck, with less than 50% subcutaneous fat exposure
4= subcutaneous fat exposure is widespread and muscles are exposed
5= partial bone exposure and charring to cranial elements
6= bone exposure, heat related fracturing, and partial calcination to cranial region
7= widespread calcination and fragmentation

Categories/Scoring for Trunk =_________

1= no charring, fresh body
2= blistering and partial skin splitting is present
3= skin splitting is widespread across the trunk, with partial charring of tissues, and less than 50% subcutaneous fat exposure
4= widespread subcutaneous fat exposure and partial muscle exposure
5= widespread muscle exposure and intestinal exposure
6= partial bone exposure, with charring of bone
7= widespread bone exposure, partial calcination, and heat related fracturing
8= widespread calcination and fragmentation

Categories/Scoring for Long bones =__________

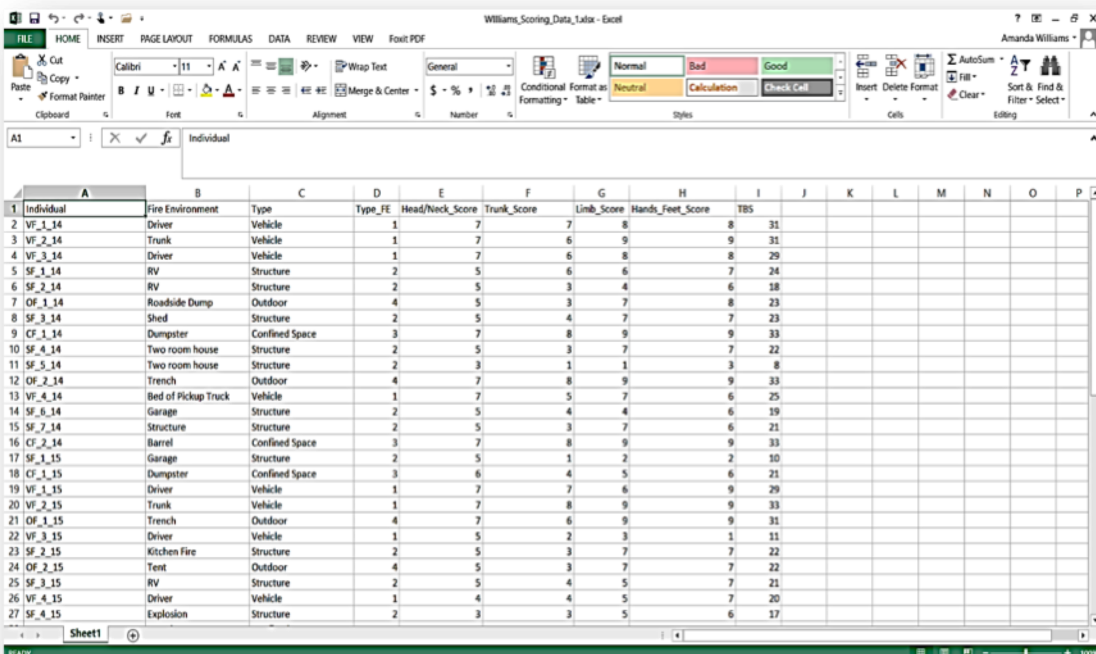
1= no charring, fresh body
2= blistering and some skin splitting is present (e.g. distal or proximal ends)
3= skin splitting is widespread across all long bones, with partial charring of tissues, and less than 50% subcutaneous fat exposure
4= widespread subcutaneous fat exposure, with partial charring of tissues
5= widespread charring of tissues on all long bones, with muscle exposure
6= puglistic posture
7= partial bone exposure and charring of bone
8= widespread bone exposure, partial calcination, and heat related fracturing
9= widespread calcination and fragmentation

Categories/scoring for Hand and Feet =_______

1= no charring, fresh body
2= blistering and partial skin splitting is present
3= widespread skin splitting on both hands and feet, with less than 50% subcutaneous fat exposure
4= widespread subcutaneous fat exposure, with partial charring of tissues
5= widespread charring of tissues, with muscle exposure
6= pugilistic posture
7= partial bone exposure and charring of bone
8= widespread bone exposure, partial calcination, and heat related fracturing
9= widespread calcination and fragmentation

= ______/33 pts (Possible)

When evaluating alterations, partial represents any alteration that covers less than 50% of the surface area in that region. Widespread represents any alteration that covers greater than 50% of the surface area. The highest scores that could be assessed were always used. For example, scores that appear to be right at 50% of the surface area were assigned the higher score. If the lower limbs exhibited bone exposure, but the upper limbs did not, the score reflected the highest degree of thermal alteration to that region. Once the visual analysis was completed, all scores for each region were added together to form a TBS. This visual assessment was made on all observational data to identify if any significant patterns existed between degree of thermal alterations and fire environment. Once visual analyses were complete, all data was subject to statistical analyses to identify key patterns. Scores were then added into an excel table and subject to further analyses (see Figure 1).



Individual	Fire Environment	Type	Type_FE	Head/Neck_Score	Trunk_Score	Limb_Score	Hands_Feet_Score	TBS
VF_1_14	Driver	Vehicle	1	7	7	8	8	31
VF_2_14	Trunk	Vehicle	1	7	6	9	9	31
VF_3_14	Driver	Vehicle	1	7	6	8	8	29
SF_1_14	RV	Structure	2	5	6	6	7	24
SF_2_14	RV	Structure	2	5	3	4	6	18
OF_1_14	Roadside Dump	Outdoor	4	5	3	7	8	23
SF_3_14	Shed	Structure	2	5	4	7	7	23
CF_1_14	Dumpster	Confined Space	3	7	8	9	9	33
SF_4_14	Two room house	Structure	2	5	3	7	7	22
SF_5_14	Two room house	Structure	2	3	1	1	3	8
OF_2_14	Trench	Outdoor	4	7	8	9	9	33
VF_4_14	Bed of Pickup Truck	Vehicle	1	7	5	7	6	25
SF_6_14	Garage	Structure	2	5	4	4	6	19
SF_7_14	Structure	Structure	2	5	3	7	6	21
CF_2_14	Barrel	Confined Space	3	7	8	9	9	33
SF_1_15	Garage	Structure	2	5	1	2	2	10
CF_1_15	Dumpster	Confined Space	3	6	4	5	6	21
VF_1_15	Driver	Vehicle	1	7	7	6	9	29
VF_2_15	Trunk	Vehicle	1	7	8	9	9	33
OF_1_15	Trench	Outdoor	4	7	6	9	9	31
VF_3_15	Driver	Vehicle	1	5	2	3	1	11
SF_2_15	Kitchen Fire	Structure	2	5	3	7	7	22
OF_2_15	Tent	Outdoor	4	5	3	7	7	22
SF_3_15	RV	Structure	2	5	4	5	7	21
VF_4_15	Driver	Vehicle	1	4	4	5	7	20
SF_4_15	Explosion	Structure	2	3	3	5	6	17

Figure 1. Images of tables with example of data collected.

The excel table included columns on the individual, fire environment, Head/Neck Score, Trunk Score, Limb Score, Hands/Feet Score, and TBS. A separate excel table was developed for analyzing exposure time, temperature, and TBS. Each column was taken and evaluated for how likely it contributes to estimating fire conditions.

Statistical Analyses

The data collected from each field season was subjected to statistical analyses to identify patterns between physical alterations of remains, environment, time, and temperature. A power test was performed to determine if additional experimental data was needed (See Appendix, Figures 1-3). All statistical analyses were performed using the statistical software programs G*Power, SPSS-24, and R. Statistical analyses used to identify patterns were Pearson's chi-squared test, multinomial linear regression, and Bayesian statistical analyses. Chi-square tests can be used to establish significant relationships between variables. Therefore, Chi-square tests were performed to see what burn scores associated best with which fire environment. However, depending on the data, it may not adequately capture all the information. For example, if the data involve summing scores, it might obscure the distinction between classifying patterns. A logistic regression analysis would be a better approach in building formulas that combine the scores to classify patterns more effectively.

Multinomial logistic regression analysis provides a way analyze how well these variables classify to the appropriate fire environment. Therefore, logistic regression analyses were also performed, as they provide a better approach in classifying patterns more effectively. Linear regression models were also utilized to determine which physical alterations to the body can best be used to predict fire environment, and exposure time to a fire. The linear models were set up to allow for interaction among variables, i.e. time and temperature, in predicting their significance in the equation. The models used temperature and time as the independent variables and the physical alterations as the dependent variables. Variables that yielded a strong correlation with one another were taken and added into a separate model for predicting fire-related conditions. If significant differences were found, the variables were added into a predictive model, which can be used to better predict when and at what temperatures these physical alterations may occur on the human body.

Temperature data was recorded on the body, and in multiple locations within each fire environment, as described above. The data used in this study came from thermocouples placed only within the body. Temperatures were documented at the highest (e.g. the ceiling) and lowest point (e.g. the floor), but this data was not used in this study. Temperatures were recorded every minute during the duration of the burn. Unfortunately, some thermocouples may have dislodged and fallen out during the burn. The dislodging of thermocouples created inconsistencies within the data. Some individuals may have approximately 60 minutes of temperature data, while others have less than 10 minutes. Individuals that had less than 5 minutes of temperature data were excluded. In addition to missing temperature data, thermocouples were not always placed in the same location and at the same depths on the body. Therefore, it could introduce error into the model. Some individuals were directly placed after being refrigerated allowing no time to thaw, while others were allowed several minutes to thaw. Therefore, there were notable differences between temperatures locations on the body, and between individuals who were burned shortly after being placed, compared to those who were allowed to thaw. It was decided the bodily temperature data would not be used due to the inconsistencies in data collection. Instead, this study relied on known temperature data based on published findings from each type of fire environment (Flynn 2009, Kerber 2012, Lentini 2012; 2013, Morgan et al. 2008). The known temperature data was taken and compared with the temperature data collected to create a minimum and maximum temperature range for each fire environment. To account for this variability, average temperature ranges were used for each type of fire environment. In using the mean, it minimizes the potentially for introducing bias into the study, which could result in the models underestimating or overestimating time. Similar approaches of using mean temperatures have been applied to studies estimating a post-mortem interval (PMI). For example, Megyesi and colleagues (2005) incorporated daily average temperatures from the National Weather Service, as it was more readily available and more realistic to actual forensic cases. Even using daily averages from weather station data, their model performed much more accurately than other post-mortem interval models that used specific temperature data. A similar approach was applied in this study as a means to address the inconsistency in temperature data, and to minimize the potential for bias and error.

Additionally, multiple linear regression analyses can be performed using the non-missing values, and through imputation processes estimate the missing values. Multiple linear regression can give a more precise estimate of what the missing temperature point might be. Though to minimize bias, it was preferred that the researcher use mean temperatures in place of missing data points. The linear model(s) created were used to identify which variables contribute significantly to the outcome and exclude those variables that show little to no significance to the burn process. Given the nature of the data set, Bayesian analyses were also performed to account for uncertainty in the data set, reduce bias, and to test the probability that each model would produce the intended outcome.

Bayesian statistical approaches provide an alternative way to account for uncertainty in data. This statistical approach provides an estimate or probability that a specific outcome will be produced, given a set of data. This type of analysis is useful in making predictions, detecting anomalies in data, and refining models to name a few (Konigsberg et al. 1998, Konigsberg 2015, Kruschke 2011, Langley-Shirley & Jantz 2010). Bayesian approaches are often applied in context where there is an observable set of conditions that one makes to predict an unknown context, outcome, or future. This statistical technique provides an avenue for mathematically expressing uncertainty, while still allowing for inferences to be made from the data. This approach also relies on having a "priori," which comprises all outside notions about the data. Once observations are made, modifications are made mathematically based on the observed data. It is through these observations that refining of parameters takes place. To increase the likelihood of a specific outcome, parameters can be added or removed to increase the likelihood of a given outcome. A Bayesian approach was applied to this study, as it provides a way to estimate the probability that the conditions of remains can predict a given outcome, which in this study would be time and fire environment.

Bayesian models were also relied upon as they provide a better way to describe relationships among complex datasets, allow for missing data, provide a means to account for uncertainty in estimates, and allow for comparisons between models (Konigsberg and Frakenberg 2013, Lynch 2006, Thevissen and Willems 2009). Similar Bayesian approaches have been used in biological anthropology including: calculating age at death estimates, estimating number of individuals within a comingled site, and paleodemographic studies within bioarcheology (Chamberlin 2000, Godde 2017, Hoppa & Vaupel 2002, Konigsberg & Herrman 2002, Langley-Shirley & Jantz 2010, Seguey et al. 2013). This statistical method was applied to account for missing data, varying sample sizes within each fire environment, and to aid in making interpretations between fire environments. This model allows the researcher to evaluate relationships between variables, by estimating the likelihood that an outcome would occur given a set of established parameters (Konigsberg and Frakenberg 2013, Konigsberg et al. 1998, Lynch 2006, Thevissen and Willems 2009). Given the nature of this data set, a Bayesian analysis was better suited for analyzing relationships between variables than the other analyses. A Bayesian approach allows for the inclusion of multiple parameters, and through the use of deductive processes the ability to refine a model. Similar analyses have been applied in age-estimation methods using dental wear, auricular surface, and pubic symphysis changes to name a few (Godde 2017, Kimmerle et al. 2008, Konigsberg 2015 Langley-Shirley & Jantz 2010, Thevissen and Willems 2009). Each of these methods relied on assessing visual changes or age-related changes in each of these regions, in estimating age at death. These studies take known conditions, like wear patterns, and predict the unknown, which would be age at death (Godde 2017, Kimmerle et al. 2008, Konigsberg 2015, Langley-Shirley & Jantz 2010). Each of these analyses relied upon the Markov Chain Monte Carlo method or constructing a hierarchical prior. These Bayesian analyses are better suited for estimating likelihood from large samples or data that contain two or more dependent parameters (Konigsberg 1998, 2015; Kruschke 2011). A similar approach was followed in this study, where known conditions of burned remains were used in predicting fire environment and exposure time to a fire. By incorporating a Bayesian approach, one can minimize bias and produce a more well-rounded model that takes into account all variables contributing to the outcome. A Bayesian approach aids in narrowing down parameters for given outcomes, and in establishing a predictive model. The summary statistics generated from each analysis illustrate which interactions were statistically significant and which variables are strongly correlated. A Bayesian analysis can determine how strongly the data is likely to predict an outcome. Based on the results, parameters that are not significantly contributing to the given outcome, can be removed to increase probability. The results can be used to adjust the parameters to develop a model with high probability.

Similar statistical approaches have been used to construct models for estimating post-mortem interval in decomposition studies (Bass 1997, Galloway et al. 1989, Love & Marks 2003, Mann et al. 1990, Meygesi et al. 2005, Swift 2010, Vass 2011). The same analyses can be applied to this study in estimating exposure time to specific fire-related conditions. The analyses would produce formulas per environment that could be used to estimate exposure time to a fire. The accumulated degree minutes model accounts for time, temperature, degree of charring, and other variables that are vital to providing an estimate of how long the individual may have been exposed to the *in situ* conditions.

Thus, this study focused on identifying variables that can be used to construct an Accumulated Degree Minutes model, or a similar measure (Accumulated Thermal Minutes for example), based on measured *in situ* conditions. Accumulated Degree Minutes is a model that will comprise those variables, i.e. time and temperature, found to be statistically significant in contributing to the burn process.

Creation and Validation of New Model

These data led to the creation of a new classification system for analyzing burned remains and a model for estimating exposure time to a fire. The new scale encompasses the changes observed during the burning process, adding in additional variables of time, temperature, muscle exposure, fat exposure, and presence or absence of protruding organs. It is important each model is validated and tested for the likelihood of misclassifying an individual, which is essential for being defended in court. The new classification method and ADM model must be tested on a separate sample of case studies to determine how well it is performing on known cases, and to produce a likelihood of misclassifying an individual. To validate the new models created, this study was tested on photos of burned remains from known conditions provided by medical examiner/corner offices. The researcher analyzed photos provided by the Montana State Crime Lab, in Missoula, MT, and from select cases provided by Mercyhurst University. A total of 105 cases were provided for a comparative sample data set. The researcher analyzed each of the fatal fire cases based on the criteria established in the new classification system. Upon completion of the researcher's initial analysis, details surrounding the fire environment were provided and used for further analysis. The results from the predictive model were compared with the known conditions or reports to evaluate how accurate the model is in estimating exposure to fire-related conditions. This test allowed for a validation of the method and helped provide error rates, which are vital for methods used in forensic anthropology.

The opportunity to collaborate with the SLOFIST program provided a unique opportunity to conduct controlled scientific research on human remains that allowed for the creation of these models at a level that has never before been attempted. This chapter described how hypothesis one and two were tested through experimental observations, and used to establish a quantifiable scoring system and predictive model. Chapter two outlined how data was generated in deriving a new classification model, and what variables were used in making assessments. In addition, this chapter discussed how multiple linear regression analyses and Bayesian statistical models were used in narrowing down variables and establishing significance. These statistical approaches were taken to help identify what variables were significantly correlated and, thus would best predict fire conditions. These variables were then used to develop a predictive model that can estimate fire-related conditions based on the burn pattern found on human remains. This chapter also described how these models were tested on a known sample of fatal fire cases from various medical examiner/corner offices. This chapter demonstrates the intricate relationship between temperature, time, and heat-related changes on the human body. It is through applying these methods, models, and approaches that one gains a better understanding of the differing fire environments, and how it is possible to model heat-related changes. The information gained from each model can be used to better predict when and at what temperatures these physical alterations may occur on the human body. More importantly, it enhances our understanding of the physical alterations that a body undergoes when exposed to a fire. The ensuing chapters outline the findings from this study, and describe how well these new models work on modern day fatal fire cases.

Chapter Three

The following chapter is written with the intent to be published separately as a book chapter. This upcoming book chapter focuses on classification systems for analyzing burned human remains, and the need for a new model. This publication will introduce the new model developed as a part of this research and discuss its impact on the medico-legal community. Therefore, some background information is reiterated in this chapter for the purpose of this future publication.

A New Classification System

This chapter describes the need for a more broadly applicable classification system within the forensic community. The following discussion explains how the new classification system was developed and how it can be best applied to fatal fire deaths. This classification system was derived as a means to better assess fatal fire deaths that are more representative of the type of fatal fire cases (like vehicle or structure fires) that the medico-legal community may examine. Previous classification models (Baby 1954, Eckert et al. 1988, Glassman and Crow 1996) are limiting in the scope and reach of their analyses, thus they are not used today. This model was developed to bridge the gap between forensic practitioners and anthropologists who many examine the same set of remains, by offering a method that can be more widely used. There is a need for a more robust model that accounts for both soft tissue and skeletal changes, and quantifies the amount of thermal damage present on a set of remains. The following discussion highlights how the model was derived and how it can be used to model heat related damage. This chapter concludes with a discussion on several case studies and how to best apply this new method to fatal fire deaths.

Need for New Model within the Forensic Sciences

There is a need within the forensic community to develop a classification system that can be more broadly applied to a wide range of fire environments. Previous classification models were derived from specific contexts, like cremations, or the 1993 events at Waco, TX, which made it more challenging to apply them to broader fatal fire cases. Given these models were derived from specific environments, they do not include all aspects of the thermal alteration process, and therefore are not used today (Baby 1954, Eckert et al. 1988, Glassman and Crow 1996). These models attempt to capture the burning process within five or less stages and provide little to no means of quantifying the amount of damage present on a human body.

