Contents lists available at Science-Gate

International Journal of Advanced and Applied Sciences

Journal homepage: http://www.science-gate.com/IJAAS.html

Lighting and orientation-lighting fire equipment: Trends and prospects

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ARTICLE INFO

Article history:
Received 25 November 2021
Received in revised form
5 January 2023
Accepted 18 January 2023

Keywords:
Fire helmet
Firefighter light
LED lighting system
Firelight cables
Fire beacon

ABSTRACT

The purpose of the article is to carry out an analysis of modern fire-fighting equipment and lighting accessories based on a review of scientific journals and technical passports of lighting equipment. A comparative analysis of fire-fighting helmets in the aspect of comparison of lighting accessories has been carried out in the article; factors that should be considered when choosing lighting equipment have been determined. A comparative analysis of qualitative and technical characteristics of fire-fighting lanterns and their positive and negative sides have been carried out based on these factors. The characteristics of auxiliary lighting equipment have been described. The materials of the study included works published during the last eleven years which made it possible to present the latest finding on the study subject and to draw the relevant for future studies conclusions. The results of the study allowed outlining the significance of the lighting and orientation of light fire equipment in eliminating fires and rescuing victims (both civilians and fire service personnel). The main functional and technical advantages and disadvantages of the widely used equipment are highlighted in the study.

1. Introduction

One of the biggest challenges in rescue operations is that firefighters' eyes are obstructed by dense smoke, even though the most important task for firefighters is to quickly figure out the fire scene. When fighting fires with limited visibility, in buildings with complex layouts, it is quite difficult to determine the focus of a fire or the location of an incident (Mufeng et al., 2021). Finding their way back and evacuating people who are in the danger zone (Ryzhenkov et al., 2020; Dadashi Haji et al., 2022) is an even greater problem, compounded by the physical fatigue of rescuers and the extreme psychological and emotional strain (Asif et al., 2022). Therefore, firefighters not only have difficulty in finding victims but are also faced with danger themselves. Besides, the smoke and gas protection service unit (SGPS) usually has a limited time to get back out, which is determined by the remaining air (oxygen) in the individual respiratory and visual protection equipment (Patel et al., 2022). The problems of orientation in difficult conditions of a smoke-filled building and fixing the return route can be partially solved by the use of fire lighting and orientation-lighting equipment. The NFPA estimates that firefighters suffered a total of 127,950 fire injuries between 2014 and 2018. The vast majority of fire injuries (84%) occurred in fires in buildings. The two main causes of injury — exposure to hazards (heat or smoke) and loss of visibility due to smoke — together account for more than half (51%) of the injuries (Campbell and Molis, 2020; Campbell, 2018).

Research hypothesis is as follows: For fire service personnel to efficiently and safely perform their duties, lighting, and orientation light fire equipment plays a significant role in eliminating fires and rescuing victims (both civilians and fire service personnel).

2. Methods

The main method of research was the analysis of scientific journals on the problem of research, fire instructions, and manuals, as well as the technical passport of lighting equipment posted by manufacturers in the public domain on the Internet. When forming a source base for the study to obtain a reference on the Internet we used keywords such as "lighting fire equipment" and "limited visibility in a fire." The criterion for choosing data sources on the problem of research was the period of 2012-2022 to increase the relevance of the source base. The results of the keyword search on the Internet led to the

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selection of 8 literary sources most relevant to the research topic.

3. Results

Lighting is necessary in the following cases:

1. At night fires
2. In low-light conditions
3. In closed rooms where there is no lighting

The analysis of the literature (IFSTA, 2013) showed that firefighting equipment used to illuminate the places of firefighting and to provide light orientation for firefighters (rescuers) can be divided roughly into:

- According to their functional purpose: lighting and orientation-lighting
- According to their version: stationary (an integral part of a vehicle); carrying/mobile (equipped with a separate constructional device for movement); hand-held (construction and weight-dimension capacities allow operation by one person); portable (to be carried on the elements of equipment)
- According to the power supply: with external electric power supply and with self-contained electric power supply

Installation of stationary light sources is carried out on a specialized vehicle equipped for their connection with an onboard generator or other power sources. Stationary light sources are used when general illumination of the fire site is required. The place of installation of stationary light sources is telescopic supports, adapted for raising, lowering, or turning around an axis. In some cases, stationary light sources are combined into lighting units with a power of 500-1500 W, the number of which is limited only by the power of the power supply sources (IFSTA, 2013).

