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Experimental study on the fuel requirements for the thermal degradation of bodies by means of open pyre cremation

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ABSTRACT

The results of a systematic study of open pyre cremation of bodies is reported here with the aim of providing quantitative information on the mechanisms controlling the cremation process and the relationship between the characteristics of a fire and the level of consumption of a body. Systematically constructed timber pyres and recently euthanized pig carcasses (as surrogates for human bodies) were used to establish the importance of fuel quantity, methodology of fuel application, body size and body arrangement. The results indicate that a fuel/body mass ratio greater than 9 is necessary to overcome the endothermic effect of the body on the pyre. Even with a fuel/body mass ratio of 9 and ideal burning conditions full destruction of all organic matter could not be attained.

1. Introduction

For centuries, cremation has been used as a means to dispose of bodies. The reasons encouraging the use of cremation can range from sanitation to religious beliefs or disposal of bodies after criminal acts. Bodies affected by intense heat can also be a source of information. In the event of unwanted fires that result in fatalities, thermally degraded bodies can be a vital piece of evidence. A key element of forensic investigations is the identification of the bodies from the cremation remnants [1]. The capacity to establish the identity of the bodies relates closely to the level of destruction. Dentures and DNA are some of the most important means of identification and generally allow for the establishment of the identity of the bodies even under very severe burning conditions [2]. The degradation of the bodies has to be correlated with the dynamics of the fire to complete a forensic investigation. Consistency between the level of destruction of a body and the burning efficiency, intensity and duration of possible fires has to be demonstrated to infer the validity of a cremation hypothesis [1,2].

A very high-profile example where this correlation became key to establishing the validity of a forensic hypothesis relates to what has been referred to as the “Historical Truth” in the case of the 43 disappeared students in Ayotzinapa, Mexico [3]. A forensic investigation concluded that multiple bodies (up to 43 bodies) were cremated in the municipal dump of Cocula. The human remains discovered in the dump showed no remnants of DNA due to the high level of heat exposure. A subsequent expert panel concluded that there was a need to conduct realistic experiments to establish the detailed characteristics of the fire necessary to achieve the observed levels of cremation (i.e. intensity of the fire, amount of combustible materials necessary, etc.) [4]. To reach this conclusion the panel verified that the necessary experimental data was not available. It is not uncommon that after a fire, those conducting the investigation, find that necessary quantitative data is not available. As established by the expert panel [4], an area where there is little quantitative data is thermal interaction between a fire and those individuals exposed to the fire.

The interactions of a body with a flame are extremely complex, thus empirical data is one of the few means to characterize the manner in which a body can be affected by flames. While information on different forms of cremation seems to populate the literature, none of this information provides quantitative data on the amount of fuel necessary for the complete destruction of a body using an open-air pyre, the necessary burning duration, the effect of multiple body interactions and the net energy output of a body under different levels of exposure. The present study was conducted to provide adequate data that allows one to infer the interaction between a body and the fuel during the process of open pyre

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cremation.

A human body contains on average of 65%–70% water, 20% organic matter and the rest are bones (10%–15%) [5]. Incineration aims at the destruction of organic matter and has to overcome the energy required to vaporize the water. Schmidt and Symes [2] summarize the typical characteristics of human body cremation. They indicate that for incineration to be legal, bone residues cannot have organic matter for body identification. The bone remains are fragile but they generally maintain similarity with their original characteristics. Colour changes to white, and when they are moved away from the furnace, they tend to fracture. Generally, the data shows that the legal incineration of an adult body, in a crematory furnace, requires a temperature between 800 °C and 1000 °C for 90–120 min. These values vary, according to the literature, because of the variability of bodies [5], furnaces and fuel to be used [2]. Nevertheless, the reported temperatures and times are mostly within the ranges indicated above.

The design of a crematory furnace is not simple [6]. The design objectives are to maintain a homogeneous temperature, to quickly evacuate degradation products (keep the furnace ventilated) and concentrate the combustion energy to achieve a high efficiency. It is important to emphasize that efficiency is defined on the basis of the amount of fuel necessary to maintain the desired temperature during the cremation period. Water vapour and combustion products have an important effect in the efficiency of the burners of an incineration furnace. The effective elimination of these products from the combustion furnace can ensure a more complete combustion and thus a higher efficiency. Therefore, ventilation is essential to maintain an efficient and homogeneous combustion. Furnaces are lined with low-density refractory bricks so that the bricks surface can rapidly heat to the temperature of the gases, thereby, converting all the energy into radiation. This refractory material enables the furnace to provide the body with a homogeneous heat flow ensuring a complete cremation of the whole body [6].