Baby (1954) derived a classification model based upon his analysis of cremated burials at Hopewell and Adena sites. Baby's (1954) model provides three general categories for classifying remains. These categories include terms like "completely incinerated," "incompletely incinerated," and "non-incinerated" (Baby 1954: 2). Given the context, this classification model accounts primarily for the latter stages of the thermal alteration process, which are the most likely alterations to occur with cremations. Descriptions of soft tissue alterations are relatively absent in Baby's classification system, therefore rendering it inapplicable to broader fatal fire cases. Ekert and colleagues (1988) model was also derived from cremation cases and severely burned remains. Their model evaluated severely burned remains using descriptive terms like “complete,” “incomplete,” “partial,” and “charred.” This model also accounted for very little soft tissue changes, other than the presence of organs. The lack of soft tissue variables limited its applicability to broader fatal fire cases, thus it is not used today. Glassman and Crow (1996) also developed a classification system as a means to assess the remains recovered from the events at Waco, Texas. The Crow-Glassman model expanded descriptions just beyond impartial and complete, to include further elaboration on skeletal and soft tissue alterations, including descriptions like blistering and charring. However, this model still lacks descriptions of many soft tissue alterations, including skin splitting, subcutaneous fat exposure, muscle exposure, to name a few. Within each stage of the Crow-Glassman (1996) scale, there is often overlap in descriptions with little focus on each bodily region. The stages are broadly described, with the progression of thermal alterations progressing quickly from one to five in set stages. The lack of inclusion of all thermal alterations and the quick progression of stages, limits the applicability of this model to broader fatal fire cases. For example, in the Crow-Glassman scale (1996), descriptions of the remains are generally described, like “severe” damage to arms or legs, or “small” portion of arms and legs are damaged. The general description of terms “severe” and “small” allow for subjectivity to be entered into the analysis. Therefore, these stages cannot be consistently applied across all fire environments. The stages attempt to describe the overall damage of the human body, by a numerical stage, rather than breaking the assessment down further. The descriptions provided often were derived from entire sets of remains, rather than per each bodily area. Each of the previous models attempted to describe the condition of the remains by utilizing stages. The stages primarily focused on the later sequences of thermal alteration process, including calcination and fragmentation, with little to no descriptions of blistering, skin splitting or other soft tissue alterations. None of the previous models contained descriptions that went beyond five stages. The lack of a more detailed model limits the applicability of previous models to modern day fatal fire cases. Within anthropology, there is a need for a new classification model that assesses thermal alterations per bodily region and attempts to not only describe the amount of damage present, but also seeks to quantify it.

Additionally, medico-legal models (e.g. rule of nines) have attempted to minimally quantify the amount of surface area affected on a human body. Pathologists analyze burned remains by evaluating the amount of surface area affected (TBSA), and calculating a percentage. These models do incorporate more of a bodily region approach, however they do not account for the hands and feet in their estimates. These approaches are not applied in situations where bone is exposed, therefore limiting its applicability to a wider range of fatal fire cases. Therefore, there is a mismatch in the way pathologists describe thermal alterations to a body, and the way anthropologists describe thermal alterations to a set of remains. Within anthropology, there are very few models that exist for describing burned remains, outside of cremation contexts. Unfortunately, the models that do exist are limited in their scope, and do not cover the wide arrange of thermal alterations known to occur. There is a need to develop a more broadly applicable method that can be more consistently applied within the forensic community, while also providing a more quantitative approach to describing thermal alterations. Previous models are primarily descriptive, with little to no attempt at quantifying the amount of thermal damage on a human body. Thus, this study aims to develop a classification model with a more quantifiable approach that can be used to model the amount of heat related damage and can be used to infer about *in-situ* conditions.

Creation of a New Classification System

Unlike previous models, this new classification system is derived from experimental observations of burning human cadavers. Prior models (Baby 1954 & Eckert et al. 1988) were based on cremations or severely burned cases, illustrating why there is a lack of soft tissue alterations represented in many of the descriptions. By using experimental observations, the entire thermal alteration process can be captured and incorporated into the new classification system. This model is based on experimental data of burned human cadavers that comes from a range of fire environments, including structure, vehicle, confined space, and outdoor fires. Experimental observations were conducted as a part of the San Luis Obispo Fire Investigation Strike Team training (SLOFIST) course. Each year SLOFISTS conducts a fatal fire death investigation course for forensic professionals in examining fatal fire deaths and scenes. The course involved the burning of donated human remains (e.g. training aids) in vehicle, structure, outdoor, and confined space fire contexts. Data collected during this training course comprised approximately 87 individuals. The burning process was recorded and documented, along with a visual assessment of the burned remains.

The progression of thermal damage to the human body was noted, and formed the basis for the development of this new classification system. The classification system begins with a “fresh” stage or unburned stage and progresses through the thermal alteration process. The lower scores on this new classification system represent the earliest stages of the burning process or those that are observed to occur first on a human body, like blistering, skin splitting, and subcutaneous fat exposure. The later scores in the classification system reflect the latter stages of the burn process, including bone exposure, calcination, and fragmentation.

From these many observations, it was noted that the body does not burn equally among all regions, therefore this classification system is broken down by bodily region to account for this variability. Other experimental observations have noted the hands and feet tend to be one of the first elements to burn and expose bone, followed by the frontal region of the skull (DeHaan 2008, 2009, Pope & Smith 2004, Symes et al. 2008, Thompson & Chudak 2006). Unlike previous models, this classification system assesses thermal alterations from the skull/neck, the trunk, the long bones, and the hands/feet. This new model covers the entire range of thermal alterations from skin blistering to fragmentation in each bodily region. Each region is evaluated based on the progression of these alterations on the human body. Given the variation that is likely to exist in each region, it is unlikely that a body would be equally burned in all bodily regions, thus making it impossible to utilize previous models. The new classification system adds on to these descriptions, and provides a means to quantify the amount of thermal damage on a set of remains.

The new model draws from taphonomic studies that utilize a similar quantitative method for describing the condition of remains during the decomposition process. Many of these studies (Bass 1984, Galloway et al. 1989, Komar 1998, Megeysi et al. 2005) draw upon physical changes in the condition of the body and use it to score the progression of changes that are present. Accumulated models take the condition of the remains and provide a score per body region. Scores are added together to formulate an accumulated total body score. A similar approach was applied in the development of this new model, as it is more encompassing of the changes that can occur on a body regardless of fire environment. This new model accounts for all thermal alterations, and thus, rather than providing a percentage of surface area affected, provides an accumulated score summing all the regions. A summation of physical alterations more adequately captures the burning process, and thus, the variability that can occur.

The new classification system takes into consideration the limitations and challenges of previous models, and demonstrates a more holistic approach to analyzing burned human remains. The following method illustrates this new accumulated scoring model.

Categories/Scoring for Head and Neck =__________

1= no charring, fresh body
2= blistering and partial skin splitting is present
3= skin splitting is widespread across head and neck, with less than 50% subcutaneous fat exposure
4= subcutaneous fat exposure is widespread and muscles are exposed
5= partial bone exposure and charring to cranial elements
6= bone exposure, heat related fracturing, and partial calcination to cranial region
7= widespread calcination and fragmentation

Categories/Scoring for Trunk =_________

1= no charring, fresh body
2= blistering and partial skin splitting is present
3= skin splitting is widespread across the trunk, with partial charring of tissues, and less than 50% subcutaneous fat exposure
4= widespread subcutaneous fat exposure and partial muscle exposure
5= widespread muscle exposure and intestinal exposure
6= partial bone exposure, with charring of bone
7= widespread bone exposure, partial calcination, and heat related fracturing
8= widespread calcination and fragmentation

Categories/Scoring for Long bones =__________

1= no charring, fresh body
2= blistering and some skin splitting is present (e.g. distal or proximal ends)
3= skin splitting is widespread across all long bones, with partial charring of tissues, and less than 50% subcutaneous fat exposure
4= widespread subcutaneous fat exposure, with partial charring of tissues
5= widespread charring of tissues on all long bones, with muscle exposure
6= pugilistic posture
7= partial bone exposure and charring of bone
8= widespread bone exposure, partial calcination, and heat related fracturing
9= widespread calcination and fragmentation

Categories/scoring for Hand and Feet =_______

1= no charring, fresh body
2= blistering and partial skin splitting is present
3= widespread skin splitting on both hands and feet, with less than 50% subcutaneous fat exposure
4= widespread subcutaneous fat exposure, with partial charring of tissues
5= widespread charring of tissues, with muscle exposure
6= pugilistic posture
7= partial bone exposure and charring of bone
8= widespread bone exposure, partial calcination, and heat related fracturing
9= widespread calcination and fragmentation

= ______/33 pts (Possible)

Best Practices in Applying this New Model

This classification system can be best applied to remains that exhibit a variety of conditions, including soft tissue and skeletal alterations. When applying this new model, remains should be assessed independently per body region. Thus, this model is broken down into four main regions: the head and neck, trunk, long bones, and the hands and feet. Scores are based on the stage or condition of the remains in that specific bodily region. When evaluating remains for skin splitting, subcutaneous fat exposure, and charring to name a few, one must evaluate the alteration based on the percentage of surface area affected. One should examine each bodily region noting what alterations are present, and how much of the surface area is affected. For example, if the torso region exhibits widespread charring, muscle exposure, and intestinal exposure, then one would score the individual at a stage five. Given intestinal exposure was the highest thermal alteration observed, and no bone exposure was found, it would not be scored any higher on this new model. Each scoring stage encompasses terms such as partial and widespread to describe the amount of surface area covered. Partial represents alterations that cover less than 50 percent of the surface area, whereas widespread represents alterations that cover greater than 50 percent of the surface area. If a region exhibits variability in physical alterations, one should always use the highest score that can be applied. For example, if the lower limbs exhibited charring and bone exposure, but the upper limbs do not, then the highest score that could be awarded would be a seven due to bone exposure being present on the lower limbs.

Once scores are recorded for each region, they are added together to form a total body score (TBS). The following case studies illustrate how to best apply this new classification system.

Case Study #1

Case study #1 comprises an individual that was recovered from a vehicle fire. The new model described above was used in creating a total body score to describe the condition or state of the remains. This individual exhibited calcination on the mandible, the frontal portion of skull, the left zygomatic, and the left maxilla (see Figures 3 & 5). Calcination was found on some regions of the skull, but not all, and did not comprise over 50 percent of the surface area. Given there were regions on the skull that did not have any calcination or bone exposure present, this individual was scored at a stage six on this new model.

When evaluating the trunk region, this individual had widespread muscle exposure from the sternum down through the ribs that covered greater than 50 percent of the surface area. This individual also had widespread subcutaneous fat exposure and intestinal exposure (see Figures 3 & 4), thus was scored at a stage five. Given, there was no bone exposure present in this region, the trunk was not scored higher on this new model.

When evaluating the long bones, the arms exhibit widespread muscle exposure, with some bone exposure on the lower right arm (see Figure 3); whereas the legs exhibited muscle exposure and widespread charring (see Figures 3 & 6). Given there was bone exposure on the right arm, this individual was scored at a stage seven. There was not enough widespread bone exposure or calcination on the limbs to be scored any higher.

When evaluating the hands and feet, the hands exhibited muscle exposure, charring, with the right hand exhibiting some bone exposure (see Figure 3). The feet exhibited widespread charring, with little to no bone exposure (see Figure 6). Given the right hand exhibits partial bone exposure and charring, this individual was scored at a stage seven. Scores from all regions were added together (6 + 5 + 7 + 7), and this individual was given a total body score of 25.

Figure 3. Individual with intestinal exposure (highlighted in blue box above), and bone exposure on right hand (yellow arrow above).

Figure 4. Individual with widespread muscle exposure and intestinal exposure.

Figure 5. Individual with calcination to frontal, mandible, and left zygomatic.

Figure 6. Individual with charring and muscle exposure on left lower limb and foot.

Case Study #2

Case study #2 comprises an individual recovered from a structure fire. This individual exhibited calcination on the frontal, both parietal bones, and the temporal region of the skull (see Figures 8 & 9). No calcination was observed on the mandible, maxilla, or the zygomatics. Given there is partial calcination and bone exposure, this individual was scored at a stage six in the head and neck region. There was not enough calcination and fragmentation to score this region any higher.

When evaluating the trunk, this individual exhibited an unburned region that comprised greater than 50% of the surface area on the left side of the torso (see Figures 7 & 10), with partial charring of tissues on the right side. Given there is a portion of the torso that exhibits charring, this individual was scored at a stage three. There was not enough subcutaneous fat exposure, muscle exposure, or intestinal exposure to score this region any higher.

When evaluating the limbs, the legs exhibited widespread muscle exposure that comprised more than 50% of the surface area (see Figures 7 & 11). The arms also comprised widespread muscle exposure, with some bone exposure and calcination to the right arm only (see Figures 10 & 12). Given the presence of some bone exposure and calcination, this individual was scored at a stage eight.

When evaluating the hands and feet, the feet exhibit widespread muscle exposure and charring; whereas the hands exhibit bone exposure, calcination, and the pugilistic posture (see Figures 11 & 12). Given the right hand exhibits calcination and fragmentation, this individual is scored at a stage eight. Scores from all regions were added together (6 + 3 + 8 + 8), and this individual was given a total body score (TBS) of 27.

Figure 7. Individual with calcination on skull and right hand (highlighted in blue box above).

Figure 8. Individual with calcination on frontal, both parietals, and a portion of the temporal bone.

Figure 9. Individual with little to no calcination on mandible, zygomatics, or maxilla.

Figure 10. Individual with partial charring on torso.

Figure 11. Individual with muscle exposure and charring on lower limbs and feet.

Figure 12. Individual in the pugilistic posture, with calcination on right hand.

Case Study #3

Case study #3 comprises an individual recovered from a structure fire. This individual exhibited widespread (greater than 50%) charring and muscle exposure across all regions of the skull, with some bone exposure on the frontal region (see Figures 13 & 15). Given, there is some bone exposure present, this individual was scored at a stage five.

When evaluating the trunk, the torso exhibited less than 50% charring across the total surface area, with intestinal exposure (see Figures 13 & 15). Given the intestines were exposed, this individual was scored at a stage five.

When evaluating the limbs, the legs exhibited partial (less than 50%) subcutaneous fat exposure and muscle exposure, with bone exposure on the left tibia (see Figure 14). The arms exhibited widespread muscle exposure and charring, but no bone exposure (see Figures 15 & 16). Given there is bone exposure and charring on the left Tibia, this individual was scored at a stage seven.

When evaluating the hands and feet, the hands exhibited the pugilistic posture, whereas the feet exhibited bone exposure and charring of bone (see Figures 15 & 16). Given there is charring of bone on the feet, this individual was scored at a stage seven. Scores were added all together (5 + 5 + 7 + 7), and this individual was given a total body score of 24.

Figure 13. Individual with limited (less than 50%) charring to torso.

Figure 14. Individual with muscle exposure, subcutaneous fat exposure on lower limbs, and bone exposure on feet.

Figure 15. Individual exhibiting pugilistic posture in both hands, and intestinal exposure (highlighted in blue box).

Figure 16. Individual with widespread charring and bone exposure.

Case Study #4

Case study #4 comprises an individual recovered from an outdoor context, specifically a trench. The individual had been burned in a trench and then buried. This individual exhibited widespread calcination and fragmentation across all regions of the body (see Figure 17). When evaluating the head and neck region, this individual exhibited widespread calcination to the frontal, both parietals, both temporal bones, and the occipital region (see Figures 17-19). Given calcination comprised greater than 50% of the surface area on the skull and mandible, this individual was scored at a stage 7.

When evaluating the trunk, this individual exhibited partial calcination and fragmentation to the ribs and sternum area of the torso (see Figures 17 & 19). Given there was a large portion of muscle still present in this region, the remains were not considered to exhibit widespread calcination and therefore were scored at a stage 7.

When evaluating the long bones, this individual exhibited widespread calcination and fragmentation to both the upper and lower limbs (see Figures 19 & 20). The individual exhibited calcination, heat related fracturing both on the humerus, femur, and tibia. Given the remains were in a highly fragmented and calcined state, it was considered to be widespread, and therefore the remains were scored at a stage 9.

When evaluating the hands and feet, this individual exhibited widespread calcination and fragmentation (see Figure 17). Given the high degree of fragmentation and calcination present, this individual was scored at a stage 9. Scores were added all together (7 + 7 + 9 + 9), and this individual was given a total body score of 32.

Figure 17. Individual with widespread calcination and fragmentation (blue box highlights fragmentary remains of hands & feet).

Figure 18. Individual with widespread calcination and fragmentation to the frontal, both parietals, temporal, and occipital regions of the skull.

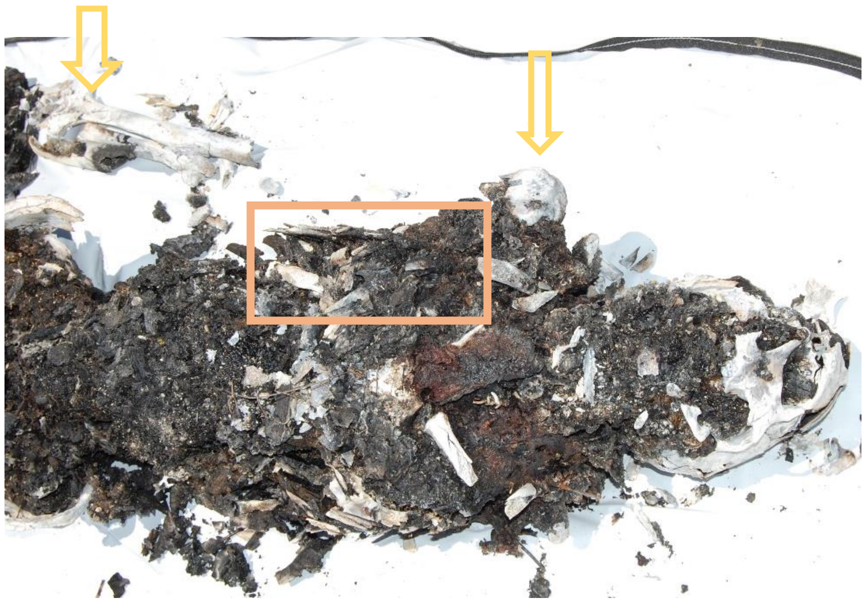


Figure 19. Individual with calcined and fragmented ribs (highlighted in orange box above), and a right proximal and distal humerus (yellow arrows above).

Figure 20. Individual with a fragmented and calcined distal femur and proximal tibia (highlighted in orange box above).

Case Study #5

Case study #5 comprises an individual from a garage fire or structure fire. This individual exhibited widespread muscle exposure on the neck and craniofacial regions, with some bone exposure and charring to the partial bones and mandible (see Figure 21). Given there is only partial bone exposure and no calcination present, this individual was scored at a stage 5.

When evaluating the trunk, this individual exhibited widespread skin splitting and subcutaneous fat exposure on the torso (see Figure 22). Given there was no partial muscle exposure or bone exposure in this region, this individual was scored at a stage 3.

When evaluating the long bones, this individual exhibited widespread muscle exposure on the upper limbs, and partial skin splitting and limited charring to the lower limbs (see Figures 22-24). Given the upper limbs exhibited widespread muscle exposure, the highest score that can be awarded for this individual is a stage 5.

When evaluating the hands and feet, this individual exhibited differential charring in these regions. The hands exhibited the pugilistic posture, widespread charring and muscle exposure, while the feet exhibited partial skin splits with little to no charring (see Figures 22-24). Given the hands exhibited the pugilistic posture, this individual was scored at a stage 6. No bone exposure or charring of bone was found in either the hands or feet, so this individual was not scored any higher on this new model. Scores were added all together (5 + 3 + 5 + 6), and this individual was given a total body score of 19.

Figure 21. Individual with bone exposure on skull (yellow arrow above), and muscle exposure on neck and upper arm regions.

Figure 22. Individual with widespread muscle exposure to upper arms (yellow arrow above).

Figure 23. Individual with partial charring on lower limbs.

Figure 24. Individual with partial skin splitting, and little to no charring on feet.

Summary

This chapter highlighted the need within the forensic sciences for a new classification system for analyzing burned human remains. Previous models provided limited descriptions of thermal alterations, and thus are not widely used today. Previous models (Baby 1954, Eckert et al. 1988, Crow & Glassman 1996) progress quickly through the sequence of thermal alterations, often only including a limited amount of soft tissue variables in their descriptions. There is a need within the forensic community for a new classification system that is more broadly applicable to fatal fire cases. This study developed a new model based on experimental observations surrounding vehicle, structure, confined space, and outdoor fire contexts. These settings provide a more representative sample of the cases that the medico-legal community are likely to examine. The model developed covers the entire range of thermal alterations from skin blistering to fragmentation. The model also assess alterations per bodily region, and provides a total body score to describe the nature of the remains. This chapter described how the new classification system was derived and demonstrated how to best apply this new classification system to fatal fire deaths. The case studies mentioned above illustrate how one would go about using this new model to assess thermal alterations. In contexts where alterations may vary between elements (e.g. upper and lower limbs), it is advised that one should use the highest score possible. Once scores are assessed for each region, they are added together to formulate a total body score (TBS). Total body scores are then taken and added into a model to predict fire conditions and timing of death events.