The main portable source of lighting for firefighting units in case of firefighting is helmet-mounted lighting, which includes lighting modules built into the helmet or accessories for attaching fire lights (Park et al., 2014; Nayak et al., 2014).

The design of fire helmets has been divided into reactive and traditional helmets (Lee et al., 2014).

1. Reactive helmets have a fieldless design that prevents snagging when traveling through confined spaces during a fire. The cut of the helmet also provides increased protection of the head, especially the occipital lobe, while allowing the head to move in all directions, including up and down (which is more difficult in traditional fire helmets). The new models contain communications technology built into the helmet which can be fully integrated into the existing communications systems used by the fire brigades. Besides, features in the helmet, such as LED lights, can reduce snagging and the need to carry lighting accessories. In some models, the lights are placed on the sides of the helmet, improving visibility and reducing the chance of blinding others. Helmet manufacturers typically specialize in Europe (though some US manufacturers also offer reactive helmets).
2. Traditional helmets are heavier than reactive helmets and have front and back fields. Given their design, these helmets are more prone to snagging at the scene, which can be distracting and dangerous for firefighters. Traditional helmets also do not have the built-in lighting available in the newer reactive designs, requiring firefighters to operate separate lighting accessories.

A comparative analysis of eight fire helmet models in terms of a comparison of lighting accessories is made and shown in Table 1.

Table 1: Comparative analysis of fire helmets

No.	Model	Manufacturer	Brief characteristics	Lighting
1	Cairns XF1	MSA, the US	Fire helmets of the reactive type without fields. Features a built-in light module, a rugged, compact light accessory placed inside the helmet, reducing exposure to heat, flame, and bumps. The modular design of the helmet allows for quick disassembling for thorough inspection, care, and maintenance	A flashlight built into the helmet
2	Pacific F15	Pacific Helmets Ltd, New Zealand	Combines unique Kevlar protection technology with a fiberglass-reinforced composite case. The helmet is a reactive type, utilizing an elliptical double rotation system to provide full coverage and an inner face shield that can be fully deployed. The helmet can be used with additional sidelights, which are fixed low and tight on the case to maintain an optimum center of gravity and reduce the risk of snagging	Available accessory for the flashlight
3	Gallet F1 XF	MSA Europe, Germany	Has a customizable design for responding to structural and outdoor fires, technical rescues, and traffic collisions. Contains a fully integrated lighting module to support operation and safe navigation in the dark, as well as a helmet-mounted headset for communication. This model is commonly used by French fire services	Contains a built-in light module
4	Magma®	Bullard GmbH, Germany (parent company is American)	The Magma helmet system of the reactive type is based on a platform that allows the user to customize their helmet. The system allows for individual selection without compromising comfort, safety, and functionality	Available accessory for the flashlight
5	Solo TI	Halo Tliemial Imaging, the UK	Fire helmet of the reactive type, consisting of a fiberglass/kevlar case bonded with flame retardant resin. Contains a communication system structure that must be integrated with corresponding radio systems. The mask includes a head-mounted thermal imaging camera and a thermal imaging sensor. The design provides complete protection for the head, face, and neck	Uses integrated thermal imaging
6	MSA Cairns® 1044	MSA, the US	A traditional helmet that provides thermal and penetration protection. Equipped with interchangeable padded items which can be easily removed and cleaned. Contains no integrated communications or lighting systems, but a lightweight accessory can be attached to the brim	A lightweight accessory can be attached to the side fields
7	USRX Series	Bullard USA, the US	Thermoplastic helmet specially designed for extreme search and rescue conditions. Has traditional brims with a streamlined ridge on the top to prevent snagging. Helmets are made from lightweight materials to prevent fatigue during rescue operations	Integrated LED lighting system

Let us take a look at the Bullard TrakLite® LED illumination system (Bullard, 2019). TrakLite consists of eight high-power white LEDs, which, due to the additional protection made of heat-resistant glass, function effectively in any smoky room. In addition to the block of eight LEDs located in front of the helmet, there is a bright blue indicator in its rear part, which allows one to track the owner of the helmet (firefighter).

