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# Performance assessment of the firefighting personal protective tunic

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**Abstract**

Although there have been reported cases of rapid improvement in the research and development of materials used for the betterment of firefighting tunics in developed countries, however, in developing countries, especially in Nigeria, the dearth of such research and development has led to the loss of lives and properties on numerous occasions due to the use of substandard firefighting tunics when combating fire. Hence, it is necessary to carry out a performance assessment on the firefighting tunic available in Nigeria. The safety of the firefighters is important as it is only then that they can fully carry out their duties and tasks. Of all the products that make up a complete assemble of the firefighters' Personal Protective Equipment (PPE), it is their personal protective tunic that was employed for this research. The city of Ota in Nigeria was used as a case study due to the high concentration of industries and teeming population which makes it a target for pipeline explosions amongst others. Having a single fire station in the city, a sample of the firefighters' personal protective tunic was obtained and specified experiments were carried out to determine its thermophysical and elemental properties with a goal to understand its quality and standard. The research seeks to provide useful information to stakeholders in the firefighting industry on the standard of protective tunics used in fire stations.



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## *1. Introduction*

Firefighting is a physically demanding and risky occupation even though it is not necessarily an occupation involving day-to-day activities[1]. Due to the high risk involved in carrying out actions such as rescuing victims and moving heavy objects under stressful conditions, the lives of the firefighters are constantly threatened[2]. Firefighting activities exposes firefighters to hazards such as biological and chemical toxins in addition to regular flame impact, high temperatures and radiant heat. However, firefighting continues to remain an integral and essential occupation and has accounted for the rescue of countless lives across the globe. It is also worth noting that firefighters are not limited to rescuing victims from fire incidences alone, as they also engage in such activities for various other incidences including floods, road accidents, building collapses and chemical spills[3]. According to data from The Fire Brigades Union, an average of 105 lives are saved per day in England. Moreover, figures from another English based firefighting service, West Midlands Fire Service, show that 38,144 lives were saved in England alone between April 2014 and March 2015[3]. These statistics further emphasize the relevance of firefighting to humanity as a whole. As such, it is imperative that fire services should be provided with the best available resources at all times to enable them effectively carry out their tasks. These tasks include structural firefighting, rescue work, wildland firefighting, specialized firefighting and hazardous materials' response which are classified based on level of fire exposure and type of hazard[4]. To this effect, consideration must be made when choosing tools and equipment to be used by firefighters in combating fire incidences given the wide range of variance in quality of such tools and equipment. As part of the concern for the safety of the firefighter when fighting fire, this project focuses on the firefighters' tunic. The function of the firefighters' tunic is basically to protect the firefighter against fire and other harmful hazards as well as provide comfortable mobility to the user when on duty[4]. When it comes to purchasing a tunic (jacket and trousers inclusive), the product sellers will do what is in their power to ensure their product is sold and it is left to the buyer to believe what he has bought is really what he wants to buy, hence, "Caveat Emptor" which is Latin for "buyers beware"[5]. The purpose of firefighting tunics is to protect their wearers from the effects of heat and flames so that such persons can work with safety in environments where they risk injury or even death without the tunic's protection.

**Nomenclature**

| | |
|---|---|
| A | area |
| ρ | density |
| R | thermal resistivity |
| k | thermal conductivity |
| α | thermal diffusivity |
| SHC | specific heat capacity |

### 1.1. Firefighting tunic

Firefighting tunics are in various varieties. While this spurs from the ever-continuous research and development carried out by different organizations in order to make the tunic jackets and trousers safer and more durable, there are certain standards that these tunics must meet in our world today for them to be qualified to use in firefighting. A certain standard that firefighter tunics must meet is being fire resistant. This of course, is necessary, given that the job description mainly constitutes of literally fighting fire.