The following chapters evaluate these bodily scores and assess whether there are any significant relationships between temperature, time, and type of fire environment. Significant variables will be taken and used to create a model for estimating *in-situ* conditions. The ensuing chapters discuss the statistical findings from this study and its implications to the forensic community.

Chapter Four

Results

This chapter outlines the results from the visual assessment of the burned remains, and the results from the statistical analyses that were performed. The chapter discusses how there were notable differences between time, temperature, and bodily conditions in each fire environment. The ensuing discussion describes how these visual patterns were tested quantitatively to determine if similar patterns could be distinguished and therefore used in a predictive model. A chi-square test was performed to test for significant relationships between bodily scores, total body score, time, temperature, and fire environment. A multiple regression was performed to determine which physical alterations to the body can best be used to predict fire environment, and exposure time to a fire. The linear model(s) created were used to identify which variables contribute significantly to the outcome and exclude those variables that show little to no significance to the burn process. The summary statistics generated from each analysis illustrates which interactions were statistically significant and which variables were strongly correlated. Variables that yielded a strong correlation with one another were taken and added into a separate model for predicting fire-related conditions. If significant differences were found, the variables were added into a predictive model, which can be used to better predict when and at what temperatures these physical alterations may occur on the human body. The following discussion describes the results that were found.

Power Tests

A post-hoc test was performed on a sample of 57 individuals to determine if additional data would be needed to adequately predict an effect between variables without attributing it to chance. A power test was performed on the existing data set using the G*Power software program (Faul et al. 2007). With a sample of approximately 57 individuals to begin with, the power error probability is -0.5449 (see Appendix, Figure 1). This result suggests more samples are needed to adequately predict an effect between physical alterations and fire environment. The power for this sample needs to be 0.80 or greater to not attribute an effect to chance (Faul et al. 2007). Additional power tests were performed to determine the minimum and maximum number of individuals needed (see Appendix, Figures 2-3). In the social sciences, 0.8 is considered a sufficient power level to analyze an effect (Cohen 1991; Faul et al. 2007). To achieve a power of 0.80, the sample would need to contain a minimum of 90 individuals, which would produce a good ability to detect an effect between variables. To achieve a power of 0.95, the sample would need to contain a maximum of 138 individuals, which is considered an excellent ability to detect an effect. The power test suggests the experimental sample needs to be increased by a minimum of 30 individuals and a maximum of 80 to adequately capture an effect between variables. An additional 30 individuals were added to the sample for a total of 87 individuals.

Visual Assessment of Remains

This study found all four fire environments displayed varied levels of thermal damage, including notable differences within each environment. The amount of thermal damage to remains was correlated with maximum temperatures and exposure times in each fire environment see Figures 25 -27 & Table 1). Outdoor and confined space fires exhibited the longest duration of burning, followed by vehicle fires and structure fires (see Figure 25). Confined space and outdoor fire environments also exhibited the highest minimum and maximum temperatures, followed by vehicle and structure fires (see Figures 25-27 & Table 1).

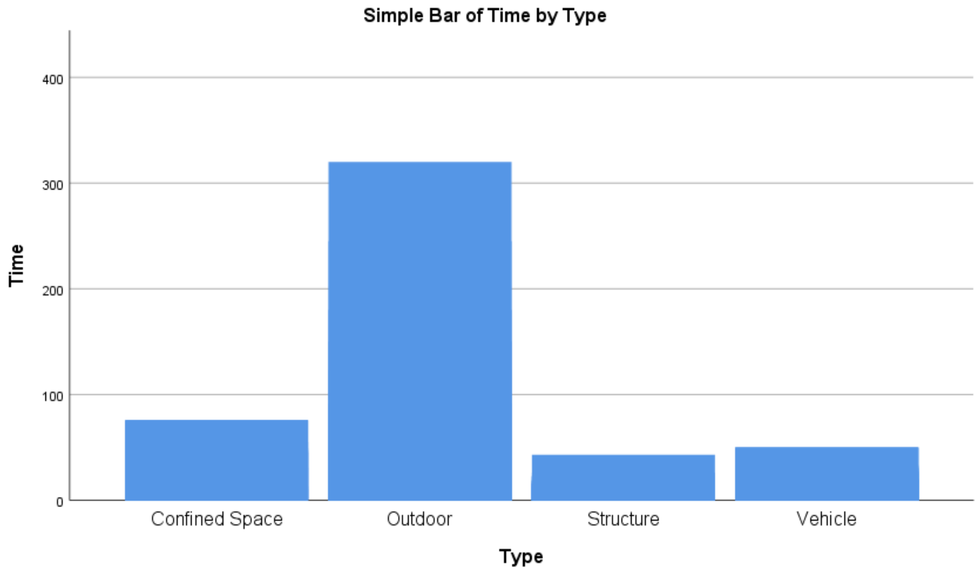


Figure 25. Illustrates a pattern between Fire Environment and duration of burn.

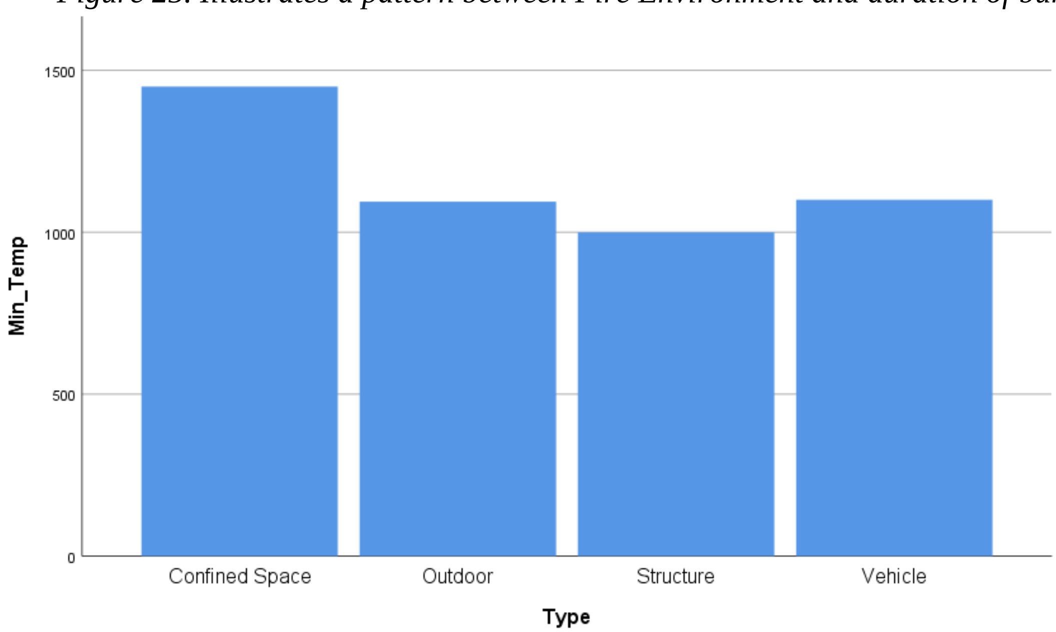


Figure 26. Illustrates confined space and outdoor fire environments exhibit highest minimum temperatures.

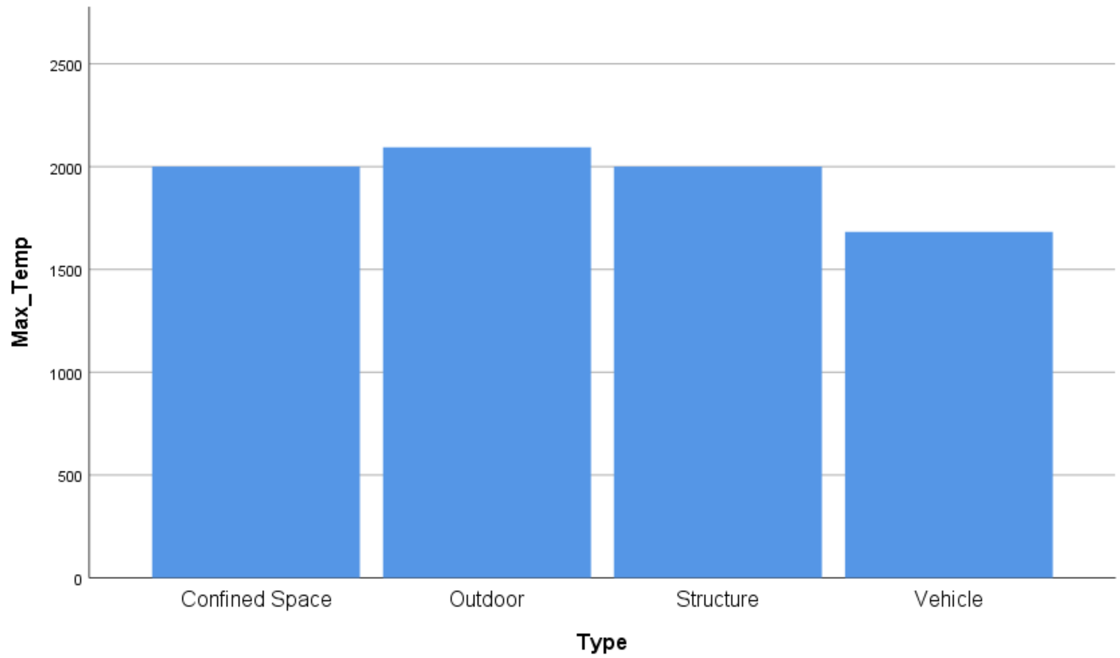


Figure 27. Illustrates outdoor and confined space fire environments exhibited maximum temperatures of 2000℉ or greater (Structure fires < 2000℉).

Confined space, vehicle, and outdoor fires also exhibited some of the highest total body scores recorded (see Figures 28 & Table 2). The highest total body scores were also found to correspond to some of the highest minimum temperatures (see Tables 1 & 2). All scoring subcategories, including head and neck score, trunk score, limb score, and hands and feet score, illustrated the same pattern and relationship. Confined space and outdoor fires burned on averaged between a half an hour to over an hour; with outdoor fires exhibiting the longest durations (see Figure 28). The longer the duration of the burn, the higher the body score (see Appendix, Figures 9-12). There were notable differences in total body score, time, and temperature depending on fire environment, illustrating a relationship between these variables. More importantly, it demonstrates there is a pattern between fire environment and bodily conditions, making it possible to model heat related damage. The following discussion highlights differences observed in bodily conditions among each fire environment.

Type of Fire Environment	Average Length of Burn	Average Temperature
Vehicle Fires	~25 minutes	1400°F
Structure Fires	~15 minutes	1500°F
Outdoor Fires	~88 minutes	1600°F
Confined Space Fires	~45 minutes	1725°F

Table 1. Illustrates average time and temperature per fire environment.

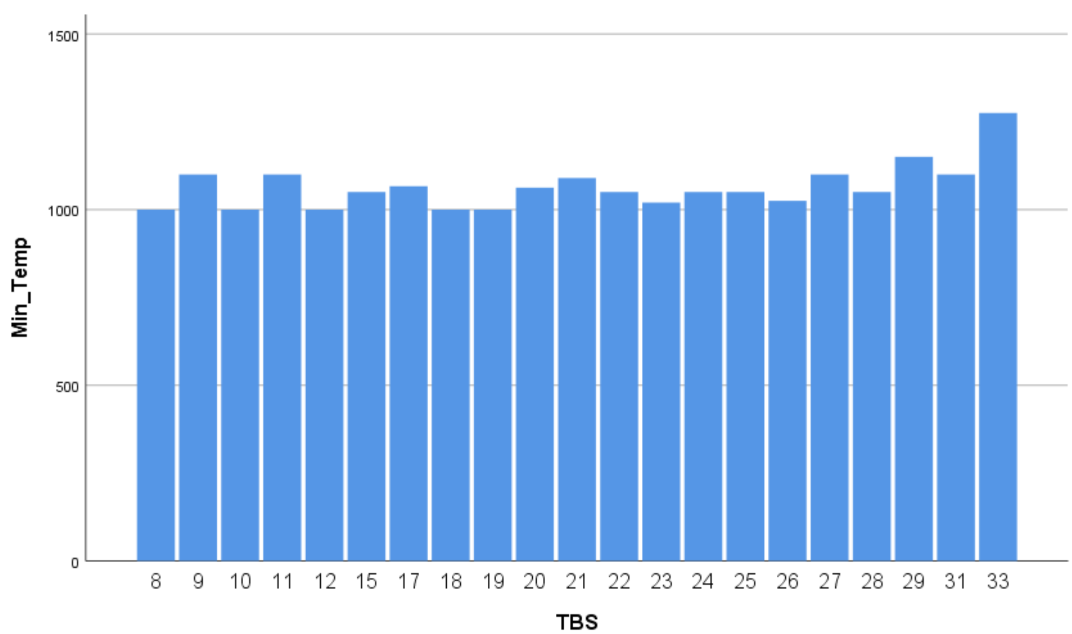


Figure 28. Illustrating a pattern between highest total body scores and highest minimum temperatures.

Fire Environment	Average TBS	Average Head & Neck Score	Average Torso Score	Average Limb Score	Average Hands and Feet Score
Vehicle Fires	24	6	5	6	7
Structure Fires	20	5	4	5	6
Outdoor Fires	28	6	6	8	8
Confined Space	31	7	7	8	9

Table 2. Illustrates average total body scores and average body scores per region based on fire environment.

Vehicle Fires

There were notable differences found between individuals burned within compartment spaces (e.g. driver's seat) of a vehicle compared to the confined space of a trunk. Individuals placed in the front seat of interior compartment of a vehicle often exhibited limited soft tissue loss in the torso region, bone exposure and calcination to hands and feet, charring and bone exposure on the frontal portion of crania, and limited bone exposure to upper and lower limbs, which is consistent with exposure to high temperatures. Individuals placed in the compartment of a vehicle exhibited total body scores that ranged from 19 to 27 with most averaging a score of 26, with 33 being the highest score possible (see Tables 2 & 3). Compartment individuals had head and neck scores ranging from 4 to 7, with most scoring on the latter end of the scale. These individuals also had torso scores ranging from 2-5, with 8 being the highest score possible. Compartment individuals exhibited limb scores ranging from 3 to 8, with most scoring on the latter end of the scale. These individuals also exhibited hands and feet scores ranging from 6 to 9, with 9 being the highest score possible (see Appendix, Figures 13-17). The major distinguishing factor between compartment and trunk individuals was the torso region. Compartment individuals tended to exhibit more soft tissue, muscle exposure and charring than trunk individuals.

Individuals placed in trunks exhibited partial to complete skeletonization, charring, calcination, and fragmentation on the: skull, upper and lower limbs, hands, and feet, which is consistent with prolonged exposure to high temperatures. These individuals exhibited total body scores that ranged from 25 to 33, with the average score being 27 out of 33 (see Table 3). Individuals recovered from a trunk setting exhibited head and neck scores that ranged from 4-7, with most scoring on the latter end of this scale. Individuals exhibited torso scores ranging from 2 to 8, with most scoring on the latter end of this scale. Vehicle fire individuals had limb scores that ranged from 6-9, with most scoring between 8 and 9 on this scale. These individuals also exhibited hands and feet scores ranging from 5 to 9, with most scoring between and 8 or 9 on this scale. Within this fire environment, trunk individuals exhibited the highest degrees of fragmentation and calcination on skull, limbs, and hands and feet, consistent with prolonged exposure to high temperatures (see Figure 29, Appendix Figures 13-17). Compartment individuals exhibited less charring to the torso region and lesser degrees of fragmentation and calcination to upper and lower limbs, which is consistent with being in a more ventilated environment.

Vehicle Fires	Average TBS	Average Head and Neck Score	Average Torso Score	Average Limb Score	Average Hands and Feet Score
Compartment	24	6	5	6	7
Trunk	27	6	5	8	8

Table 3. Illustrates average bodily scores between compartment and trunk individuals.

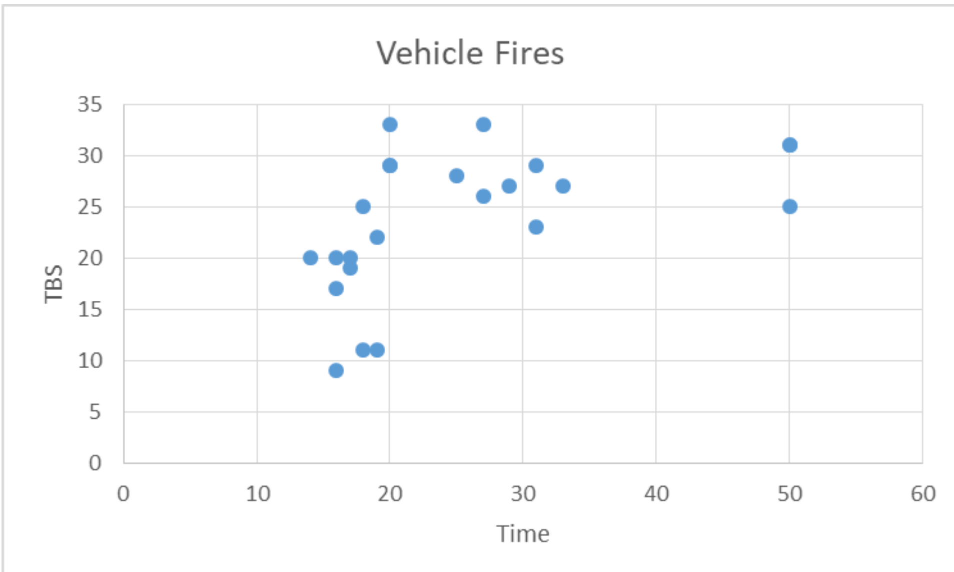


Figure 29. Scatter plot illustrates longer remains were exposed to in-situ conditions, higher the TBS.

Structure Fires

Remains from the structure fires exhibited multiple types of heat-related soft tissue changes (like skin splits, subcutaneous fat exposure, and muscle exposure) with partial soft tissue loss and minimal bone exposure at the joints of the upper and lower limbs, which produced total body scores (TBS) that ranged from 8 to 25 with most averaging a score of 20 (see Table 2 & Figure 30). This environment produced the most individuals with soft tissue still present on most regions of the body (see Appendix, Figures 13-17). Individuals recovered from this setting exhibited head and neck scores ranging from 2 to 5, with 7 being the highest score possible. The individuals exhibited trunk scores ranging from 1 to 5, with 8 being the highest score possible. Structural fire individuals also exhibited limb scores ranging from 3 to 7, with 9 being the highest score possible. These individuals also exhibited hands and feet scores ranging from 4 to 7, with 9 being the highest score possible. The presence of soft tissue alterations (like skin splits and subcutaneous fat) and minimal bone exposure is consistent with shorter exposure times to high temperatures (see Figure 30).

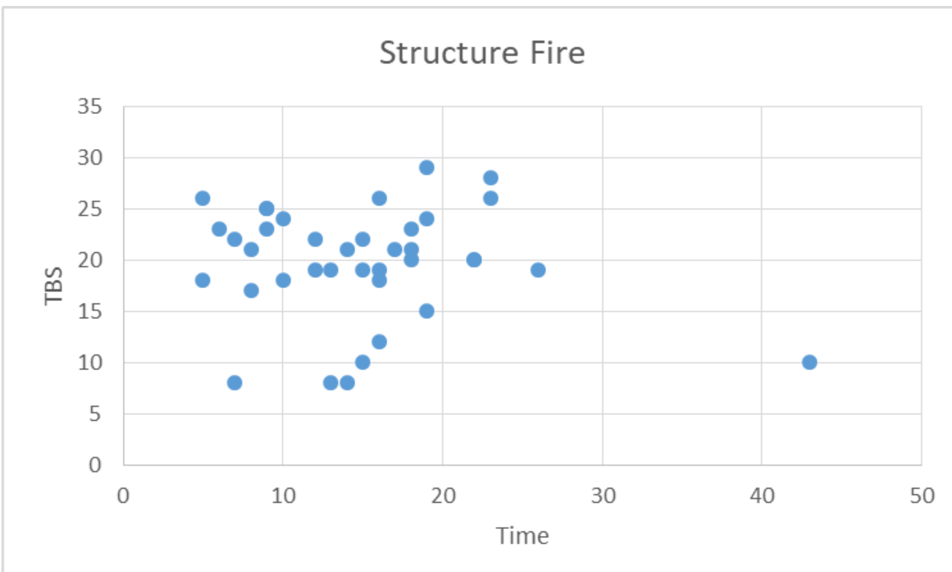


Figure 30. Scatter plot illustrates structure fires had on average short exposure time, resulting on average lower body scores.