Combustion in a crematory furnace is generated by gas burners that approximate complete combustion and therefore is highly efficient. Open air burning, where all the fuel is placed horizontally, is at the other extreme of efficiency. The supply of fuel and air is complex and inefficient [7]. Crematory pyres have been studied using reconstructions that follow traditional practices. Studies show that the temperatures at the core of a pyre may exceed 800 °C for several hours. Nevertheless, large amounts of fuel are necessary to maintain the cremation process until most of the organic matter is destroyed [8]. According to McKinley [8] an ideal crematory pyre design improves combustion efficiency so that only 700–900 kg of wood are necessary to deliver bones free of organic residues. If the pyre is smaller than the body, then cold air will not allow cremation of the body's limbs. Therefore, the customary dimensions of a pyre surface are around 2.5 m. x 1.5 m [8]. The typical duration for fuel load consumption is about 6–7 h [8], allowing for 6 or 7 additional hours during which the corpse is left to be consumed by the embers [3].

The most well-known tests involving cremation of bodies for forensic investigation purposes were conducted by DeHaan with pig remains [9] which are summarized in Ref. [1]. Those tests show that when the body is wrapped in clothes, allowing the carbonization of skin and clothes, they act as a wick enabling subcutaneous fat (approximately 20% of the body mass [5]) to maintain combustion. While some quantitative information is provided, most of the results are qualitative and do not allow one to infer the exact amount of fuel necessary for cremation. An important conclusion is that the net energetic balance of a body is positive with exothermic average heats of combustion of the order of 17 MJ/kg [10] and for body fats of 39.8 MJ/kg [9]. This has commonly lead to the conclusion that once the fats are released the combustion of a body can be self-sustained [3].

An aspect that is not covered in any of these tests is the interaction between the body and the fuel. As explained above, the organic materials in the body have enough energy to evaporate the water resulting in a positive net heat release rate. Experimental studies have reported that, under specific burning conditions, peak heat release rates of up to 250 kW per body [10] can be attained. Nevertheless, depending on the efficiency of the burning process, the body might deliver a positive or negative net heat contribution to the fuel driving the cremation. The most comprehensive study on this matter is presented by Bohnert et al. [11] but it only relates to cremation chambers and does not include the interaction of multiple bodies and the impact of these interactions on the cremation process.

The only quantitative data on multiple body cremation in open air can be found in the US Department of agriculture guidelines where detailed arrangements for animal disposal are described for different animals. In the case of pigs, the report indicates that an approximate amount of 170–200 kg of fuel per carcass is necessary [12]. The fuel was a combination of hay, carbon and timber arranged in a manner that optimizes heat feedback to the carcass. The influence of different size animals and of multiple body interactions are described qualitatively. These guidelines do not indicate the level of destruction attained.

Combustion of solid or liquid combustible materials (fats) adhered to non-combustible materials (bones) can be maintained as long as there is enough energy to sustain the gasification of the combustible material [13]. The energy comes from the flame, part of the energy is lost to the environment and part is transferred to non-combustible materials to which the fuel is adhered. As the combustible material is consumed, the residual combustible material is increasingly lower, thereby reducing the energy generated by the flame and increasing the fraction of the energy lost to the non-combustible material (bones and water). Finally, the flame is extinguished. Therefore, attainment of complete destruction of organic matter is not only related to the exothermicity of the body but it is mostly an extinction problem linked to the net heat feedback to the fuel. The literature describes this process of extinction as quenching and relates it to the need to attain a minimum heat feedback that maintains the flame at a temperature sufficient for combustion to occur (critical mass transfer number) [13]. Heat transfer is configuration dependent, thus very much affected by the burning conditions and geometry. To characterize the extinction process for an open pyre burning of multiple bodies, it is therefore necessary to study the cremation process in the specific configuration.

Most of DeHaan's tests [9] were voluntarily extinguished, except for one of the tests in which, after a burning period of almost 4 h, the fire was allowed to extinguish naturally. DeHaan reports that when the fire fully extinguished (after 6 h) about 50% of body mass (including significant organic residues) remained. Data that enables one to understand the extinction process is therefore not available.

The present study attempts to fill a gap in the literature by reporting on a series of systematic experiments that address complete destruction of organic matter during open pyre incineration by focusing on extinction. The results include the amount of fuel necessary for the complete destruction of a body using an open-air pyre, the necessary burning duration, the effect of multiple body interactions and the net energy output of a body under different levels of exposure.

2. Experimental setup

Six experiments were conducted in an open field. The experiments consisted of burning pig carcasses on top of a wood pyre (fuel), using different numbers of carcasses and different fuel-to-animal mass ratios (F/A). The pigs were always placed as close as possible to the centre of the pyre making sure that there was good contact between the carcass and the wood. Details of these experiments are summarized in Table 1.

Pig carcasses have been commonly used as surrogates for human bodies, and while differences between organic matter from a pig and a human body are significant [14], the similarities have been long recognized [15].

For the experiments with one pig carcass (1–4), a blank test was conducted at the same time, using an identical second pyre but without a pig carcass on top. The two fires were set at 15 metres apart to avoid feedback or interaction between the two fires. Both fires were ignited at