Figure 1: Firefighting tunic (jacket & trouser)

Both firefighting tunic jackets and trousers consist of three distinct layers which includes the outer covering, thermal liner and moisture layer [6]. The outer covering, being a woven fabric (which prevents tear), provides 25-30% of the tunic's thermal protection and is the first layer to be exposed to the physical hazards of a fire scene. It is so constructed to also reduce water absorption. The outer covering is the fire-resistant layer, which can be made from various fire-resistant materials such as aramid fibres (para and meta). The inclusion of viscose and wool (both being flame-retardant) serves to increase the rate at which moisture is absorbed for the outer covering fabrics and these fabrics are produced using ripstop or twill woven fabrics which weigh 195-270 $g/m^2$. The kind of fabric used is also affected by the type of task to be performed. For example, aluminized fabrics can consist of flame-retardant cotton or wool and are used in some cases for specialized or structural firefighting. The aluminium can be used in various ways including as an aluminized film or thin foil. The objectives of the research are as follows:

- To determine the thermophysical properties of the firefighting tunic using thermal apparatus such as the automated Lee's Disc apparatus and bomb calorimeter.
- To investigate the effectiveness of the tunic material based on the elemental analysis

## 2. Literature survey

Although there are quite a good number of standardization organizations such as the International Organization for Standardization (ISO) and the European Committee for Standardization (CEN), the most internationally recognized standardization organization in the firefighting industry is the National Fire Protection Association (herein referred to as NFPA). The NFPA is a fire services organization based in the United States and is responsible for forming over 275 codes and standards that govern not only firefighting equipment and services, but as well as building, design, process and installation [7]. The NFPA is actually not an enforcing agency in itself but even so has its standards approved and enforced by all levels of government. This goes to show how highly their codes and standards are regarded. The NFPA revises each standard of theirs every five years to ensure it is up to date with current knowledge and technologies in fire protection. Its wide international reception comes due to the openness it provides to various committees in contributing to such codes and standards and thus, operates with the idea of voluntary consensus standards writing. An example of an NPFA standard is the Independent Service Provider (ISP), which requires a cleaning company to be independently verified by an independent third-party agency before being allowed to repair, clean or inspect fire departments [8]. Another standard is that which requires firefighting tunics to be disposed of after a duration of ten years from its manufacture date or when it becomes irreparable and can no longer pass an NFPA 1851 Advanced Inspection. The NFPA 1971 is the standard set as the benchmark for quality when it comes to firefighting tunics. Hence, though products from different companies may vary in cut, style and closure of the tunic, they must attain this standard in order for acceptance and viability [9]. Such is the strife to attain the standard that there are cases where models possess qualities that even go beyond NFPA 1971 the specifications. Makinen[4]wrote extensively in his journal, *Firefighters' Protective Clothing*, on the measurements and procedures implored by organizations such as the NFPA, CEN and ISO in determining the standard compliance of materials used for the performance assessment of firefighting tunics. From his work a general idea is given on the categories available in performing such experiments which include laboratory experiments such as material and biophysical measurements (biophysical measurements using dummies equipped with sensors for heat or cold measurement), as well as using human subjects. Dąbrowska[10] performed an experiment to discover the effect of structural (design) solutions on the thermal resistance of firefighters' protective tunics, as she found that there existed some sort of relationship. By design solutions she means implemented structures, materials textiles and so on used in the production of protective tunics. From her experiment she found that such design solutions can shape both the tunic's overall and local thermal resistance. Test dummies were used in this experiment so as to give a human-like simulation of the effect. Among her findings, a discovery was made in the use of a bib in the tunic's trousers which had a paramount effect on the tunic's thermal resistance. Other design solutions with positive effects included the jacket's length as well as the use of hoods. Also, the use of other design solutions such as reflective strips, jacket fixings and pockets were found to have minimal impact. Thermal protective performance (TPP) is a standard method for testing the thermophysical properties of a material, developed by the NFPA. Heat loss of a material is the amount of heat that leaves the fabric of such material and may be in the form of convection, radiation or conduction as well as a combination of any of them [1]. The total heat loss (THL) and thermal protective performance form the two main test parameters used in investigating the standard of a firefighter's protective tunic [11]. It has been found that a relationship exists between these two parameters as tested in a given experiment. Jung-Hyun *et al.*[11]performed an experiment in a laboratory to determine the kind of relationship that existed between these two parameters using dummies as test subjects and in order to also determine its effect on the dummies. Three firefighter tunics were used for the experiment and were obtained from South Korea, Europe and the United States. The testing method involved immersing the various tunic types in gulfs of fire. He and his team of researchers came to a conclusion that there was an inverse relationship between the TPP and THL ($r=-.949$, $p<.001$) and their effect on the test dummies gave the following results:

- In terms of second and third-degree burns, total predicted area was given as 7.2 ± 1.6, 19.7 ± 4.1 which gave a 5.0 ± 1.0% for all three firefighting tunics
- THL and TPP gave readings of F=34.630, p=0.001, R2=.920 for the same criteria
- The results also showed that most burns occurred around the limbs and head

These results conclude that the inverse relationship between TTP and THL has an adverse effect on the firefighter tunics tested, given the level of burns sustained.