Outdoor Fires

Individuals from the outdoor fires exhibited calcination, fragmentation, and heat-related fracturing on upper and lower limbs and the hands and feet, consistent with some of the highest total body scores observed (see Appendix, Figures 13-17). Individuals recovered from this context had total body scores that ranged from 23 to 33, with most ranging from 28-33 (see Table 2 & Figure 31). These individual exhibited head and neck scores ranging from 4 to 7, with most scoring a 6 or greater on the scale. Outdoor individuals also exhibited torso scores ranging from 6-8, with 8 being the highest score possible. These individuals had limb scores ranging from 5 to 9, with 9 being the highest score possible. Outdoor individuals exhibited hands and feet scores ranging from 7 to 9, with 9 being the highest score possible. Individuals from outdoor fires also exhibited high percentages of fragmentation and calcination compared to structure and vehicle fires, which is consistent with prolonged exposure to high temperatures (see Figure 31). Some individuals within this setting also had many soft tissue variables present (like. subcutaneous fat, etc.) on the torso. The presence of some soft tissue could be due to an increased ventilation in this setting.

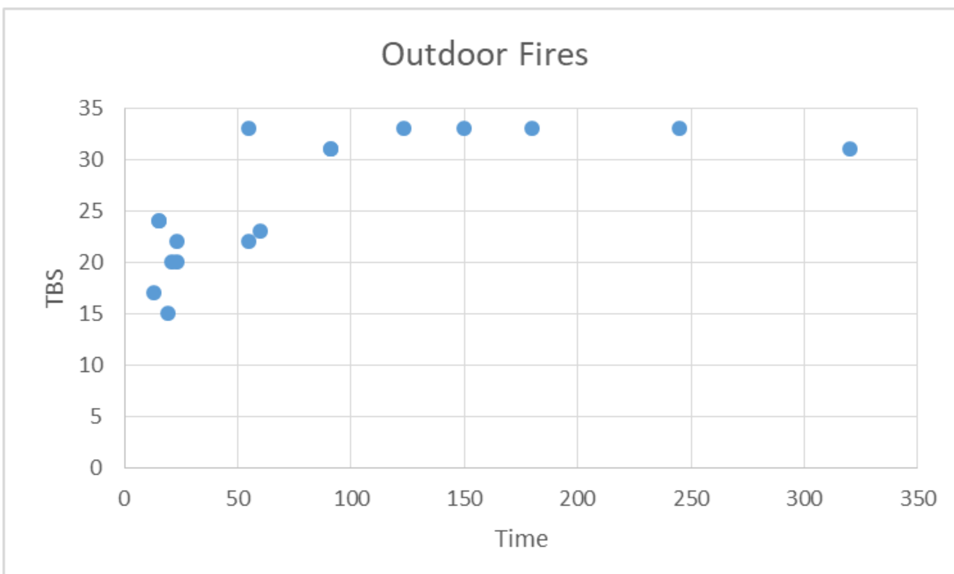


Figure 31. Scatter Plot illustrates outdoor individuals had increased exposure to higher temperatures contributing to higher total body scores.

Confined Space Fires

Remains from the confined space fires exhibited charring, calcination and fragmentation across head and neck and hands and feet, with some muscle exposure on upper and limbs and torso regions (see Appendix, Figures 13-17). Confined space fire individuals exhibited total body scores (TBS) ranging from 21 to 33, with most individuals scoring from 29 to 33 on the new model (see Table 2 & Figure 32). Individuals recovered from this setting exhibited head and neck score ranging between 6 and 7, with most scoring a 7 (the highest score possible). Individuals exhibited torso scores ranging from 4 to 8, with 8 being the highest score possible. These individuals also exhibited limb scores ranging from 5 to 9, with most scoring from 7 to 9 (with 9 being the highest score possible). Confined space individuals exhibited hands and feet scores ranging from 6 to 9, with most scoring a 9 (which is highest score possible). The presence of a high degree of calcination and fragmentation is consistent with prolonged exposure to high temperatures, and limited ventilation (see Figure 32).

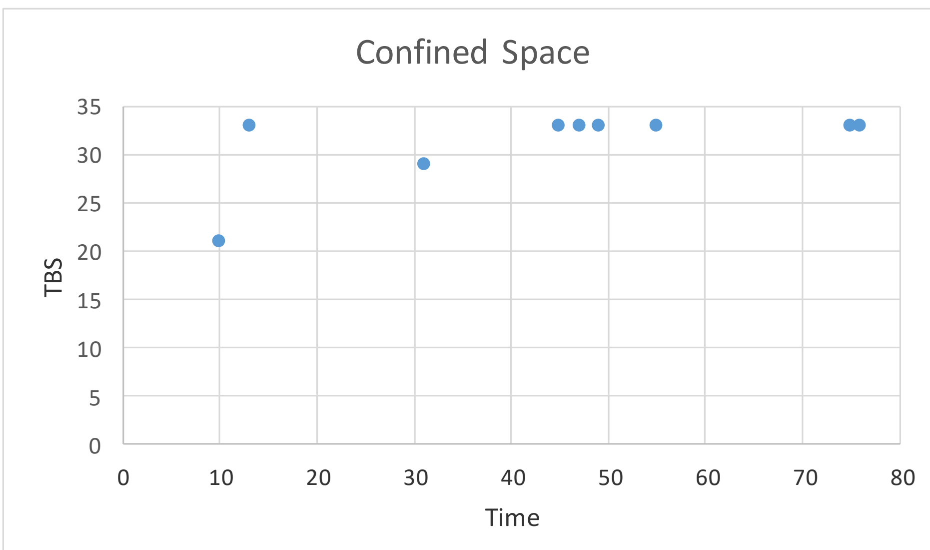


Figure 32. Scatter plot illustrates confined space individuals were exposed to higher temperatures for longer periods of time contributing to higher TBS scores.

The visual analysis of bodily conditions demonstrates there are varying degrees of thermal damage that can occur depending on the fire environment. Outdoor contexts, confined space fires, and trunk fires produced the greatest degree of thermal alterations found, whereas structure and compartment seat individuals exhibited a greater degree of variation of thermal alterations. These visual assessments were analyzed further to determine if statistically significant correlations existed between total body scores, time, temperature, and fire environment. The following statistically analyses were conducted to determine what variables likely contributed the most to the bodily conditions observed.

Chi-Square Results

A chi-square test was performed (using SPSS v.26) to see what variables are best associated with fire environment. The chi-square test showed there was a significant association between all variables (head and neck score, limb score, hands and feet score, trunk score, and TBS), and fire environment (see Appendix, Figures 4-8). The p-value for all scoring subcategories (e.g. head and neck score, trunk score, limb score, and hands and feet score) was 0.045 or less (see Appendix, Figures 4-8), which is less than the significance level of 0.05. Given all p-values were less than 0.05, the result is significant, and we can reject the null hypothesis that there is no relationship between these variables and fire environment. There is a relationship between all scoring subcategories and fire environment.

Total body score had a p-value of 0.007, which is greater than 0.05 (see Figure 33). Given, the p-value is less than 0.05, we can reject the null hypothesis and establish there is a significant relationship between total body score and fire environment. Since TBS and all scoring subcategories were found be significant, there is a correlation between bodily conditions and fire environment, which lends support to the patterns identified in the visual assessment.

Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	90.251[a]	60	.007
Likelihood Ratio	99.391	60	.001
N of Valid Cases	87		

Figure 33. Chi-square test between total body score (TBS) & fire environment (p=0.007).

A chi-square test was also performed to see if time (duration of burn) and temperature had a significant relationship with type of fire environment. The p-value for time was 0.001 (see Figure 34). Given, the p-value is less than 0.05, the result is significant, and we can reject the null hypothesis. There is an association between time and fire environment.

Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	165.999[a]	114	.001
Likelihood Ratio	152.383	114	.010
N of Valid Cases	87		

Figure 34. Chi-Square test between length of burn and fire environment (p=0.001).

The p-value for minimum temperature is greater than or equal to 0.000 (see Figure 35). Given the p-value is less than 0.05, the result is significant, and we can reject the null hypothesis. There is an association between minimum temperature and fire environment.

Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	167.795[a]	6	.000
Likelihood Ratio	156.777	6	.000
N of Valid Cases	86		

Figure 35. Chi-Square test between Min Temp & fire environment ($p < 0.001$).

The p-value for maximum temperature is < 0.001 (see Figure 36), which is less than 0.05. Given, the p-value is less than 0.05, the result is significant, and we can reject the null hypothesis. There is an association between maximum temperature and fire environment.

Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	167.176[a]	9	.000
Likelihood Ratio	164.871	9	.000
N of Valid Cases	87		

Figure 36. Chi-Square test between Max Temp & Fire environment ($p < 0.001$).

The chi-square analyses determined there were significant associations between all variables and type of fire environment, including time, maximum and minimum temperatures, and total body score (TBS). These results illustrate there is an association between variables that can be modeled, and lends support that there are distinguishable patterns between fire environments.

Multinomial Logistic Regression

A logistic regression analysis provides a way to build formulas that can combine scores to classify patterns more effectively. Therefore, a multinomial logistic regression analysis was performed using SPSS v.26. In a multinomial regression, one is able to assess relationships between variables to determine how it well it associates with an outcome measure (UCLA Statistical Consulting Group 2020). The results illustrate how well the variables can be used to predict an effect or outcome. All variables (including scoring subcategories) were included in this analysis, along with time and temperature. In the model fitting table, the final sig. value is 0.876 (see Figure 37), which is greater than 0.05 suggesting the result is not significant and the model did not fit. Fit is referring to how well the variables can be used to predict an outcome (UCLA Statistical Consulting Group 2020). The result suggests at least one of the regression coefficients is not equal to zero, therefore the model needs refining. Since the final model is not significant, we cannot reject the null hypothesis of lack of an effect between the variables, and accept this final model. The results suggest a revision of the model is needed to make the model fit better The lack of fitness suggest that our model is not likely to predict any better or accurately than a null model (Starkweather & Moske 2011). It is likely some variables are creating additional noise to the model, and therefore need to be removed. In the goodness of fit test, the Pearson value is 1.000 (see Figure 38), which is greater than 0.05. Since the Pearson value is greater than 0.05, we can accept the null hypothesis that this model somewhat fit, at least for some aspects.

Model Fitting Information

	Model Fitting Criteria	Likelihood Ratio Tests		
Model	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	217.806			
Final	.001	217.806	243	.876

Figure 37. When all variables included, model fitting test, p-value =0.876 (not significant).

Goodness-of-Fit

	Chi-Square	df	Sig.
Pearson	.000	6	1.000
Deviance	.001	6	1.000

Figure 38. Goodness-of-Fit, Pearson value = 1.000 (significant).

Based on these two tables, we can conclude that the model we developed needs some refining. The model fitting table demonstrates the parameters in which the model is fit. When a model is fit, it indicates the maximum likelihood the predictor variables are likely to produce the intended outcome (UCLA Statistical Consulting Group 2020). The degrees of freedom, or df listed above, is 243 and is defined by the number of predictors in the model. This statistic is perhaps too large, and suggests some variables need to be refined to make the model a better fit. Based on the classification results, the variables classified approximately 100 % (see Figure 39) of the time to the appropriate fire environment. A 100% classification percentage is good, despite needing some slight refining to reduce noise within the dataset. However, the findings suggest some variables need to be reduced to increase the fitness of this model.

Classification

	Predicted				
Observed	Confined Space	Outdoor	Structure	Vehicle	Percent Correct
Confined Space	9	0	0	0	100.0%
Outdoor	0	17	0	0	100.0%
Structure	0	0	38	0	100.0%
Vehicle	0	0	0	22	100.0%
Overall Percentage	10.5%	19.8%	44.2%	25.6%	100.0%

Figure 39. The likelihood variables classified to appropriate fire environment.

Given the results from the first multinomial logistic regression (where all variables were included), a second multinomial logistic regression was performed omitting all scoring subcategories (like head and neck score, trunk score, limb score, and hands and feet score), given there was some redundancy in these variables with TBS. There was significant overlap between these variables and total body score, as TBS represents the summation on these regions and can produce additional noise within the dataset. In omitting the subcategories, the following results were found:

In the model fitting table, the final sig. value is 0.04 (see Figure 40), which is less than 0.05 and suggests the result is significant and the model is fit. Since the final model is significant, we can reject the null hypothesis, and accept this final model. In the goodness of fit test, the Pearson value is 1.000 (see Figure 41), which is greater than 0.05. Since the Pearson value is greater than 0.05, we can accept the null hypothesis that this model is adequately fit.

Model Fitting Information

Model	Model Fitting Criteria -2 Log Likelihood	Likelihood Ratio Tests Chi-Square	df	Sig.
Intercept Only	217.806			
Final	.001	217.806	183	.040

Figure 40. Model fitting test, p-value =0.040 (significant).

Goodness-of-Fit

	Chi-Square	df	Sig.
Pearson	.000	54	1.000
Deviance	.001	54	1.000

Figure 41.Goodness-of-Fit, Pearson value = 1.000 (significant).

Based on these two tables, we can conclude that the model we are developing is good. Based on the classification results, the variables classified approximately 100 % (see Figure 42) of the time to the appropriate fire environment.

Classification

Observed	Predicted: Confined Space	Outdoor	Structure	Vehicle	Percent Correct
Confined Space	9	0	0	0	100.0%
Outdoor	0	17	0	0	100.0%
Structure	0	0	38	0	100.0%
Vehicle	0	0	0	22	100.0%
Overall Percentage	10.5%	19.8%	44.2%	25.6%	100.0%

Figure 42. The likelihood variables classified to the appropriate fire environment.

Based on the classification results, the variables were classified approximately 100.0 % (highlighted in blue above) of the time to the appropriate fire environment. It is likely the other subcategories of scoring variables were creating additional noise in the model. Therefore, only using TBS produced a more significant and fit model. The addition of temperature and time also increased the classification from 75% to 100% (See Figure 43).

Classification

Observed	Predicted: Confined Space	Outdoor	Structure	Vehicle	Percent Correct
Confined Space	8	0	0	1	88.9%
Outdoor	5	6	4	2	35.3%
Structure	0	1	36	1	94.7%
Vehicle	2	2	4	15	65.2%
Overall Percentage	17.2%	10.3%	50.6%	21.8%	74.7%

Classification

Observed	Predicted: Confined Space	Outdoor	Structure	Vehicle	Percent Correct
Confined Space	9	0	0	0	100.0%
Outdoor	0	17	0	0	100.0%
Structure	0	0	38	0	100.0%
Vehicle	0	0	0	22	100.0%
Overall Percentage	10.5%	19.8%	44.2%	25.6%	100.0%

Figure 43. Comparison of Classification results with temperature and time included (highlighted in yellow above), and without (highlighted in blue above).

The multinomial logistic regression aided in determining which variables were most significantly contributing to the outcome and those that were not. It was found head and neck score, trunk score, limb score, and hands and feet score were contributing additional noise to model, and therefore were removed from the analysis to better capture the underlying variables contributing to the burn process.

Hierarchal Linear Regression

In order to determine which variables were significantly contributing to the model, a hierarchical linear regression analysis was performed. A hierarchical linear regression allows one to add in predictor variables one at a time to determine their contribution to the outcome (Krusche 2011, Stramer 2018). In estimating fire environment, the predictor variables were time, total body score, minimum and maximum temperatures, and all scoring subcategories. The results found there were high collinearity between variables, therefore the model needed to be refined. When all variables were included, they together could explain 73% of the variation. However, all scoring subcategories were found to exhibit a collinearity value of 0.7 or greater, and were excluded from the analysis.

A second hierarchical regression was run using the predictor variables of time, total body score, minimum and maximum temperatures. The results indicate that total body score on its own was found to explain approximately 5% of the variation, while total body score and time together explained 20% of the variability. However, the predictors of time, maximum and minimum temperatures, and total body score together can adequately explain 80% of the variation in the model (see Figure 44). The variables are found to be contributing significantly to the outcome and should be taken and added into a predictive model.

Model Summary[d]

					Change Statistics				
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	R Square Change	F Change	df1	df2	Sig. F Change
1	.257[a]	.066	.055	1.024	.066	5.924	1	84	.017
2	.481[b]	.231	.212	.935	.165	17.807	1	83	.000
3	.900[c]	.810	.801	.470	.580	123.852	2	81	.000

a. Predictors: (Constant), TBS

b. Predictors: (Constant), TBS, Time

c. Predictors: (Constant), TBS, Time, Max_Temp, Min_Temp

d. Dependent Variable: Type_FE

Figure 44. Illustrates the third model with all variables together can explain 80% of the variation in model.

In estimating total body score from fire environment and all sub-scoring categories, these variables together contributed to explaining 100% of the variation in the model. Additionally, all variables (including time and temperature) together adequately explain 100% of the variation within the model (see Figure 45). This finding is also consistent with the classification percentage observed in the multinomial logistic regression analysis that was performed. While all variables can contribute to explaining the variability, there were overlapping variables with high collinearity that can be omitted. This finding suggests this model still can be used with missing information.

Model Summary[c]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics: R Square Change	Change Statistics: F Change		
1	1.000[a]	1.000	1.000	.108	1.000	70803.809		
2	1.000[b]	1.000	1.000	.109	.000	.266		

Figure 45. Illustrates all variables (including time & temperature) explain 100% of the variation in model.

The hierarchical regression analysis identified variables that had a high collinearity and omitted them from the analysis. It was determined that the scoring subcategories exhibited high collinearity with total body score, so they were removed from the predictive model. This finding makes sense as total body score represents a summation of all these scoring subcategories. In addition, several variables exhibited high collinearity and therefore were not as meaningful to the model, as there was overlap with other variables. A high collinearity is identified by a collinear value of 0.7 or greater (Stramer 2018). Minimum temperature had a high collinearity with max temperature, as minimum temperature had a collinear value of 0.7 (see Figure 46). Maximum temperature had a collinearity of .290, which is less than 0.7. Time exhibited a collinearity of 0.640, which is less than 0.7. Therefore, minimum temperature was omitted from the predictive model and maximum temperature and time were left in the analysis.

Excluded Variables[a]

Model		Beta In	t	Sig.	Partial Correlation	Collinearity Statistics Tolerance
1	Min_Temp	-.001[b]	-.550	.584	-.062	.659
	Max_Temp	-.001[b]	-.456	.650	-.051	.290
	Time	.001[b]	.424	.673	.048	.640

Figure 46. Illustrates minimum temperature had a high collinearity and therefore is not contributing significantly to the model.

Linear model

The results from the previous analyses were used in constructing a linear model for estimating exposure time to a fire and for estimating fire environment. A linear regression model was chosen over a logistic regression, as a linear regression allows for one to predict a continuous outcome (like time), whereas a logistic regression only predicts binary outcomes (Kacaboff 2017; Stramer 2018). Time in this data set is a continuous variable, therefore a linear model was more suitable. Additionally, fire environment is not a binary outcome, therefore a linear model was also more suitable for this second model. Unfortunately given the composition of my data, predicting fire environment as a “binary” outcome is not possible, unless I were to reclassify fire environment into categories like “indoor vs outdoor.” These categories provide more broad descriptions and are unlikely to capture the full array of changes that were found within all four fire environments. Therefore, rather than reduce and reclassify my fire environments and potentially loose valuable information, a linear regression analysis was performed. The assumptions and requirements of a multinomial regression (linear regression) are a little more flexible with this type of analysis with multiple categories.

