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Review

# Estimating temperature exposure of burnt bone — A methodological review

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ABSTRACT

Forensic anthropologists are frequently confronted with the need to interpret burnt bone. Regardless of the context, one of the key factors for the correct interpretation of the remains and a reconstruction of the incidents leading to incineration is the estimation of the maximum exposure temperature. The recent years have seen an influx in experimental research focusing on temperature estimation, spanning from colour assessment, mechanical strength measurements, histology and structural observations, biochemical changes and crystallinity studies, vastly advancing the understanding of heat induced changes in bone, thus facilitating a more accurate interpretation. This paper draws together and evaluates all currently available methodologies for temperature estimation.



**Contents**



## 1. Introduction

The past decades have seen an increase in burnt bone research, facilitating an increasingly comprehensive understanding of the complex changes undergone by the bone matrix when exposed to burning at different temperatures and how these changes reflect on the information which can be gleaned from the skeletal material, and a number of review papers on the current developments in burnt bone analysis have been published [1–4]. The necessity to interpret burnt skeletal remains is something personnel from multiple disciplines frequently find themselves confronted with; be the context forensic, management in the aftermath of disaster or archaeological, the common denominator in all these situations is the necessity to reconstruct the events leading up to incineration. Skeletal remains provide crucial information to achieve this. Particularly if the original context has been disrupted, the bones

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might be the sole source of information left. In essence, heated bone undergoes four stages of transformation [4,5]: 1) dehydration, the breaking of the hydroxyl-bonds and the loss of water loosely mechanically bound to the matrix, 2) decomposition, marked by the removal of the bones' organic components by pyrolysis, 3) inversion, the loss of the bone's carbonate, and finally 4) fusion, characterized by the melting and coalescing of the crystal matrix. The micro- and nano-structural changes attending those phases manifest themselves, amongst others, in observable alterations to the bones' colour, morphology, microstructure, mechanical strength and crystallinity. Bone exposed to fire can undergo several distinct stages, that should be distinguished, all of which fall under the umbrella term of “burnt bone”. “Charred bone” refers to bone that has been exposed to direct contact with a heat source, exhibiting a black appearance due the carbonization of skeletal material and soft tissue [6]. “Calcined” or “incinerated” bone has been thermally altered to such an extent that all organic material and moisture has been lost, leaving the bone distorted, warped and fractured with a white appearance [6]. Another term, which frequently appears in the literature, is that of “cremains”. Cremains is a neologism introduced by the funerary industry, which refers to the calcined skeletal fragments and particles remaining after the cremation of human remains. The cremains may be further processed by mechanical grinding to a fine powder, commonly referred to as “bone ashes” [7]. Burnt bone analysis is an anthropological sub-discipline, as fast developing and dynamic as it is multi-facetted. This review will focus solely on the estimation of the maximum burn temperature, knowledge of which gives vital information about the incineration conditions. Depending on the circumstances, exposure temperatures vary quite significantly; an average campfire reaches temperatures of around 400 °C, a house fire 700 °C, a burning motor vehicle can reach 900 to 1100 °C, especially if petrol or other accelerants are involved, commercial crematoria operate at 900 to 1000 °C and natural firestorms have been reported to reach temperatures of up to 2000 °C [6–8]. This paper will review all approaches to burn temperature estimation from bone which to date have been described in the literature, as well as evince possibilities for valuable future research to increase accuracy and refine methods of burn temperature predictions.