It is common knowledge that the less weight one carries, the lighter the person becomes which enables and facilitates faster movement. The same knowledge can be applied in the context of this subtopic where Park[12] sought to perform an experiment (biomechanical experiment) with a team of fellow researchers, to determine the level of influence the firefighter's protective tunic, along with other working equipment, had on the firefighters in question using four female and eight male firefighters as test subjects. In addition to the overall tunic, other firefighter equipment used for the experiment included boots (rubber and leather) and self-contained respiratory equipment. This led to the finding that while a firefighter is fully equipped with these essentials, there is a limitation to movement, especially at the feet and this was backed up by the observed decrease in walking trajectory being the medial-lateral excursion and anterior-posterior of the COP- centre of plantar pressure [13]

*3. Materials*

For this project there is only one material used in performing experiments which is a cut-out part (pocket for precision) of the firefighting protective tunic obtained from the Ota Fire Station, in Ota, Ogun State.

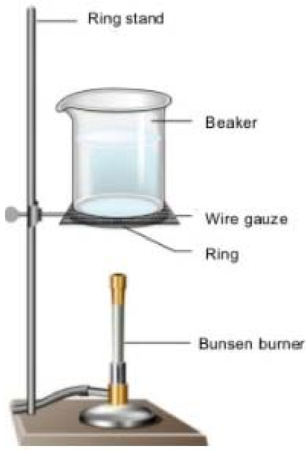
Figure 2: Spherical cut-out of Ota firefighting tunic sample material

*3.1 Methods*

The test for the specific heat capacity of the sample material was the first experiment conducted. The specific heat capacity of a material or substance is the exact amount of heat needed by a unit mass of that material (either in addition or subtraction) for its temperature to change by one Kelvin. To perform this experiment, the following apparatus were used:

- A thermometer
- A copper calorimeter
- One Bunsen burner
- One 250 ml beaker
- Thread
- An electric beam balance
- Wire gauze with ring and ring stand


250 ml Beaker




Copper Calorimeter

Beaker and Bunsen burner set up

Figure 3: Apparatus for specific heat capacity of sample by method of mixtures

This apparatus for thermal conductivity called the automated Lee's Disc apparatus was developed by Phillip and Fagbenle[14]as a digital alternative to the original. It constitutes a set of electrical wirings enclosed in a rectangular wooden box with two small digital screens arranged one above the other at the surface front. Two wires extend from the back with metal discs attached to each. These metal discs are the heat source and sink and are attached to a heating element coupled with a thermocouple. Its mode of operation is simple as the user need only firmly set the material in between the metal discs by tightening them together with a screw as there is a provision for that. Next, the apparatus is put on through its wire on plugging to a power source.


Figure 4: front and rear view of automatic Lee's disc apparatus[14]

The procedure employed in using the automated Lee's disc apparatus for the second experiment is explained below:

- Firstly, a suitable temperature-controlled environment with minimal heat interaction was used for this experiment
- The apparatus' discs are 50 mm in diameter and so a portion of the sample was cut to that size using a pair of scissors. The cut out sample piece was placed between the discs and firmly tightened. This is in order to ensure that heat will be supplied at a steady state from the source to the sample and to the sink
- On the digital screens, set both to initial temperatures of 50 ºC and switch the apparatus on by plugging to a power source.
- The temperature supplied to the sample forms the initial and final temperatures $T_1$ and $T_2$ and the values as seen on the screens (top screen for $T_1$ and lower screen for $T_2$) are recorded every 5 minutes for up till an hour after which the sample is removed then the metal disc is heated say 10ºC above the heating temperature and allowed to cool off steadily up till 5 minutes below the final heating temperature to determine the rate of heat loss from the base plate
- These steps are repeated three times with intervals of about 30 minutes to determine the average temperatures to be used in calculations

## 3.2 Heat of combustion

The oxygen bomb calorimeter is a calorimeter type used to determine the heat of combustion of a given material (be it in solid or liquid state). It comprises of water, oxygen (from an oxygen cylinder), the sample material, and a stainless-steel bomb. In the crucible, the sample material is placed and oxygen is used to pressurize the bomb. A wire is placed on the material and current passes through to cause an ignition. At the end of combustion, there is a rise in temperature of both the bomb and the water bath and that rise is recorded.