However, given the experimental dataset does not exhibit a normal distribution, a log transformation was performed (see Appendix, Figures 18-21). After the data was log transformed, it exhibited a somewhat normal distribution allowing for a linear model to be applied (Kabacoff 2017, Stramer 2018). A linear regression analysis was performed (using R v.26) using the variables of total body score, time, and maximum temperature given their significance in previous analyses. However, a linear regression analysis was also preformed including both maximum and minimum temperatures along with TBS. The results showed that minimum temperature did not make a significant contribution to the model, which is a consistent finding from other analyses (see Appendix, Figure 22). Therefore, minimum temperature was excluded from the model.

Two regression analyses were performed. The first linear regression examined the effects of total body score and maximum temperature in predicting fire environment. Time was not included due to the inability to validate this variable through actual forensic cases. In actual forensic cases, it is rare for duration of burn to be known. The following results were found:

```
Coefficients:
                       Std. Error t value Pr(>|t|)
(Intercept) -9.0423275  0.7528980 -12.010  < 2e-16 ***
TBS          0.0362308  0.0086084   4.209  6.4e-05 ***
Max_Temp     0.0053921  0.0003762  14.333  < 2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘
’ 1

Residual standard error: 0.08588 on 84 degrees of freedom
Multiple R-squared:  0.8413,     Adjusted R-squared:
0.8375
F-statistic: 222.6 on 2 and 84 DF, p-value: < 2.2e-16
```

Figure 47. Illustrates TBS and Maximum temperature are contributing significantly to the model (p-value < 0.000).

Based on the coefficients table, the model intercept, total body score, and maximum temperature were all found to be significant in predicting fire environment (see Figure 47). Total body score and maximum temperature had p-values less than 0.001, which suggest they are significantly contributing to the outcome. Given the results from this table, a model can be created for predicting fire environment from bodily conditions. To generate a logarithmic equation, one would take the y- intercept (listed in first column) add the slope for total body score multiplied by the actual total body score, then added the slope for maximum temperature, multiplied by the maximum temperature for that fire environment. The logarithmic equation would result as follows:

Log10Type_FE= -9.042 + 0.036*TBS + 0.0053*Maximum Temperature -12.010 ± 0.752

Or to simplify it further:

$$\text{Type\_FE}=10^{(-9.042+0.036*TBS+0.0053*MaxTemp-12.010)} \pm 0.752$$

To generate a more precise estimate with a 95% confidence interval, one should use the following equation:

```
confint(fit, level=0.95)
                   2.5 %       97.5 %

(Intercept) -10.539547670 -7.545107248
TBS           0.019112184  0.053349502
Max_Temp      0.004644021  0.006140248
```

Figure 48. Illustrating the y-intercept and slopes for a 97.5% interval.

Log10Type_FE = -7.545 + 0.053*TBS + 0.006*Maximum Temperature - 12.010±0.752

Or to simplify it further:

$$\text{Type\_Fe}=10^{(-7.545+0.053*TBS+0.006*MaxTemp-12.010)}\pm 0.752$$

The R-squared for this model is 0.84, which represents how well the variables contribute to estimating fire environment (see Figure 48). This model has an r-squared value of 0.84, which suggest it is a good model. The p-value of this log-likelihood ratio is 0 or very small, which suggest the R squared value is not due to chance (see Figure 47).

While fire environment was given the numerical values of 1-4, these were only assigned to assist the R program in appropriately reading the data. They are not necessarily assigned to provide additional weight or value to this variable. The analysis assumes that there is no relation/ties between variables (Uniaky & Guller 2013: 235). Additionally, the equations generated in R account for interaction between my predictor variables and the predicted outcomes, like fire environment (James et al. 2014, Kabacoff 2017, Stramer 2018).

A second regression analysis was performed using different numerical scores for each fire environment and the results were found to be the same. There was no change in the output, as the intercept, slope for TBS, slope for temperature, and the constant all remained the same despite adjusting the coding for each fire environment. The results demonstrate that the numerical scores for fire environment are categories and do not carry weight (see Appendix, Figure 26-27).

A second linear regression was performed to estimate timing of bodily conditions based on total body score and maximum temperature. Based on the coefficients table, total body score (TBS) and maximum temperature were found to be significant in predicting time (see Figure 49). Total body score and maximum temperature had p-values less than 0.001, which is statistically significant (p-value < 0.05). Given the results in the coefficients table, a model can be created for estimating time. The following logarithmic equation was generated from these results.

```
Coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept) -176.45779    5.27824  -3.081  0.00279 **
TBS            3.21257    0.65490   4.905 4.51e-06 ***
Max_Temp       0.07078    0.02862   2.473  0.01541 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '
' 1
```

Figure 49. Illustrates total body score (TBS) and maximum temperatures are significantly contributing to the model (p-value < 0.01).

The model is predicting time from total body score and maximum temperature. To generate an equation, one would take the y- intercept (listed in first column) and the slope for total body score multiplied by the actual total body score, added to the slope for maximum temperature, multiplied by the maximum temperature for that fire environment. The logarithmic equation would result as follows:

Log10Time = -176.48 + 3.213*TBS + 0.071*Maximum temperature -3.081 ±5.27

Or to simplify it futher:

$$Time=10^{(-176.48+3.212*TBS+0.071*Max\ Temp-3.081)}\pm 5.27$$

For a more precise estimate within a 95% confidence interval, the following equation should be used:

```
                     confint(fit, level=0.95)
                    2.5 %      97.5 %
(Intercept) -290.36184428 -62.5537401
TBS            1.91023336   4.5149065
Max_Temp       0.01386673   0.1276952
```

Figure 50. Illustrates the y-intercept, and slopes of each variable for constructing a 95% confidence interval.

Log10Time = -62.5537 + 4.515*TBS + 0.127*Maximum temperature -3.081

±5.27

Or to simplify it further:

$$Time=10^{(-62.55372+4.515*TBS+0.127*Max\ Temp-3.081)}\pm 5.27$$

The R squared for this model is 0.25, which represents the overall effect size (see Appendix, Figure 25). The p-value of this log-likelihood ratio is 0 or very small, which suggest the R squared value is not due to chance (Starmer 2018). Both regression analyses produced significant models that are not due to chance. One model was created to estimate fire environment based on bodily conditions and temperature. The other model was created to estimate exposure time to a fire, based on bodily conditions and maximum temperature. These models were then tested on a series of forensic cases provided by medical examiner and corner offices. The ensuing discussion demonstrates how well these models performed on this testing dataset.

Cross Validation

The experimental dataset was used as a “training” dataset in building the linear models and used in refining and optimizing the models to acquire the best fit. The training dataset allowed for the narrowing of variables to include only those that were found to significantly contribute to the outcome (those with a p-value < 0.05). A second “testing” dataset comprised of forensic cases was used to determine how well the predictive model performed. The testing data set comprised approximately 107 fatal fire cases covering the four major fire environments analyzed in this study (e.g. vehicle, structure, confined space, and outdoor). The individuals in this data set were analyzed using the new scoring model and given a total body score. A k-fold cross validation was performed to determine how well the models perform on a different data set. When taking the linear model for estimating fire environment and applying the model to the test sample of medical examiner cases, the model exhibited a low minimal predictive error. The model exhibited a cross validated error estimate of 0.0012 (see Figure 51). The cross validated standard error estimate is an average sum of the squared differences between predicted and known values, and indicates how likely the model is to misclassify ((James et al. 2014, Kassambara 2018, Starmer 2018). Overall, the model performed well on the testing data set, and exhibited a small predictive error rate, which would be the expected rate at which burn victims would be misclassified to fire type.

```
[1] 0.001750506
```

Figure 51. Illustrates the predictive error rate for the linear model predicting fire environment.

The same approach was applied to the second linear model for estimating time. The model for time was also taken and applied it to the testing data set. This model exhibited a slightly larger predictive error. The model exhibited a cross validated error estimate of 6.653, or the expected at which burn victims would be misclassified due to time (see Figure 52).

```
[1] 6.653187
```

Figure 52. Illustrates the error rate for the linear model predicting time.

A k-fold cross validation was performed to determine how well the models perform on this different data set. A k-fold cross validation was chosen as opposed to another validation method, as it is thought to produce some of the more accurate error rates (James et al. 2014). The model for estimating fire environment exhibited an R-squared value of 0.73 on the testing data set, and a RMSE value of 0.49 (see Figure 53). The R-squared value represents the correlation between the observed and the predicted values (James et al. 2014, Kassambara 2018, Starmer 2018). The RMSE represents the average prediction error. The lower the RMSE score the better the model. The MAE is the average difference between the observed and predicted, with the lower the score indicating the better the model. The fire environment model had RMSE and MAE scores of 0.49 and 0.39 respectively, which are low and suggest the model is good a predictor of fire environment.

```
106 samples
  2 predictor

No pre-processing
Resampling: Cross-Validated (10 fold)
Summary of sample sizes: 95, 95, 96, 96, 95, 96, ...
Resampling results:

  RMSE       Rsquared   MAE
  0.4899018  0.7332582  0.3917705
```

Figure 53. Illustrates both a low RMSE and MAE score.

The model for estimating timing exhibited an R-squared value of 0.40 on the testing data set, and a RMSE value of 36.52 (see Figure 54). The R-squared value represents the correlation between the observed and the predicted values (James et al. 2014, Kassambara 2018, Starmer 2018).

```
No pre-processing
Resampling: Cross-Validated (10 fold)
Summary of sample sizes: 78, 79, 78, 78, 79, 78, ...
Resampling results:

  RMSE      Rsquared   MAE
  36.52042  0.4060257  26.16011
```

Figure 54. Illustrates a high RMSE and MAE score.

The RMSE represents the average prediction error. The lower the RMSE score the better the model. The MAE is the average difference between the observed and predicted, with the lower the score indicating the better the model. The model for estimating time had RMSE and MAE scores of 36.52 and 26.16 respectively, which are high and suggest the model is moderate predictor of time. When dividing the RMSE value by the average outcome variable, one would get the prediction error rate (see Figure 54). There is not a standardized average value of RMSE to serve as a benchmark in evaluating or comparing RMSE scores. The general rule of thumb most scholars follow is the lower the RMSE value the better the model. The value varies depending on dataset, therefore an average comparative value does not exist, as each dataset is unique. In general, the error rate should be a small as possible or close to zero for the model to be considered a good predictor of time (James et al. 2014). The error for this model is slight over 1.0, therefore is only a moderate predictor of time (see Figure 55). To formulate a classification percentage, the predictive error was divided by average time (approximately 35 minutes) to get a percentage of error (James et al. 2018, Kassambara 2018). The model was found to misclassify approximately 30% of time. Therefore, the model correctly predicted time in about 70% cases analyzed.

```
[1] 1.050035-prediction error rate
```

Figure 55. The model produced an error rate of 1.05, indicating a moderate error rate.

Applying New Models

In applying the fire environment model, it is recommended one should use the range of maximum temperatures provided with this study. Fire environment does not need to be known in order to use this model, as a range of maximum temperatures that represent all fire environments is provided. If one were to use the temperature ranges observed, the model would produce an outcome that could be compared to the corresponding chart (see Appendix, Figure 28). The maximum temperatures in this dataset ranged from 1700 - 2100°F, with the average max temperature for this dataset being approximately 1900°F. Therefore, one could apply this model without having to know maximum temperatures for a specific fire environment. To provide a case study example, if an individual exhibited a total body score of 30, and was exposed to any of the maximum temperatures provided above, the individual would score between 3.4 - 4.2 when applying this new model. These values are within an outdoor fire environment, and when validating the findings, it is the environment from which the individual came.

Ranges are typically used within the forensic sciences in estimating age and stature. Therefore, I can foresee this working as an investigator running the equation would use the range of maximum fire temperatures provided to estimate which fire environment the remains likely came from. It is recommended the user apply this equation using the lowest maximum temperature (1700°F) provided, the average (1900°F), and the highest maximum temperature (2100°F) to adequately estimate fire environment. Additionally, a range can be established by using one of the temperatures provided above, and applying the standard error for this equation which is 0.752 to the end result. One would take the result and add and subtract the standard error to develop a range comparable to the chart provided (see Appendix, Figure 28). Therefore, providing an average range would work to better classify an individual and work to avoid under or over estimating fire environment.

In applying the model on time, one should also use the temperatures provided. In estimating time, the standard error for model was ± 5.27. In applying this model, one should use the standard error for this model to derive an exposure time range. By using the standard error, it will provide the minimum exposure time and maximum exposure time possible for a specific individual. One should calculate a total body score (TBS) and use the range of temperatures (1700°F, 1900°F, and 2100°F) provided to then calculate an estimated exposure time. Once a result is derived, one should then subtract -5.27 to get a minimum exposure time, and add 5.27to get a maximum exposure time possible for that individual. It is recommended to estimate time as a range, rather than a single point in time, as to avoid misclassifying any individual. This model misclassified on the testing dataset in approximately 30% of the cases analyzed. So, in the 27 fire cases (30% used to test), it would assign eight cases to the wrong known time. When comparing known and predictive values, the model was found to be off between 3 to 9 minutes. While it did not exactly pinpoint the exact time, it was within range of 2-3 minutes in some cases, and at most off by 8-9 minutes in others, which is still a fairly acceptable rate of error. On average, the model was found to be off by 5 to 6 minutes, which is within the range of standard error reported. It is likely in order to increase accuracy and reduce misclassification, a range should be used to estimate time. Within forensic anthropology, aging methods and stature estimation methods both rely on ranges to adequately characterize human remains (Brooks and Suchey 1990, Kerley 1965, Lovejoy et al. 1985, Meindl et al. 1985). A similar approach can be applied when using this new model.

Summary

This chapter identified key differences within each fire environment based on bodily conditions, temperature, and time establishing the possibility to model heat related conditions. A Chi-square test was performed to determine if statistically significant relationships existed between variables. The chi-square test determined all scoring variables were significantly correlated with fire environment, as well a time and temperature. A multilinear logistic regression was performed to determine how well the variables performed at classifying patterns. The results demonstrated that with all variables included they classified 100% of the time to the appropriate environment. Additional statistical analyses were performed to narrow down the predictive models, and to determine which variables contributed most to the predicted outcome. It was determined that total body score and the scoring subcategories overlapped, so only total body score was used. Additionally, there was high collinearity with maximum and minimum temperature, so only maximum temperatures were used, as they established the most significance in estimating the outcome. It was determined that total body score and maximum temperature significantly contributed to predicting both type of fire environment and estimating time. Therefore, these variables were used in developing two separate linear models.

The models were then validated on a "testing" dataset comprised of medical examiner cases from known fatal fire environments. The model estimating fire environment was found to have a low misclassification rate, which suggest it is a good model for predicting fire environment from bodily conditions and temperature. A second linear model was developed for estimating timing of death events. The model exhibited a moderately low misclassification rate, however it had a high RMSE score, suggesting it is only a moderately good predictor for estimating time. Both models exhibited good fits with slightly different error rates, demonstrating their applicability to forensic community. The ensuing discussion explains how to best apply each model, and provides a detailed discussion on the findings from this study.

Chapter Five

Discussion

This chapter offers a detailed exploration of the findings from this study and the implications to the forensic community. In general, identifiable patterns were noted that distinguished compartment and trunk individuals within a vehicle fire environment. Observed differences were also noted between structure, confined, and outdoor fire contexts. There were observed differences in bodily conditions, time, and temperatures. These patterns were analyzed statistically and used to formulate a model for estimating timing of bodily conditions. The ensuing discussion explains the findings from this study, and how these models can be used to enhance our overall understanding of the burn process on human remains.

Differences between Fire Environments

The degree of thermal damage was found to differ depending on the type of fire environment, temperatures, duration, and presence or absence of ventilation. The variation in heat related damage on the body is directly correlated with duration of fire and the range of temperatures in each environment. The longer duration of the confined space and outdoor fires made them less like the structure and vehicle fires that lasted for several minutes, thus resulting in earlier stages of heat-related changes to the outer tissues of the body. Structure fires had the shortest durations and lower average temperatures, compared to other fire environments. The structure fires were extinguished with water between 5 and 20 minutes, while vehicle fires burned for 15 minutes to an hour. Fires were extinguished at different points in an attempt to replicate the actual forensic cases they were based on. A shorter duration in structure fires is consistent with responses times to these type of fires (Flynn 2009, Kerber 2012). On average, structure fire individuals exhibited shorter exposure to high temperatures, which led to lower total body scores. Outdoor and confined space individuals exhibited longer durations of high temperatures contributing to the advanced thermal alterations observed. The longer exposure to high temperatures led to higher total body scores. The shorter exposure to high temperatures led to lower total body scores. There were also notable differences between individuals placed in a trunk and those placed in a compartment of a vehicle, which can be explained by differing levels of ventilation in these locations. While length of exposure to high temperatures plays a role in the bodily conditions observed, ventilation also indirectly affects burn patterns on human remains. The ensuing discussions explains how each fire environment reflects differing amounts of ventilation which can contribute to altering bodily conditions.

Role of Ventilation

Structure fires are ventilation-controlled, meaning that air is limited, which produced limited soft tissue damage, patterned areas of bone exposure, lower temperatures, and far shorter durations. Outdoor fires and vehicle fires were ventilation-driven, which accounts for the higher and sustained temperatures (Lentini 2012; 2013; 2019). Lentini (2019) suggested ventilation plays a key role in creating fire patterns. His study addressed the implications of ventilation or presence of oxygen in fire environments and how it contributes to altering fire patterns. Lentini felt the lack of considering how ventilation impacts fire patterns has contributed to the misinterpretation of these patterns by fire investigators. Historically, investigators have mistakenly identified wrong points of origin within fire environments, and therefore misinterpreted fire scenes, which Lentini argues was due to the lack of consideration investigators gave to ventilation altering patterns (Lentini 2012:2013). While this study, did not necessarily set out to quantitatively attempt to measure oxygen levels in each fire environment, it indirectly ended up doing so. Lentini describes how ventilation is known to alter wall and floor burn patterns, particularly within structure fire environments. His study found that "temperatures in fully involved compartments move in-near perfect alignment with the oxygen concentration, until it reaches flashover" (Lentini 2019: 41). Flashovers cause the fire to escape out of the contained structure, introducing more oxygen, which results in a drop of temperatures.

This research also found ventilation plays a role in contributing to the amount of thermal damage found on a body. The differing types of fire environments in this study capture to a degree the differing levels of ventilation that can result in fire scenes. Oxygen is an essential component to maintaining a fire and providing the adequate fuel to keep it going (Chen et al. 2009, Utiskul & Quintiere 2005, Utiskul et al. 2005, Wang et al. 2008). When a fire is starved of oxygen, it often subsides and can result in limited amount of thermal damage. Structure fires were ventilation controlled, as no windows or doors were opened to introduce oxygen into this environment. The lack of oxygen along with reduced exposure to high temperatures contributed to the lower total body scores (see Table 4). Outdoor fires are ventilation driven and further feed a fire contributing to the higher total body scores.

Vehicle fires comprise two types of ventilation patterns depending on where a body maybe located. Individuals placed within compartment are in limited ventilation environments, compared to those placed in a trunk. Trunk individuals are in ventilation controlled spaces, which can contribute to the differences in burn patterns observed between locations. In this study, trunk individuals were often placed in a vehicle with another individual in the compartment allowing for ventilation comparisons to be made. The differing ventilation levels can explain the slight differences in total body scores between locations. Trunk individuals were in a ventilation controlled environment, but were exposed to high temperatures for longer periods of time, which can contribute to the higher total body scores. The compartment individuals were in a limited ventilation environment, which could have contributed to the slightly lower body scores.

Confined space fires, like an open burn barrel or dumpster, were ventilation limited, as they often comprised at least one opening. Confined space fires are not ventilation controlled and not necessarily ventilation driven either, depending on the composition of their structures. Therefore, this environment best illustrates the combination of these variables in affecting bodily conditions. Confined spaces exhibited limited ventilation with increased exposure to high temperatures, which can explain the higher total body scores, compared to vehicle and structure fires. The increase in oxygen fuels a fire, and contributes to increasing levels of thermal damage on the human body.