The absence of external helmet accessories (clamps, brackets, etc.) eliminates the possibility of the helmet catching on external obstacles or weight imbalance due to the redistribution of weight between the frontal and occipital parts of the helmet, which guarantees increased safety compared to a traditional helmet lighting system. The light switch is conveniently operated with a gloved hand. The TrakLite lighting system is powered by four AAA batteries, which are charged at 50% brightness for six hours of continuous operation.

In addition to helmet-mounted lighting, fire departments use individual (hand-held, chest) and group (portable) fire lamps (searchlights).

For a firefighter, it is undoubtedly relevant to choose a flashlight that can withstand high temperatures, and intensive use, as powerful and durable as portable and controllable. By default, to avoid burns, the body of a fire lantern must be non-metallic, the lantern itself must be easy to operate with gloved hands, structurally simple, and light in weight, and also give a bright focused beam of light that penetrates without reflection to the user through smoke, water vapor, or a suspension of solid particles.

Ideally, a fire lantern should be powered by lithium-ion batteries. These batteries will last longer than older models powered by AA batteries. LED lanterns for firefighters are also more cost-effective and energy-efficient — which is why LED lanterns last longer than alternatives without LEDs.

An important tool in a firefighter's arsenal is a right-angle lantern, which has an adjustable head that can be adjusted to the light in any direction up to 90 degrees from the device's handle. Many firefighters use a rectangular lantern as a hands-free device or as a reliable backup lantern that can be attached to a bunker or tied to a shoulder strap. Rectangular lights are also a suitable choice for different types of firefighting, such as deployment for EMT use or wildland firefighting where you cannot use a standard fire helmet or can do without one (Rezazadeh and Torvi, 2011).

Factors to consider when selecting lighting equipment are shown in Table 2 and a comparative analysis of five models of fire lanterns is in Table 3. The comparative technical characteristics of the considered lanterns are shown in Table 4. Based on the previous analysis, let's look at the strengths and weaknesses of the different models of fire lanterns in Table 5.

Table 2: Factors to consider when selecting lighting equipment

No.	Factor	Content of a factor
1	Beam shape	Lanterns usually have either a wide beam, spotlight, or a narrow beam, adjustable, hybrid. A wide beam will illuminate an area, improving peripheral vision and situational awareness but may scatter in smoke and work against the user. A spotlight can give access to light, but everything will be concentrated in one spot and may impair peripheral vision. The hybrid beam type has a hot spot in the middle where most of the light is focused but has a wide beam that scatters the remaining light in a wider arc. This provides focused light as well as enough light for peripheral vision and situational awareness to navigate in the immediate surroundings
2	Beam color	Amber or "warm white" light has a longer wavelength than blue or "cool white" light. Blue light is usually slightly brighter but has a shorter wavelength and can scatter in smoke or fog. This can illuminate smoke and obscure the view rather than the object in focus
3	Gloved hand	Large buttons, mounts, or swivel heads that can be operated with a gloved hand allow one to manipulate the gear to adapt to the situation while maintaining protection
4	Can be mounted on the equipment	Many lanterns can be clipped onto helmets either as a strap or as a secure attachment on the side, while others have clips for attachment to swivel gear. Others can be slung over the shoulder or attached to the steel with a magnet

Table 3: A comparative analysis of fire lanterns

No.	Model	Type	Brief characteristics
1	LED spotlight Streamlight90770 Knucklehead Spotlight	Rectangular	A 90-degree light cone with an adjustable head; has several mounting options including a spring-loaded clip for attaching to a swivel device, a powerful magnet for attaching to steel surfaces, and a flat bottom for mounting on the ground or other surfaces. The adjustable head and power switch are easy to operate with a gloved hand. The dual power supply allows the device to be powered by nickel-cadmium batteries or replaced with 4 AA alkaline batteries on site
2	LED lantern Streamlight Vantage 180 X	Worn on the helmet	A helmet-mounted torch. The adjustable head directs the light in the desired direction and the rear blue LED indicator shows the position of the firefighter to those behind him. The Vantage 180 is attached to the helmet using hexagon socket screws but also has a quick disconnect feature, making it easy to remove and use as a hand-held torch when needed. Different mounting options make this torch a versatile one.
3	LED lantern Streamlight Fire Vulcan 180	Portable	A portable torch that is much larger and brighter than a conventional torch. Lightweight for its size and easy to carry hands-free thanks to the included quick-release shoulder strap. Blue LED lights on the back of the case help others see through the smoke and haze. Programmable switches allow one to turn on high or low beam, with or without the blue LED lights at the rear of the helmet
4	LED lantern Streamlight Survivor	Rectangular	A torch with a narrow, long-range beam of light that can be attached to a swivel mechanism using a spring clip or mounted on a flat surface. The head is not adjustable, no magnetic mount
5	LED lantern Nightstick NSP-4650B	Worn on the helmet	A small and robust helmet light. There is a smaller spotlight directed downwards on the underside of the body to illuminate the immediate surroundings to the front. Mounted with hexagon socket screws, making it difficult to mount in the field conditions