## 4.Result and discussion

For the first experiment, being test for specific heat capacity, the results obtained are shown below:
Mass of sample $M_S$ = 1.1035g

Mass of calorimeter & stirrer Mc = 500g

Mass of calorimeter & stirrer + water $M_l$ = 900g

Initial temperature of normal water, $\theta_1$ = 30 ºC = 273 + 30 = 303 K

Temperature of boiling water, $\theta_2$ = 100 ºC = 273 + 100 = 373 K

Final temperature of mixture, $\theta_3$ = 46 ºC = 273 + 46 = 319 K

Specific heat capacity (S.H.C.) of sample $C_s = \frac{Q}{m \times \Delta T}$

Thermal energy, Q = 40 W

Specific heat capacity (S.H.C.) of sample $C_s = \frac{40}{1.1035\times10^{-3} \times (319-303)}$

$$C_s = \mathbf{2265.5\ JKg^{-1}K^{-1}}$$

S.H.C. of copper calorimeter Cc = 385 $JKg^{-1}K^{-1}$

S.H.C. of water $C_w$ = 4200 $JKg^{-1}K^{-1}$

Neglecting any heat losses to the surroundings

Heat lost by solid = Heat gained by water + Heat gained by copper calorimeter & stirrer.

$M_S C_s (\theta_2 - \theta_3) = (M_l – Mc)\ Cw\ (\theta_3 - \theta_1) + Mc\ Cc\ (\theta_3 - \theta_1)$

From the above formula, (National Board for Technical Education, 2008), the specific heat capacity of the sample will be calculated as stated below:

$$C_s = \frac{(M_l - Mc)\, Cw\, (\theta_3 - \theta_1) + Mc\, Cc\, (\theta_3 - \theta_1)}{M_S\, (\theta_2 - \theta_3)}$$

$$C_s = \frac{(900\times10^{-3}-500\times10^{-3})\, 4200\, (319-303) + 500\times10^{-3} \times 385\, (319-303)}{1.1035\times10^{-3}\, (373-319)}$$

$C_s = 502777\ JKg^{-1}K^{-1}$

4.1 Thermal conductivity

This experiment was performed using the digitized innovative Lee's disc apparatus and the temperature readings for the heating and cooling temperatures obtained are shown below:

Table 1: Heating Temperature Process of Sample

| HEATING TEMPERATURE PROCESS OF SAMPLE (°C) | | | | | | |
|---|---|---|---|---|---|---|
| Time (min) | 1st Round | | 2nd Round | | 3rd Round | |
| | T1 (°C) | T2 (°C) | T1 (°C) | T2 (°C) | T1 (°C) | T2 (°C) |
| **0** | 50 | 50 | 50 | 50 | 50 | 50 |
| **5** | 29 | 30 | 28 | 29 | 31 | 31 |
| **10** | 62 | 32 | 29 | 30 | 72 | 43 |
| **15** | 57 | 40 | 31 | 30 | 63 | 44 |
| **20** | 63 | 41 | 70 | 46 | 55 | 42 |
| **25** | 62 | 50 | 58 | 51 | 50 | 40 |
| **30** | 55 | 46 | 52 | 47 | 66 | 43 |
| **35** | 50 | 45 | 60 | 46 | 60 | 42 |
| **40** | 64 | 50 | 60 | 51 | 51 | 40 |
| **45** | 52 | 47 | 53 | 49 | 65 | 39 |
| **50** | 63 | 45 | 62 | 47 | 64 | 42 |
| **55** | 56 | 44 | 58 | 51 | 56 | 41 |
| **60** | 51 | 41 | 55 | 50 | 52 | 40 |

Table 2: Cooling Temperature Process of Sample

| COOLING TEMPERATURE PROCESS OF SAMPLE (ºC) | | | |
|---|---|---|---|
| **Time (min)** | $1^{st}$ Round (ºC) | $2^{nd}$ Round (ºC) | $3^{rd}$ Round (ºC) |
| **0** | 60 | 60 | 60 |
| **1** | 42 | 48 | 42 |
| **2** | 42 | 47 | 41 |
| **3** | 41 | 46 | 40 |
| **4** | 40 | 45 | 40 |
| **5** | 40 | 45 | 39 |
| **6** | 39 | 44 | 38 |
| **7** | 38 | 43 | 38 |
| **8** | 38 | 43 | 38 |
| **9** | 38 | 42 | 37 |
| **10** | 38 | 41 | 37 |
| **11** | 38 | 41 | 37 |
| **12** | 38 | 41 | 37 |
| **13** | 37 | 40 | 36 |
| **14** | 37 | 40 | 36 |
| **15** | 37 | 39 | 35 |

From the heating table, the average values for $T_1$ and $T_2$ are given as 54.2 ºC and 46.7 ºC.