Fire Environment	Average TBS	Average Head & Neck Score	Average Torso Score	Average Limb Score	Average Hands and Feet Score
Vehicle Fires	24	6	5	6	7
Structure Fires	20	5	4	5	6
Outdoor Fires	28	6	6	8	8
Confined Space	31	7	7	8	9

Table 4. Illustrates average total body scores and average body scores per region based on fire environment.

These differences illustrate how ventilation, duration, temperature, and fire environment are strongly correlated with the amount of heat-related damage that occurs on a human body. Some environments, like structure fires, did not sustain high temperatures for a long period of time, resulting in the presence of many soft tissue alterations. Other environments, like confined space and outdoor fires, sustained high temperatures for longer periods of time, resulting in calcination and fragmentation of bone. The ensuing discussion explains how the statistical results provide us with a deeper understanding of the underlying processes that affect burned human remains. These experimental observations and statistical analyses demonstrate which variables are a necessary component for building a more robust model that can be widely applicable to the forensic community.

A New Classification Model

The primary goal of this research was to develop a new classification system for analyzing burned human remains. The first hypothesis states the following:

Hypothesis I: Burn patterns can be described based on visual interpretations of the body and be quantified using a scale that can be consistently applied based on fire conditions.

Previous classification models were primarily descriptive and constructed from specific contexts that often resulted in only the later stages of the burn process being represented. A new model was needed that captured the entire range of the thermal alteration process. This study developed a model that quantitatively scores thermal alterations by body region, and then sums the scores to get a total body score (TBS). The summation of these scores was found to adequately capture the range of thermal alterations and found to be just as significant in producing outcomes as each individual scoring subcategory. This new model changes the way forensic professionals, specifically those within the anthropology community go about analyzing burned human remains. It is likely in a forensic context that fire environments will produce remains exhibiting the spectrum of alterations known to occur, which supports why this study incorporated both soft tissue and skeletal changes in the new classification system. It offers a more quantitative approach to an analysis that has primarily remained descriptive. A quantitative method provides forensic professionals with a new tool that can be defendable in court. Additionally, the new classification system produces scores that can be used to estimate *in-situ* conditions. The scores generated from the new model can be taken and applied to a predictive model for estimating fire environment and timing of death events.

Modeling Fire Environments

This study undertook a second hypothesis that stated the following:

Hypothesis II: A formula can be modeled to estimate fire exposure time and temperature based on defined variables.

The second hypothesis was tested by taking the first hypothesis and using the observed body conditions along with time and temperature to construct a model for estimating *in-situ* conditions. The statistical results outlined in the previous chapter found some variables contributed more to the outcome than others, and therefore aided in refining and optimizing the model to produce the highest predictability. The results showed that total body score, time, and temperature were all significant variables contributing to the outcome. They each exhibited p-values less than 0.05, making them statistically significant in predicting fire environment. If one or more variables were excluded, like time or temperature, this classification percentage was found to decrease, reflecting its significance to the burn process. These statistical analyses lend support to the notion that it is a combination of both time and temperature that influence bodily conditions. Therefore, two models were created one for estimating fire environment and one for estimating exposure time to a fire. The models produced mixed results when applied to a testing dataset, as described below.

Factors Contributing to Misclassification Rate

The model created for estimating fire environment exhibited a good fit, and captured 84% of the variation, as the R-square value was 0.84. This model also had a very low misclassification rate, which makes it suitable for the forensic sciences. However, when comparing predicted versus known data, several patterns emerged within the dataset. The cases that were misclassified involved either structure fire individuals or those from an outdoor context. All vehicle and confined space individuals were classified appropriately. When comparing total body score of those that were misclassified by the model, they emerged as they outliers for their respective fire environments. Most of the misclassifications were due to these individuals scoring either lower or higher than most of the other samples within the same fire environment. For example, there was an outdoor fire individual that scored as a 23, which is lower than most other cases within this specific fire environment. This individual exhibited one of the shortest burn durations for outdoor individuals (less than an hour). The short duration is likely what contributed to the lower total body score and it being an outlier from the rest of the dataset.

Given the comparison between known fire environment and predicted scores, the outliers appear to be contributing significantly to the misclassification rate. However, the misclassification rate is still very low, which makes it a good model to use. This model has the potential to aid investigators building a legal case and can be useful in cases where investigators are unsure of the location where remains may have been burned.

Model Estimating Time

For the second model, the training dataset was split 70% to train the model and 30% to test the model on, as the medical examiner cases did not come with known time data. Questions regarding timing of death events are often ones that investigators look to be answered, as they are not readily known. So, it is expected fatal fire cases would not comprise such information. When comparing the model for estimating time of death events, a similar pattern emerged.

The model for estimating time had RMSE and MAE scores of 36.52 and 26.16 respectively, which are high and suggest the model is moderate predictor of time. In general, the error rate should be a small as possible or close to zero for the model to be considered a good predictor of time (James et al. 2014). The error for this model is slight over 1.0, therefore suggesting it is only a moderate predictor of time. Given the results, outliers also seemed to affect the predictive error in this model. In addition to outliers, the experimental data comprised a limited comparable sample, which also could have contributed to the higher misclassification rate. The data had to be partitioned to create a training and testing sample. Therefore, smaller datasets are subject to bias and error, depending on how the data was divided (James et al. 2014). Confined space and outdoor fires were underrepresented in the sample compared to vehicle and structure fires. The model is likely to be more highly variable depending on how many of each fire environment comprised the training and testing datasets. Given there was an unequal distribution between both, it is likely it contributed to the error rates observed. Despite outliers and a limited comparable sample, the model correctly predicted time in approximately 70% of cases analyzed (James et al. 2018, Kassambara 2018). It is likely this error would decrease with an overall larger comparative sample. Outliers were also found to be contributing to an increase in misclassification. An increase in outdoor and confined spaces cases perhaps would have increased the predictive ability of this model further. The model still represents a good foundation to build upon for future analysis, as there is currently no model like the one described for fatal fire deaths. An increased experimental sample size, along with removing outliers would help in refining and enhancing the model further.

Limitations

Within fatal fire cases, investigators may have questions surrounding how long it would have taken for an individual to reach certain bodily conditions. This study has laid the foundation for creating a model that can potentially answer those questions based on bodily conditions. Overall, both models provide a deeper understanding of the underlying process that influence the burn process. From the statistical results presented, this study was able to capture how much of the variation found can be explained by bodily conditions, time, and temperature. When attempting to classify by fire environment, these variables are found to be responsible for 84% of the variation present. Only 16% of the variation can be explained by other factors, like differences in body mass or differences in ventilation patterns, to name a few. This study provides a foundation for further applying quantitative methods to develop models that can be more widely applied to the forensic community. The following discussion addresses several limitations to this study that could have resulted in creating a more precise model.

There were several limitations to the development of the models created. Published data on temperatures from each fire environment were used in the creation of these models, rather than temperatures taken from the body. While bodily temperatures would be more ideal for this study, they became too problematic to use. There were inconsistencies in where temperatures were taken on the body, like near the femur or in the liver. For example, individual bodily temperatures were either taken near femur or in the abdomen, but unlikely in both locations. Therefore, it was decided this data would not be used in constructing a model for estimating *in-situ* conditions.

In the experimental dataset, temperature was not taken in a consistent manner, and thermocouples placed near the femur bone often fell out during burn due to the movement of the body. An abdominal temperature measure maybe the most logical location to secure and protect the thermocouples from falling out, as this region is protected by layers of fat and soft tissues. Given the abdomen is one of the most well protected regions, it takes a significant amount of time for these layers to burn and expose organs. While the thermocouple would be protected, it does not always capture the best overall bodily temperature readings. It provides a snapshot into how hot the abdomen region may have gotten during the burn, but does not necessarily give a more generalized reading of the temperature of the entire body. Extracting temperatures from a body during experimental observations remains a challenge. The abdomen remains a more reliable option, but may not necessarily be adequate to use in representing temperatures of the entire human body. It would be suitable for capturing the temperature of the abdomen, but would caution against applying the temperature readings to represent other regions, as we know they tend to burn differently and unequally. Each major region should be analyzed on its own to capture the entire effect of the burning process, including bodily temperatures. In general regional bodily temperature would be difficult to achieve as the body moves during fire. However, thermocouple placements in the same regions, (e.g. neck, abdomen, and femur) for all individuals provides a start to making temperature data collection more consistent.

Bodily temperatures were also excluded as it became apparent some individuals were placed in their fire environments shortly after being removed from a refrigerated environment, while others were allowed to remain in their fire environment for several minutes to allow for the body to reach room temperature. However, no individual was left overnight in their specific fire environment. At most, individuals were left in their location for less than a half hour. However, the inconsistency in timing of placements adds to the already problematic nature of this data. Remains starting out below room temperature produced different starting points for bodily temperatures making it too inconsistent to apply into this model. For example, individuals directly placed from refrigerated environments often had a body temperature of 49 degrees Fahrenheit. Individuals that were given several minutes to thaw had temperatures that ranged from 68 degrees Fahrenheit to approximately 80 degrees Fahrenheit. This study wanted to remain as close to actual forensic cases as possible, so the bodily temperature data was also excluded for this reason. A refining of approaches for collecting temperature data is needed to best adequately capture bodily temperatures from a burning body. The more precise collection techniques can be, the more likely they may contribute to strengthening the models that were created.

Given the nature of how the data is collected as a part of a training course, there is limited time available for burning, which can contribute to inconsistencies in data collection. Techniques that involve placement of individuals around the same time and allow for some thawing to occur would help in preventing inconsistencies with the temperature data. Thawing should be considered, as most fatal fire cases are unlikely to involve individuals who have been refrigerated or frozen prior to burning. Given the wide range of fire environments covered, it would be beneficial to consider an ordered pattern to the experimental burning process. For example, all structure fires are burned first, followed by vehicle fires, confined space and outdoor fires. A careful construction of the experimental burning order could help refine this technique and make it more precise.

Despite, problematic bodily temperature data, this study still produced comparable results using temperatures from known fire environments. Bodily temperatures could perhaps give a more precise estimate and refine the model further. However, the statistical results demonstrated using known temperatures worked just as well in establishing an effect to be studied. This study attempted to include both maximum and minimum temperatures for vehicle fires, structure fires, confined space fires, and outdoor contexts. Both linear regression models demonstrated that when maximum temperature was included, minimum temperature was found to not significantly contribute to predicting the outcome. These analyses showed that both temperature readings were not needed to produce a meaningful outcome. Therefore, minimal temperatures were eventually excluded from the model and maximum temperatures were only used. A more complete dataset would likely strengthen these findings further.

Another limitation to this study is the unequal number of experimental cases in each fire environment. There were significantly more cases that comprised vehicle and structure fire individuals within my experimental and training dataset. Confined space and outdoor contexts comprise the least amount of cases within my experimental dataset. Therefore, more cases of individuals recovered from outdoor contexts are needed and perhaps would increase the predictability of this model. The testing dataset (comprised of medical examiner cases) was similar in composition to the experimental dataset, with one exception. In the testing dataset, there were considerably more outdoor contexts than in my experimental dataset, which could have influenced the error rate observed. The testing data set comprised mostly vehicle and structure fires, which are the most common types of fire cases (Lentini 2019). Overall, while outdoor and confined space cases represented a smaller portion of my experimental dataset, my sample still remained comparable to the testing dataset, where vehicle and structure fires also comprised a majority of the fatal fire cases. The dataset still remained true to the overall composition of actual fatal fire cases that would likely come through medical examiner offices. The following discussion highlights the implication of these findings to the broader forensic community.

Broader Implications

This study developed a new classification system that is more representative of the fatal fire cases often encountered by the forensic community. Currently, forensic professionals typically describe the nature and condition of remains, with no attempt to quantify the amount of thermal damage present. This new model provides a way to not only describe thermal alterations, but to quantify them using a scale.

In contexts where partial remains are present, one can still apply the new model with accuracy. It is likely partial remains may be found, especially when remains exhibit the latter stages of burning (like calcination and fragmentation). It is recommended one visually assess the remains present per bodily region. If any region cannot be scored, then one would assign a score of zero to that specific area. While it is highly unlikely that all elements to a single bodily region maybe missing, it can occur. In the event, partial remains are recovered it is still possible to use this new model with a high degree of accuracy.

The comparative medical examiner data set included some cases of partial remains. These cases comprised remains that were often highly fragmented and calcined in nature. However, a total body score was derived for each of these remains, by applying a zero to bodily regions with no available elements to assess. While partial remains represented less than 10% of my comparative sample, it provided a glimpse into whether it was possible or not to use partial remains on this new model. Partial remains were given a total body score, with missing regions being scored a zero. The scores were then used in the predictive model to see how well the model performed. Each model comprises a standard deviation or error range that accounts for the variability within the data set. The standard deviation is added and subtracted from the end result to provide a minimum and maximum range for each individual. When applying the standard deviation or error, it is still possible to apply this model with a high degree of accuracy on a partial set of remains. Further research and a larger sample of partial remains is needed to adequately tell how much it affects the overall accuracy rate. With partial remains included, it was found that the models still performed with a greater degree of accuracy, it is likely if the partial remains were excluded, this accuracy rate might increase. However, with it included, the model estimated fire environment correctly in approximately 84% of the cases analyzed, and estimated time correctly in approximately 70% of the cases analyzed. It should be noted that in contexts where only a few remains were recovered, this model would not be applicable. For example, if an investigator were only able to recover a few teeth, but no other remains from other bodily regions, then one would not be able to use this model.

Investigators often have questions surrounding timing of death events, or how long it would take for a body to reach a set of conditions. The models developed aim to provide some answers to those questions. The first model estimates fire environment and can be used with a great degree of accuracy, as it had a very low misclassification percentage. This model is likely to be useful when investigators have questions surrounding origins, or if there were more than one crime scene. The second model can be used to estimate timing of death events, however the misclassification rate is slightly higher. Overall, these models provide a foundation for aiding investigators in narrowing down a perpetrator and constructing a timeline of events. Each model comes with a misclassification rate, which is a necessity for being defendable in court.

This study has laid the foundation for a more quantitative approach to be applied within fatal fire research. Primarily, fatal fire research has remained relatively descriptive, with no means to quantify the amount of damage observed. This study produced a quantifiable method with the hopes more will be developed in the future.

Fatal fires often produce some of the most challenging scenes and remains to analyze (DeHaan 2012, Lentini 2013, Symes et al. 2008), and can often lead to misinterpretations that have grave consequences for those wrongly convicted. The ability to use more than one's expertise provides a more solid approach to analyzing and interpreting fatal fire deaths.

Summary

This chapter discussed how differences in bodily conditions can be best explained by differences in temperature, time, ventilation, and fire environment. It was found that these variables adequately explain approximately 84% of the variation found to exist within fatal fire contexts. This chapter highlighted how each model performed on a testing dataset. There were key patterns that emerged when looking at instances where each model misclassified. Outliers evidently affected the predictive error, and also illustrated an imbalance in the number of cases from each fire environment. Despite these slight barriers, the model estimating fire environment still performed very well. The second model estimating time did not perform as well as the first, as it exhibited a much higher misclassification rate. Outliers and a smaller comparative sample were found to have contributed to the high misclassification rate. This chapter also identified several limitations to this study that would have potentially aided in refining or making the models more precise. Bodily temperatures were excluded due to inconsistencies in data collection techniques. However, bodily temperatures could help produce a more precise estimate, especially regarding timing of death events. More experimental samples of outdoor and confined space contexts are needed to help refine the model.

This chapter concluded with a discussion on the importance of these findings and its contribution to the forensic community. This study has laid the foundation for applying quantitative methods to fire environments, and provided the first steps in creating models that can be used to estimate *in-situ* conditions. Quantitative methods, like the one described in this study, can be used to aid investigators in building a legal case, and work to minimize misinterpretations of fatal fire scenes.

Conclusion

This study examined 87 experimental fatal fire cases, which were derived from the San Luis Obispo Fire Investigation Strike Team training course. These observations were used in developing a new classification method for analyzing burned human remains. The new method assesses thermal alterations per bodily region and is used to construct a total body score. The total body scores were then compared by fire environment and used to develop a model for estimating exposure time and *in-situ* conditions. Two separate models were developed and tested on a testing dataset. A set of 107 medical examiner cases were used to test the model estimating fire environment. A subset of the original 87 experimental cases was set aside to test the second model. The first model performed well and had a low misclassification rate. The second model was found to have a slightly higher misclassification rate, but still performed moderately well against the testing dataset. The results from this study are promising and offer an additional tool for investigators building a legal case.

This study found that time, temperature, fire environment, and bodily conditions explain approximately 84% of the variation within this dataset. This finding helps provide additional insight into the underlying processes that affect thermal alterations. Historically, many scholars have argued it is impossible to measure or uncover all the underlying conditions that shape the patterns observed, as fires are often unpredictable in nature (DeHaan 1999, Lenitini 2012; 2013). However, the results from this study offer some insight into how much time, temperature, and fire environment contribute to the observed differences in bodily conditions. This study found time contributed significantly to the outcome, but temperature did not always, as minimum temperatures did not produce the most significant outcomes. These results can be used to better understand what factors contribute the most or least to the thermal alterations observed.

The findings from this study support both Hypothesis I and II. Hypothesis I was supported by using the visual assessment of bodily conditions and demonstrating its statistical significance in estimating *in-situ* conditions. The results demonstrate that these bodily scores are significant for predicting fire environment and time, across a variety of fire scenes.

Hypothesis II was supported by demonstrating how the variables of total body score and temperature contributed significantly to predicting the outcomes of fire environment and timing of bodily conditions. These variables were found to be statistically significant and could be used to model *in-situ* conditions. Two models were developed and found to have moderately to low misclassification rates, which demonstrates their applicability to the forensic community. The findings from this study support the notion that it is possible to quantitatively model heat-related damage.

Additionally, this study laid the groundwork for developing a model for estimating exposure time to a fire, which has yet to be created and applied to the area of burned remains. Similar models exists in other related areas of taphonomic research, but no current model has been created or applied to fatal fire cases. The results were promising, as a model for estimating fire environment was found to work well and have a low error rate. However, the model for estimating time produced moderate results, suggesting a refining of the model is needed. Outliers and a small comparative sample likely contributed to a higher predictive error in the second model. Additionally, the inclusion of more experimental samples and bodily temperature data will be needed to create a more precise model that can be defendable in court. The following discussion outlines future research directions.

Future Research

This study is likely to be the first of many in attempting to adequately quantify the amount of heat related damage. For a model to become widely used and defendable in court, it needs to be replicated, widely tested, and provide misclassification rates. The assessments of each individual included in this study were made by the author. Therefore, the new classification model needs to be tested for inter and intra observer error. Within the forensic sciences, it is standard protocol for new methods to be tested for observer error, in order to better understand how likely it is to misclassify. This new model will need to undergo similar steps, if it is to be used more widely by the forensic community. Therefore, a sample dataset has been created to pursue additional research on testing observer error between individuals with little experience, some graduate training, and those with expert training in the field. Individuals would be presented with a set of photos from each bodily region, and be asked to use the new classification model to apply a total body score. The results of this study will be provided in a forthcoming publication.

Both linear models produced promising results. The model for estimating fire environment was found to have a low misclassification rate. However, it was determined outliers likely contributed to the 16% error rate. Therefore, a larger comparative sample is needed to refine and make both models more precise. A database has been created and will be used to continue to build upon this work. At the time of writing, a portion of this data had been used in applying a transition analysis to help estimate time. Transition analyses are more commonly used in estimating age at death from bodily conditions (suture closures, wear pattern on pubic symphysis or wear patterns on dentition). A similar approach can be applied to this study, as this study attempts to take bodily conditions and estimate time. The results were not included in this study, however, the preliminary results are promising. It is likely this statistical method may produce better results than a linear model. A transition analysis will be carried out on this dataset to better determine what stages are strongly correlated with specific time intervals. This method is likely to even further enhance our understanding of the thermal alteration process and the underlying factors that contribute to these changes. The results of this study will be provided in a forthcoming publication.