**Table 1**
variations in colour observations in different experimental designs (I: Wahl, II: Shipman et al., III: Quatrehomme et al.).

| Temperature | Colour observation |
|---|---|
| 100 | I. yellow-white |
| | II. neutral white/yellow |
| | III. yellowish |
| 200 | I. yellow-white |
| | II. neutral white/yellow |
| | III. yellowish |
| 300 | I. brown-black |
| | II. reddish-brown/dark brown/dark grey/reddish yellow |
| | III. dark grey |
| 400 | I. brown-black |
| | II. reddish-brown/dark brown/dark grey/reddish yellow |
| | III. grey-black |
| 500 | I. grey |
| | II. black/blue-grey/some reddish yellow patches |
| | III. black |
| 600 | I. grey |
| | II. black/blue-grey/some reddish yellow patches |
| | III. black |
| 700 | I. milky-white |
| | II. mostly white/some grey-blue patches |
| | III. light grey |
| 800 | I. white |
| | II. mostly white/some grey-blue patches |
| | III. light grey |
| 900 | I. white |
| | II. mostly white/some grey-blue patches |
| | III. white |
| 1000 | I. white |
| | II. white/some reddish-yellow patches |
| | III. white |

## 2. Visual assessment — colour

Relatively early on in the study of cremains, colour changes have been taken as an indicator for the temperature ranges bones have been exposed to [4,8,9]. Since then many studies have involved themselves with understanding the colour changes burnt bone undergoes and its consequences for the interpretation of events leading up to the incineration [10,11]. Many factors besides the exposure temperature, such as the exposure time, positioning to the heat source and oxygen availability, play a role in what colour heat exposed bone exhibits; colour changes reflect the ratio between organic and inorganic components of the bone and their response to these temperatures [4]. Fresh bone normally exhibits a light ivory colour, which turns over brown into black as a result of carbonization, the incineration of organic materials of carbon and collagen [4,10]. The next stage in the combustion process is the pyrolization of organic compounds, resulting in a grey shading of the bone, which then gives way to the bone becoming white, signalling calcinations and a complete loss of all organic compounds and fusion of bone mineral [4]. Though the actual temperatures these visual changes have been attributed to vary between the different studies and experimental setups [8,12,13] (Table 1), the sequence those stages occur in always remains constant; the temperatures at which these colour changes were reached, however, vary considerably. Nicholson [14] found the onset of colour changes to greatly vary between bones of mammals, birds and fish, attributing these observations to the differences in organic content and bone chemistry. For the same reasons subtle variations are also likely to be seen between bones of different species or even individuals. Most often the entire range of colour changes are exhibited on skeletal remains of an individual exposed to fire, frequently even on individual bones [15]. These colour gradients are produced as the bone dehydrates and becomes exposed through the loss and shrinkage of protective muscle tissue [6]. Symes et al. [6] reject other author's conclusions that the exhibition of such colour gradients does not allow any conclusions on fire dynamics involved; moreover they stress that skeletal elements and individual bones burn in predictive patterns progressing with time and depending on the anatomical area, allowing valuable insight into the progression of a fire. Bones are at first shielded by the surrounding soft tissue. The speed at which a body is completely destroyed in a fire also depends on other factors such as for example clothing or obesity, which can accelerate the process. Subsequent to the destruction of skin, the subcutaneous fat tissue is exposed, which once ignited burns independently and acts as a fuel source generating flames with temperatures of between 800 °C and 900 °C [16,17]. According to Spitz and Spitz [16] it takes around 20 min for a body to char in a blazing house fire and skeletal structures only become exposed after a considerable amount of time; research carried out by Richards [18] indicated that at an average temperature of 650 °C, rib cage and facial skeleton are exposed on average after 20 min and complete defleshing of femur and tibia occur after 35 min. These observations were confirmed by Bohnert et al. [19] who observed and documented the cremation of 15 undissected bodies. Once the soft tissue is removed and bone is exposed to the heat directly, it burns from the outside to the inside. Frequently bones which appear calcined externally merely reached the black charred stage internally. This burning is never uniform across any individual bone, it is this ununiform gradient of colour changes however, which can give valuable indications about the stage of progression of the thermal damage [6]. Symes et al. [6] further suggest the categorization of colour change progression on bone into (1) calcined, (2) charred, (3) border and (4) heat line. They define calcined as bone which is white in colour, has lost all organic components and is merely held together by a framework of fused bone salts. Charred bone exhibits a black colour after direct contact with heat and flames which carbonized the skeletal material; it frequently still has