Area of sample, $A = \pi r^2$

Radius of cut-out sample = 25 mm = 0.025 m

$$A = 3.142 \times 0.025$$

$$= \mathbf{0.0785\ m^2}$$

Sample thickness = 0.00024 m

Volume = Area × thickness

$$= 0.0785 \times 0.00024$$

$$= \mathbf{1.884 \times 10^{-5}\ m^3}$$

Density, $\boldsymbol{\rho = \frac{m}{v}}$

Mass of sample = 1.1035g = 0.0011035 kg

$$\boldsymbol{\rho = \frac{m}{v}}$$

$$\boldsymbol{\rho} = \frac{0.0011035}{0.00001884}$$

$$\boldsymbol{\rho = 58.57\ kg/m^3}$$

Thermal Conductivity, $\mathbf{k} = \frac{mcd\,(dT/dt)}{A\,(T_1 - T_2)}$

Where m = mass of sample

c = specific heat capacity of sample

d = sample diameter (50 mm)

A = cross sectional area of sample

$T_1$ & $T_2$ = initial and final temperatures (ºC)

dT/dt = temperature variation with time

The rate of loss of heat from the base plate being by radiation and convection, the base plate is polished so that radiation losses are small and Newton's law of cooling can be applied. We can assume that the heat lost from the sides of the sample itself is negligible. The rate of cooling dT/dt can be found by taking the gradient of the curve at that point, and if the mass m and specific heat capacity C of the material of the base plate are known, its rate of loss of heat can be found. The thickness d$x$ of the samples were determined using Vernier caliper and cross-sectional area, A, determined by calculation from fixed 50mm diameter marked out with a pair of compass and cut to size with a pair of scissors.

Gradient of cooling curve = 0.5828 ºC/s

$T_1$ = 54.2+273 = 327.2 K

$T_2$ = 46.7+273 = 319.7 K

$$k = \frac{0.0011035 \times 2265.5 \times 0.5828}{0.0785\ (327.2 - 319.7)}$$

**k = 2.47 W/mK**

The calculated thermal conductivity is 2.47 W/mK which signifies that the sample's ability to conduct heat is very low.

Thermal diffusivity, $\boldsymbol{\alpha = \frac{k}{\rho c}}$**,** is a material property that characterizes unsteadiness in the material's heat conduction. It shows how fast a material responds to temperature change.

$$\alpha = \frac{2.47}{58.57 \times 2265.5}$$

$\boldsymbol{\alpha = 1.86\times10^{-5}\ m^2/s}$

This means that for every change in temperature, the sample reacts at a speed of $1.86\times10^{-5}$ meters square for every second.

The thermal resistivity, R, is the reciprocal of thermal conductivity as it measures heat resistance through temperature difference.

$\mathbf{R = {}^{1}/_{k}}$

**R = 0.405 W/mK**

The result of the experiment using the digitized innovated Lee's disc apparatus gave a thermal conductivity value, k, of the sample as 2.47 W/mK under a temperature of 50 ºC. This value for any other sample purpose is very low but for the cause of firefighting protective tunics, it is quite high as such protective clothing must be able to conduct heat in the least possible way.

Also, in comparison to the ASTM C 518 standard results obtained by[15], this thermal conductivity value is very high as in the case for unconditioned materials, with an approximate range from 0.034 W/m K to 0.093 W/m K under temperatures of 20 ºC, 48 ºC, 55 ºC and 72 ºC. This comparison shows that the sample material used in this project has a high ability to conduct heat and therefore does not fall within the required standard for the thermal analysis of thermal conductivity, making it unsuitable for use as a firefighting protective tunic.

## 5. Conclusion

The result of this research shows level of substandard firefighting PPE and tunic being used in Nigerian fire stations. Thus, the Nigerian government in collaboration with the Federal Fire Service of Nigeria should ensure that fire stations are provided with the required national and international standard of protective tunics and equipment needed in order to effectively carry out firefighting activities so as to cut losses in life and property to the barest minimum.

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