An increase in sample size between outdoor and confined spaces would perhaps help increase accuracy rates. Additionally, time exhibits a log-linear relationship with total body score, as the longer one is exposed to *in-situ* conditions the higher the total body score is likely to be (see Figures 32-35). Therefore, if one were to take the log of time before applying any statistical analyses, it perhaps would aid in refining the model and making it more precise. There are future research plans to re-run the data using the "log" of time to see how it compares with using the "log" of one variable or other, the "log" of both, or using a non-linear curve fitting process to see if it would produce a better relationship. The results from this analysis will be presented in a forthcoming publication.

Overall, this study found identifiable patterns between remains recovered from a vehicle fire compared to those recovered from outdoor, structure, or confined space fire contexts. The observed differences in thermal damage were found to be correlated with differences in time, temperature, and amount of ventilation in each fire environment. Observations from each fire environment were used in developing a new classification system for analyzing heat related damage. This new classification system covered both soft tissue and skeletal changes and will be beneficial to the medico-legal community in standardizing the description of burned remains. It will also prove important in reconstructing events involved in fatal fires and will aid investigators building a legal case. Prior to this study, there has been no attempt to standardize the description of burned remains and quantify the amount of thermal damage observed. Previous models were constructed from specific fire environments, and therefore not widely applicable to the forensic community. This research laid the groundwork for applying a more quantitative approach to analyzing and interpreting burned human remains, which has never before been attempted. The information gained from this study can be used to better predict when these physical alterations may occur on the human body, and from what fire environments the remains likely were recovered. More importantly, it enhances our understanding of the underlying processes that affect thermal alterations.

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Appendix

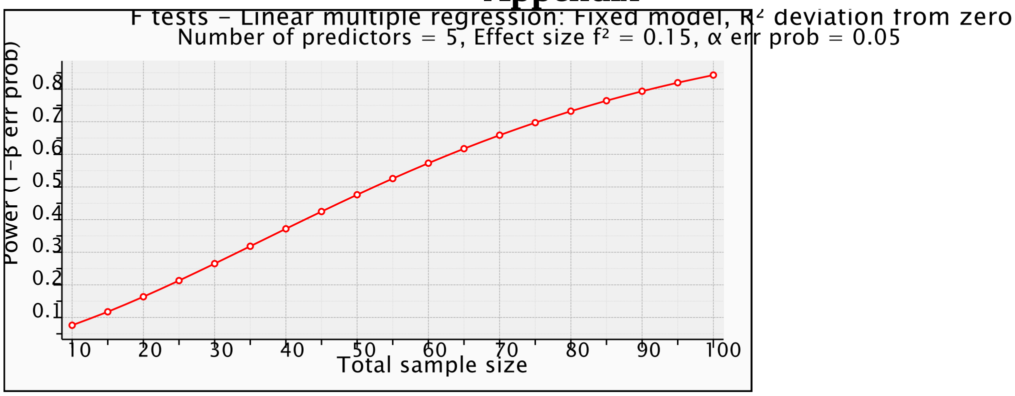

Figure 1. Post-hoc test = 57 samples, with 5 predictor variables

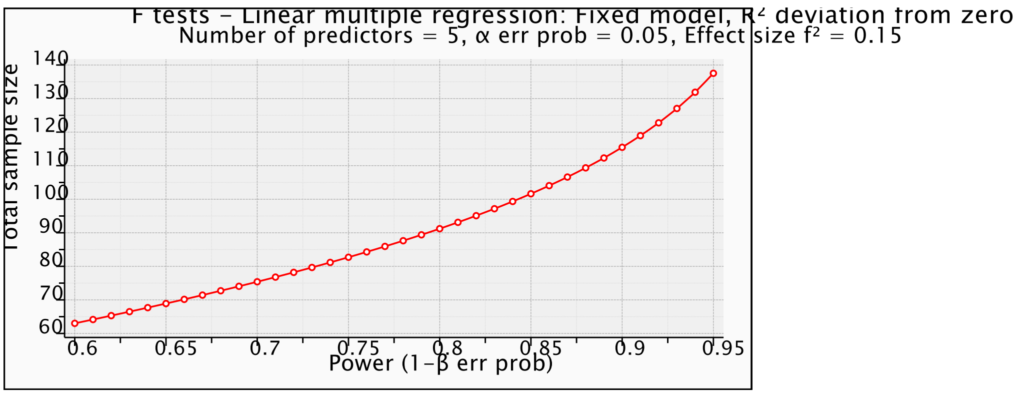

Figure 2. Minimum Total sample = 90, with power at 0.80 (minimum level)

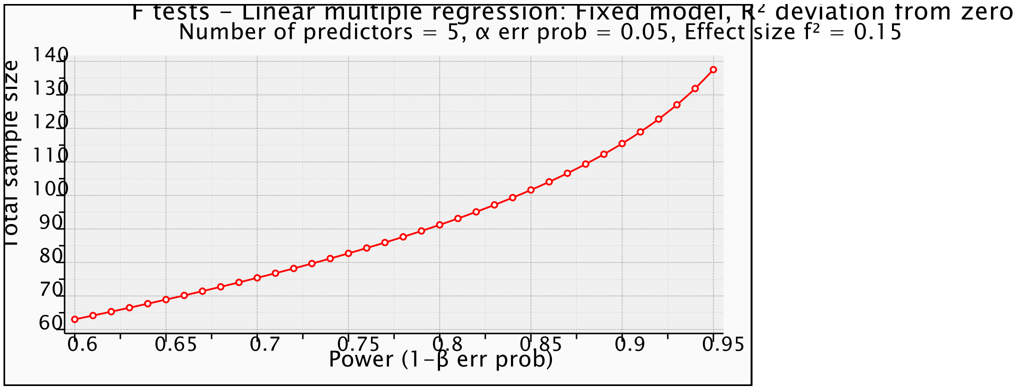

Figure 3. Maximum Total Sample Size = 138 (with power at 0.95/excellent level)

Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	25.347[a]	15	.045
Likelihood Ratio	29.840	15	.013
N of Valid Cases	87		

Figure 4. Chi-Square Test: Head & Neck Score & Fire Environment

Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	51.659[a]	21	.000
Likelihood Ratio	52.770	21	.000
N of Valid Cases	87		

Figure 5. Chi-Square Test: Trunk Score & Fire Environment

Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	52.626[a]	24	.001
Likelihood Ratio	59.376	24	.000
N of Valid Cases	87		

Figure 6. Chi-Square Test: Limb Score & Fire Environment

Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	65.321[a]	24	.000
Likelihood Ratio	72.166	24	.000
N of Valid Cases	87		

Figure 7. Hands & Feet Score & Fire Environment

Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	90.251[a]	60	.007
Likelihood Ratio	99.391	60	.001
N of Valid Cases	87		

Figure 8. TBS & Fire Environment

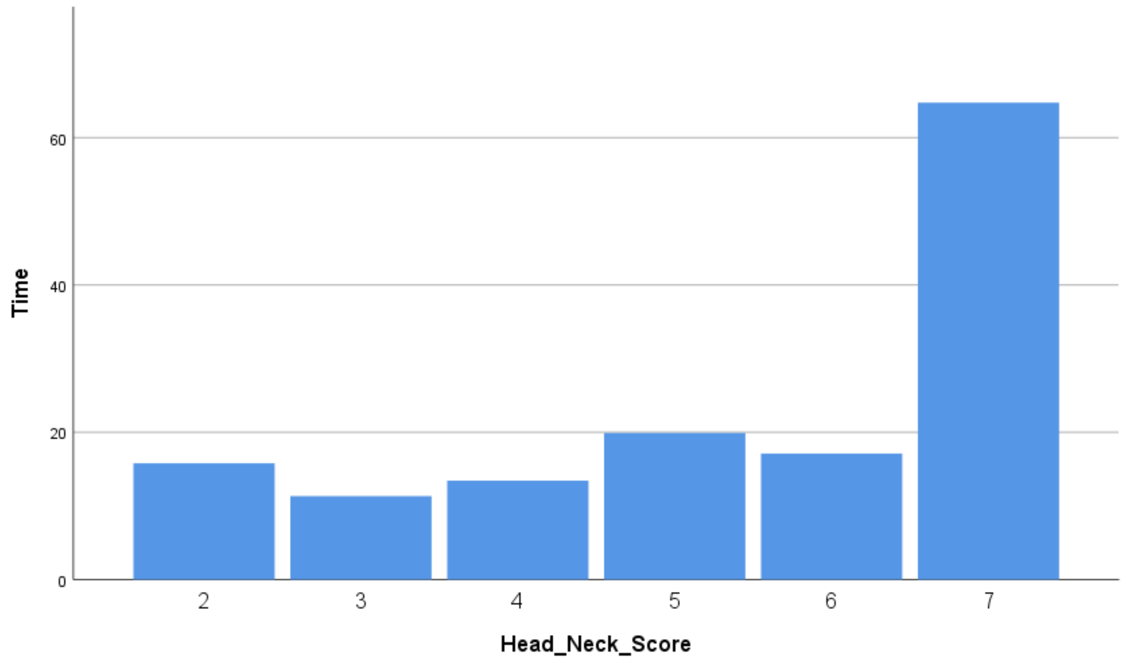

Figure 9. Head and Neck Score & Duration of Burn

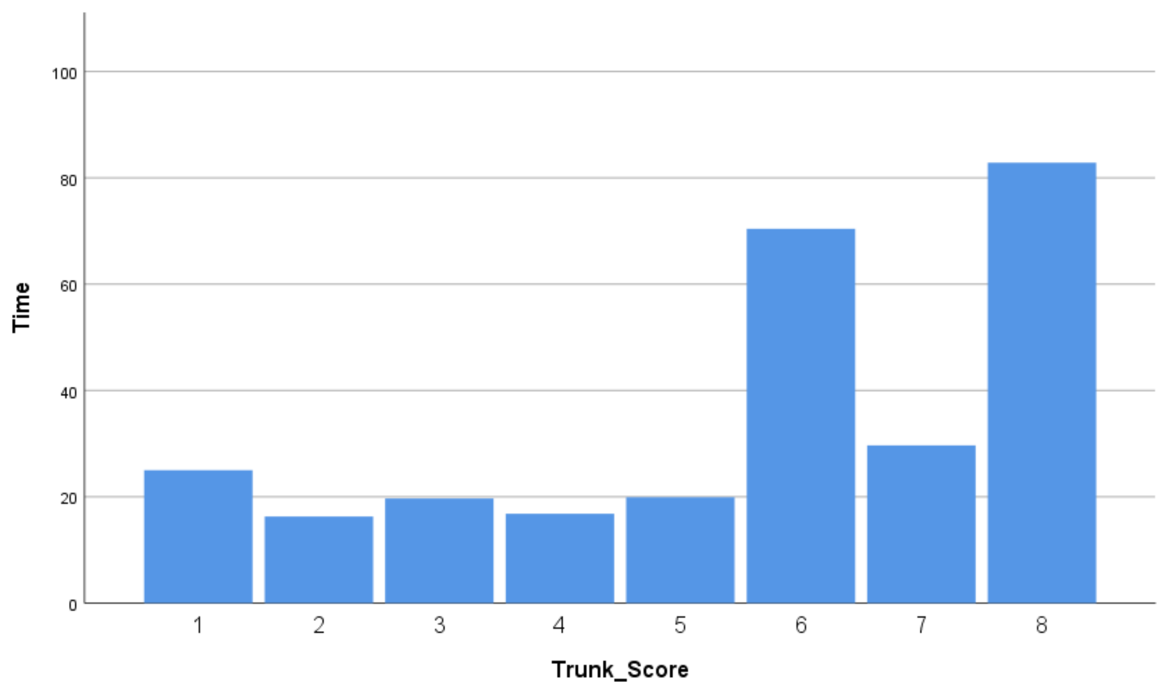

Figure 10. Trunk score & Duration of Burn.

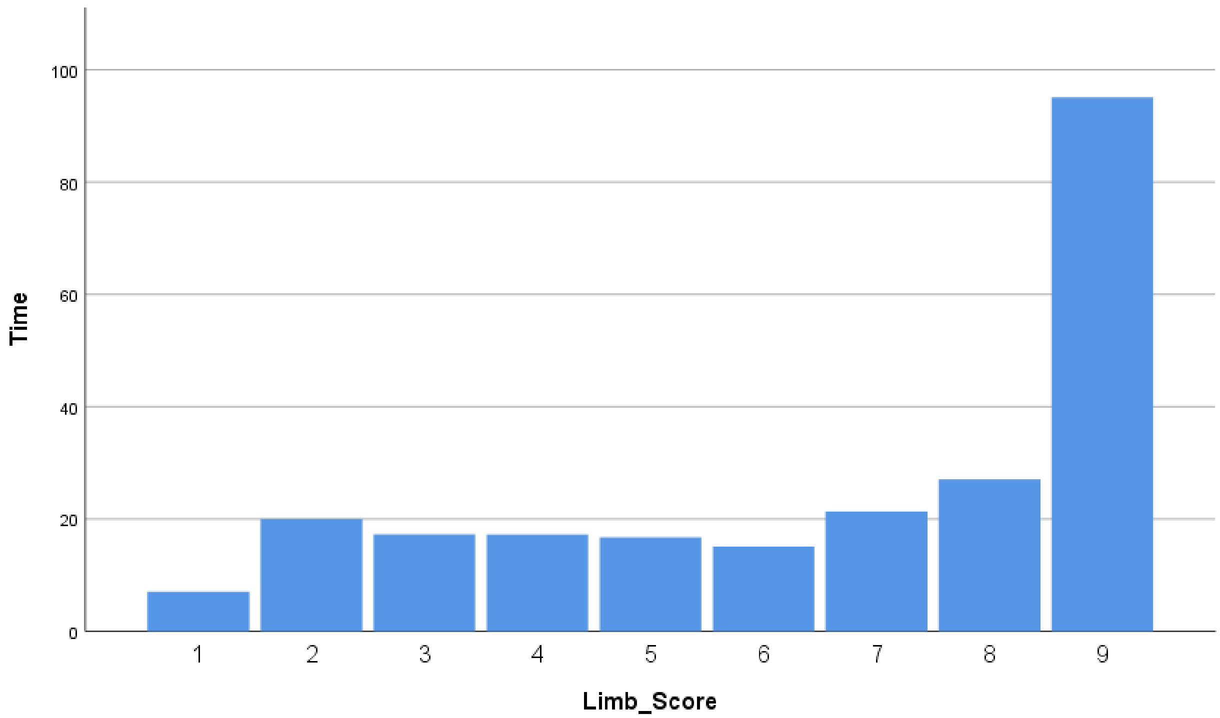

Figure 11. Limb score and Duration of Burn.

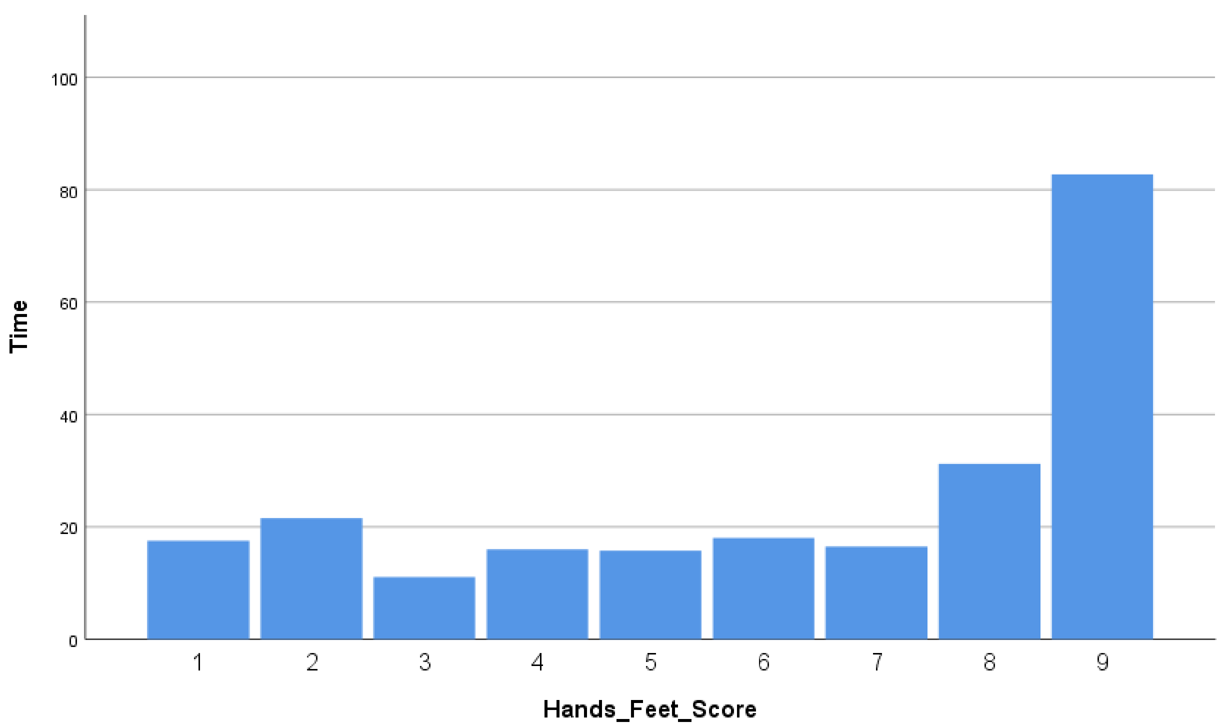

Figure 12. Hands and feet score and duration of burn.

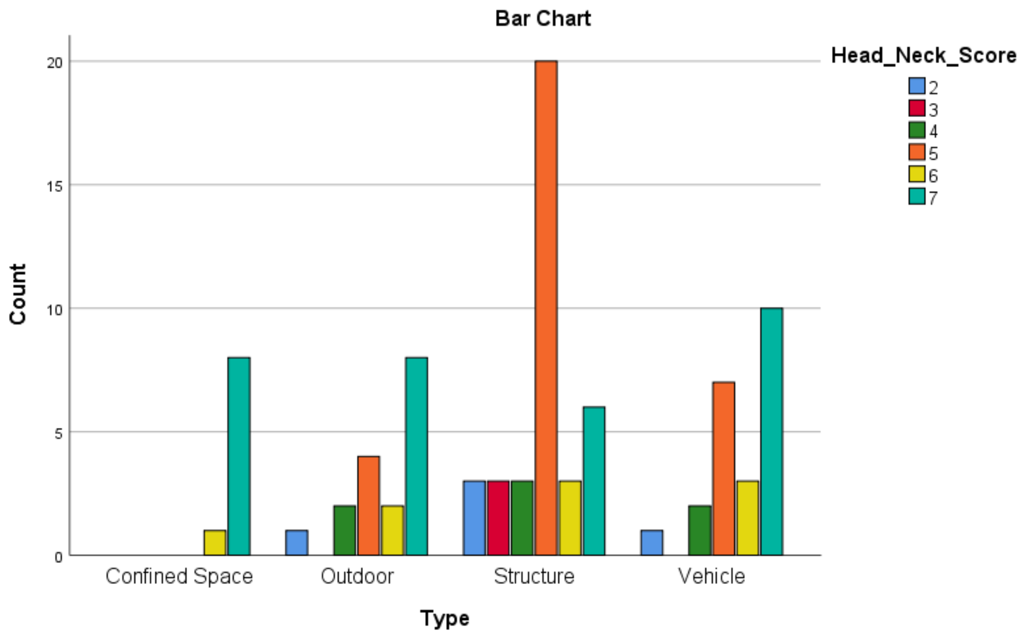

Figure 13. Confined Spaces and Outdoor fires exhibited highest head & neck scores.

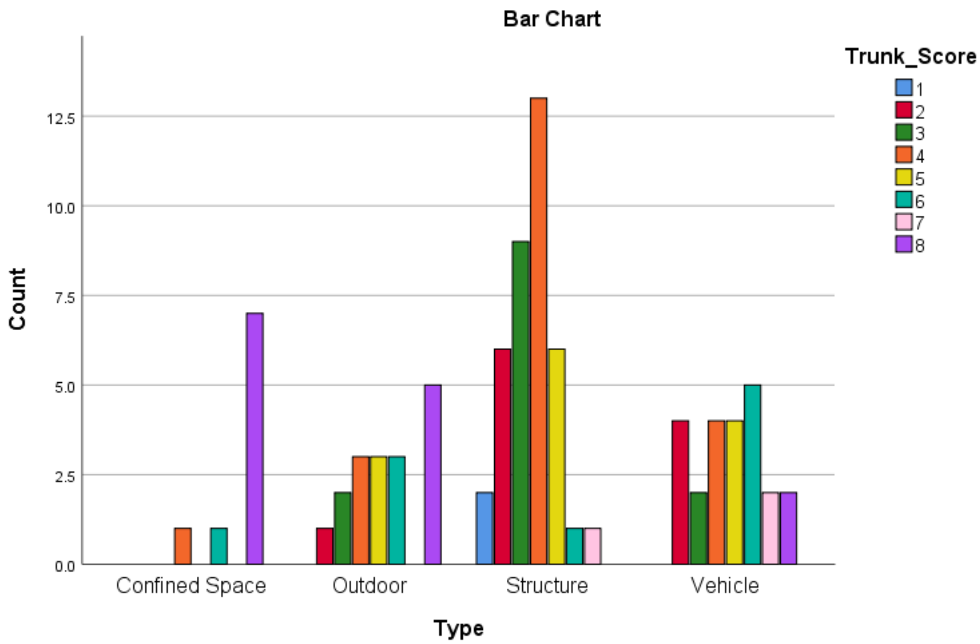

Figure 14. Confined space and outdoor fires exhibit highest number of high trunk scores.

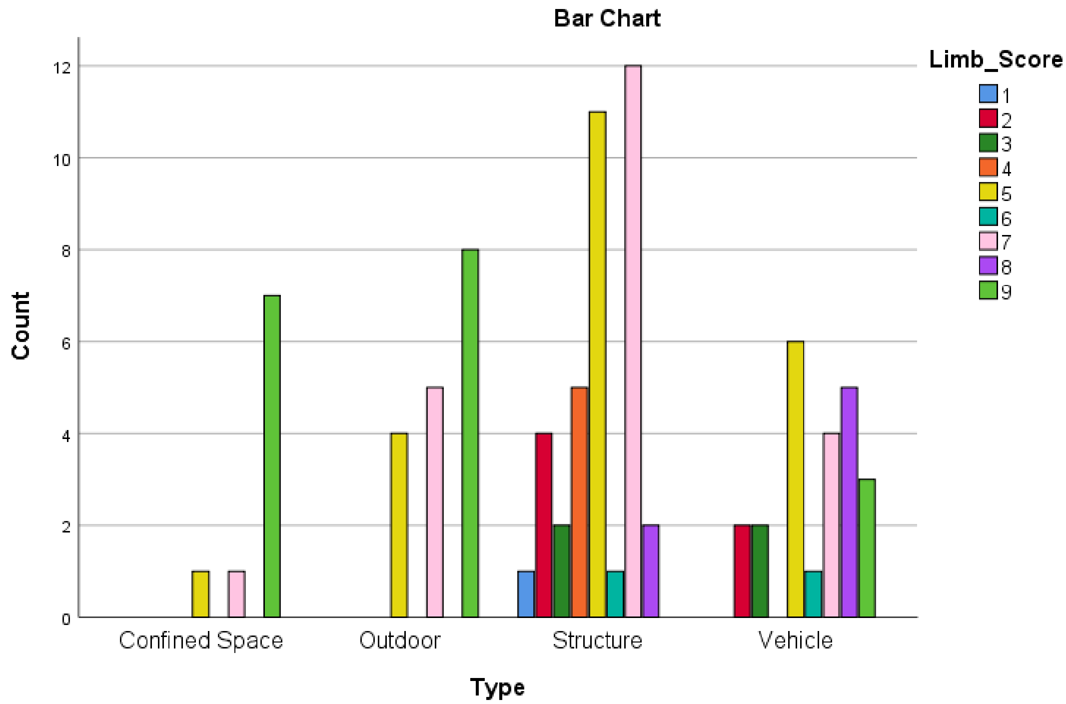

Figure 15. Outdoor and Confined space exhibited highest numbers of limb scores between 7-9.

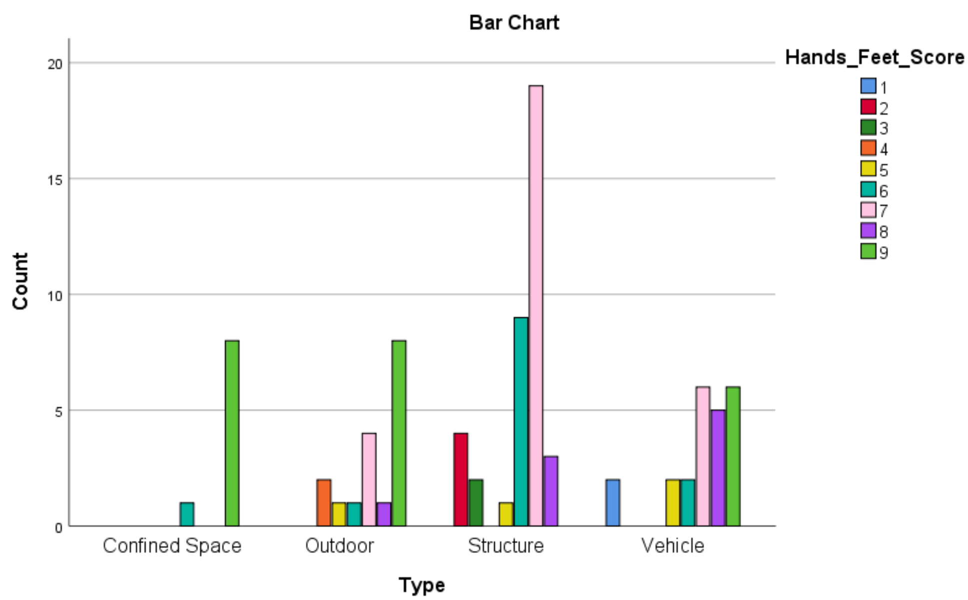

Figure 16. Confined space and outdoor fires exhibited highest number of hands and feets scores (which is hihglighted in lime green or a score of 9).

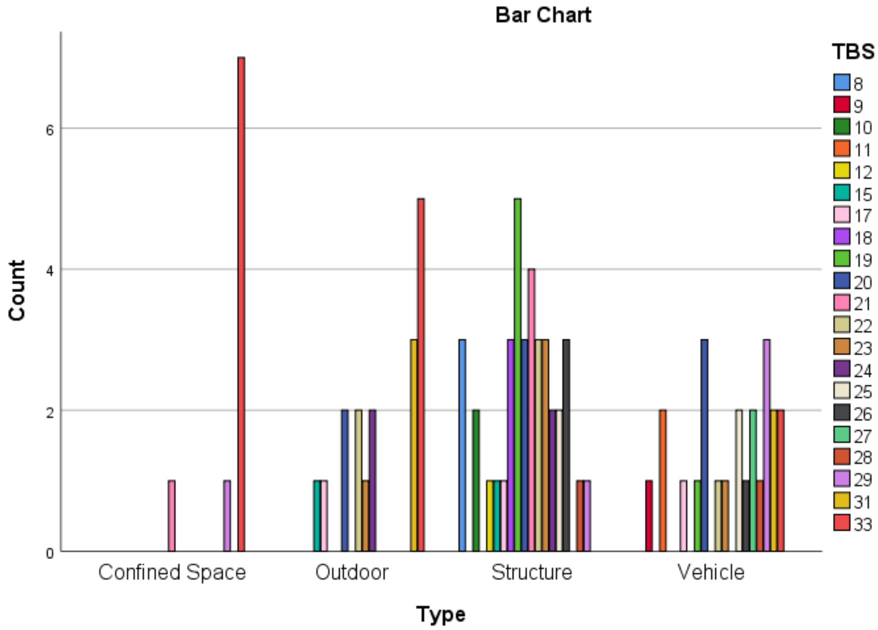

Figure 17. Illustrates confined space and outdoor environments exhibited more individuals with higher total body scores (ranging from 28-33).

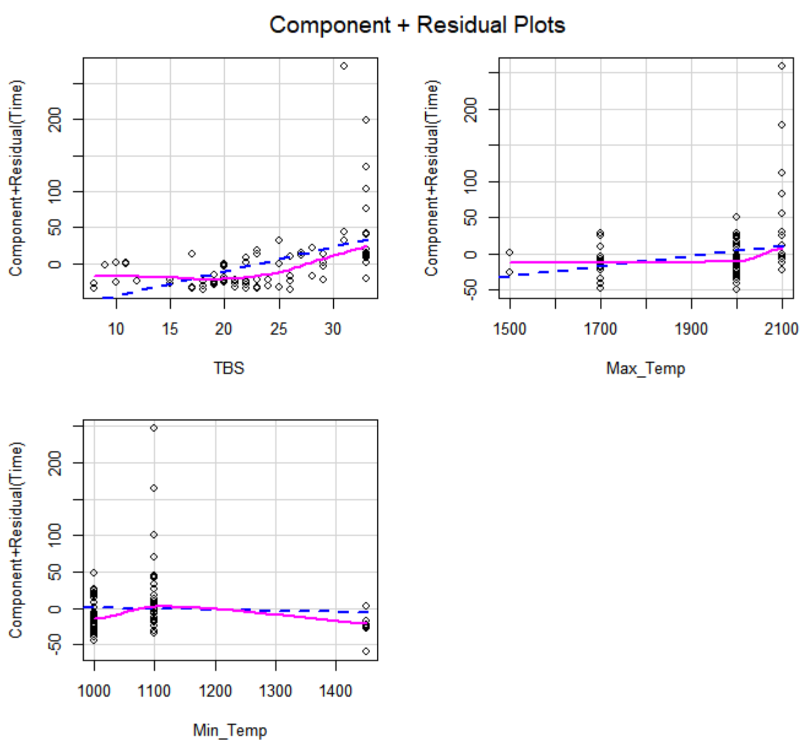

Figure 18. Illustrating data is non-linear.

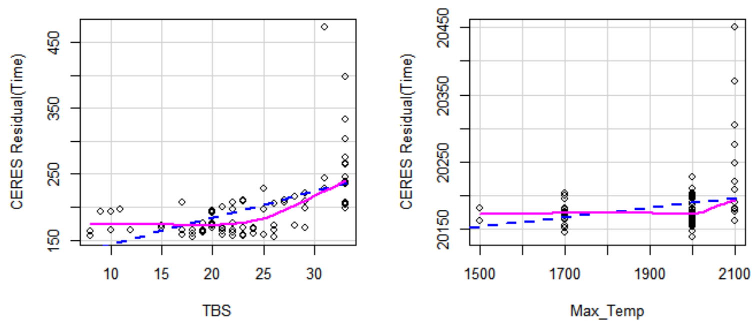

Figure 19. Illustrating non-linear data.

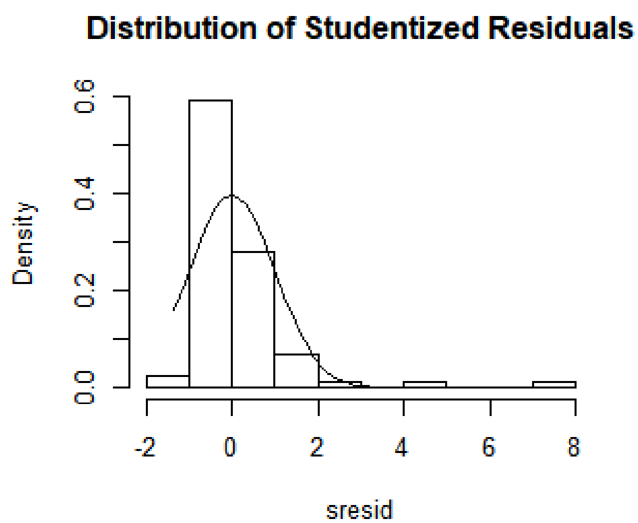

Figure 20. Data exhibits somewhat "normal" distribution after log transformation.

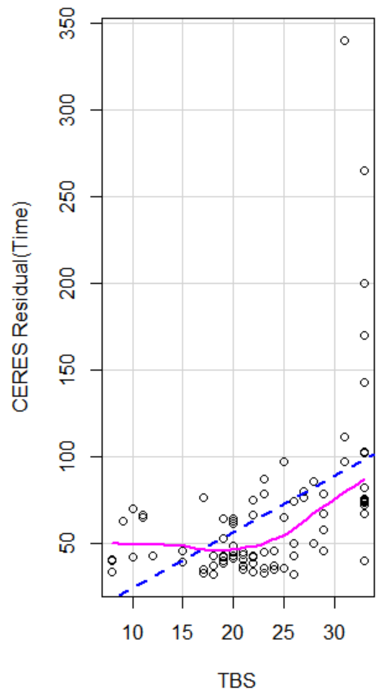

Figure 21. Illustrates a more linear relationship between Time and TBS after being log transformed.

```
Response: Time
          Df Sum Sq Mean Sq F value    Pr(>F)    
TBS        1  43526   43526 29.0098 6.885e-07 ***
Max_Temp   1  11032   11032  7.3531  0.008172 ** 
Min_Temp   1    256     256  0.1709  0.680443    
Type_FE    1  27750   27750 18.4952 4.719e-05 ***
Residuals 81 121531    1500                      
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Figure 22. Linear regression estimating time from TBS, Max and Min Temp, and Fire environment. Min Temp was found not to be significant.

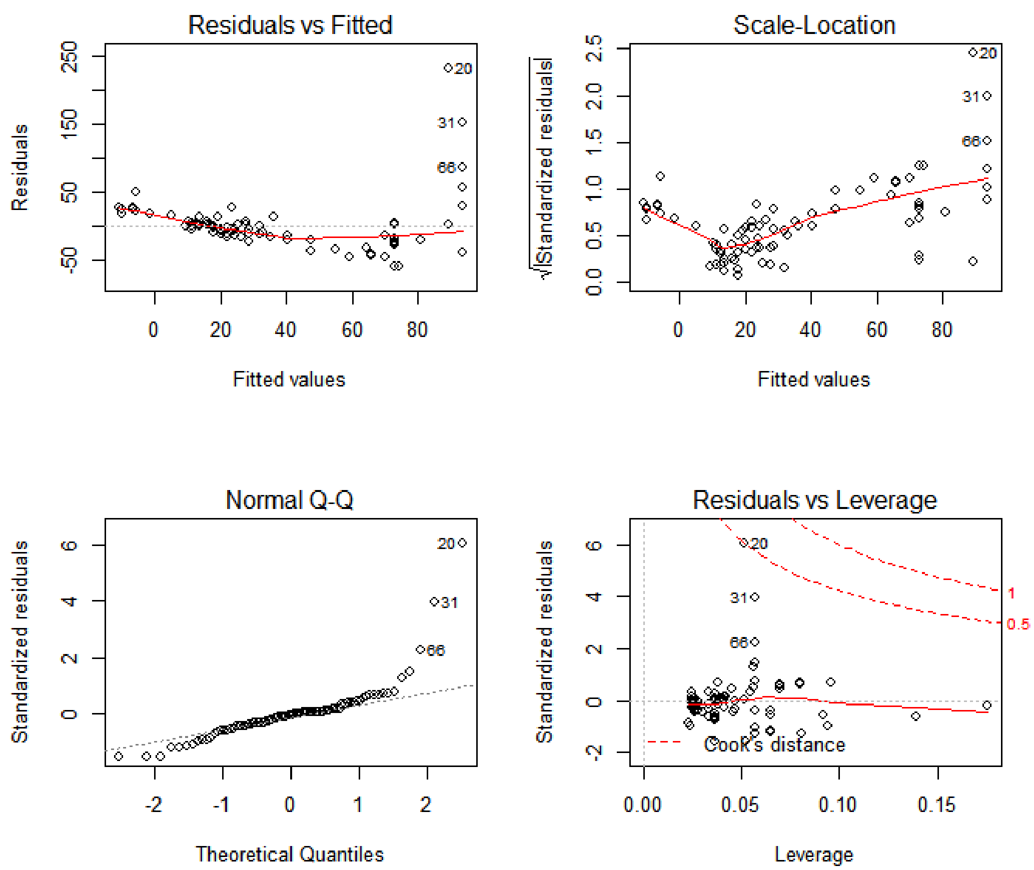

Figure 23. Plot of residuals for linear model estimating type of fire environment.

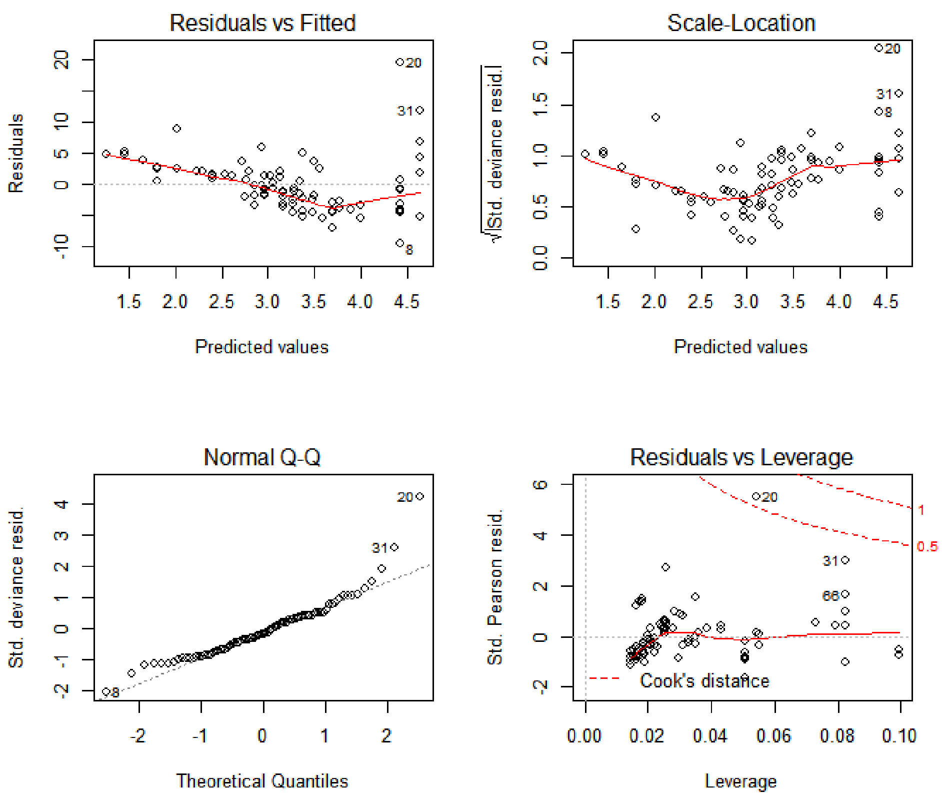

Figure 24. Plot of residuals from linear model estimating time.

```
Residual standard error: 42.21 on 84 degrees of freedom
Multiple R-squared:  0.2678,	Adjusted R-squared:  0.2503
F-statistic: 15.36 on 2 and 84 DF,  p-value: 2.068e-06
```

Figure 25. Illustrates the R-squared from linear model estimating time (R-squared= 0.25).

```
Coefficients:
              Estimate Std. Error t value Pr(>|t|)    
(Intercept) -9.0423275  0.7528980 -12.010  < 2e-16 ***
TBS          0.0362308  0.0086084   4.209  6.4e-05 ***
Max_Temp     0.0053921  0.0003762  14.333  < 2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Figure 26. Illustrates regression analysis output with fire environment scored using numerical values 1-4.

```
Coefficients:
              Estimate Std. Error t value Pr(>|t|)    
(Intercept) -9.0423275  0.7528980 -12.010  < 2e-16 ***
TBS          0.0362308  0.0086084   4.209  6.4e-05 ***
Max_Temp     0.0053921  0.0003762  14.333  < 2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘
’ 1
```

Figure 27. Illustrates regression analysis output with fire environment scored in opposite order using numerical values 1-4.

0.1-1.4 = Vehicle Fire

1.5-2.4 = Structure Fire

2.5-3.4= Confined Space Fire

3.5-4.0 = Outdoor Fire

Figure 26. Illustrates the possible outcomes for the fire environment model.