Table 4: A comparative analysis of the specifications of fire lanterns

Specifications	Indicator values (technical passport)				
	Streamlight90770Knucklehead Spotlight	Streamlight Vantage 180 X	Streamlight Fire Vulcan 180	Streamlight Survivor	Nightstick NSP-4650B
Battery	1 NiCd battery or 4 AA batteries	lithium-ion battery 18650	2 lithium-ion rechargeable batteries	NiCad or 4 AA batteries	2 lithium cells CR123
Beam color	warm white	neutral white	neutral white	neutral white	neutral white
Luminous flux, lm	2 lighting modes: 180, 55	2 lighting modes: 250, 100	2 lighting modes: 180, 80	3 lighting modes: 175, 60, moonlight	3 lighting modes: 15, 50, 100; 3 flash modes: 30, 100, 220
Peak luminous intensity, cd	11,000	7,200	100,000	41,000	8,073
Useful beam range, m	210	170	-	405	183
Size, mm	235 x 72	1,320 length	190 x 127	1,792 length	82 x 36
Weight, g	655	167	840	510	184

Table 5: Strengths and weaknesses of fire lanterns

No.	Model	Strengths	Weaknesses
1	Streamlight 90770 Knucklehead Spotlight	The required level of lighting and brightness, including for remote objects Controlled light intensity Waterproof, shockproof housing Versatile design fits all helmets	Quite bulky
2	Streamlight Vantage 180 X	The production uses LED C4 technology, which guarantees increased power compared to other LED flashlights Glove-friendly switch A bright blue lantern effective even in dense smoke Compact and lightweight	Uncomfortable battery cover
3	Streamlight Fire Vulcan 180	LED operating time up to 50 thousand hours Recharging a set of lithium-ion batteries in just five hours Easy to attach to a firefighting suit Optimal brightness and peripheral illumination	Very expensive
4	Streamlight Survivor	Shockproof Multifunctionality (works in different environments) Manufactured using C4 LED technology Choice of several lighting settings	-
5	Nightstick NSP-4650B	High level of brightness in any smoke Convenience of operation, simplicity of design, lightweight Dual light mode Choice of several lighting settings	Difficult to use with gloves on

In high-density smoke-filled buildings, which means that when illuminated by a 21 W light bulb with a 400 Lm luminous flux, the visibility of objects does not exceed 3 m. (Xiao et al., 2022), it is recommended to use lighting systems with increased luminous flux.

An example of this would be the multifunctional Rosenbauer LED lighting system (models RLS1000, RLS2000), which has the following main advantages:

- An integrated rechargeable battery for several hours of lighting
- Analog of daylight due to color temperature of 6500 K
- Luminous flux can be increased up to 150% in 10 minutes
- Unlimited operation time when using a power adapter
- Interchangeable focus: for light output adapted to the situation — from a Long light beam to a wide spotlight
- Flashing light in four different colors (red, green, yellow, and blue)
- All-round moving light head consisting of 30 high-performance LEDs with a special lens system and 16 multicolored LEDs
- Three LED light panels allow 360° illumination

The individual technical passport data of the Rosenbauer multifunctional LED lighting system is shown in Table 6.

Table 6: Technical passport data for individual model indicators RLS1000, RLS2000

Name of the indicator	Indicator values for sample lanterns (technical passport)	
	RLS1000	RLS2000
Luminous flux at 100% power, lm	4500	8,500
Luminous flux at power 150%, lm	6,000	12,500
Color temperature of radiation, K	6,500 (similar to daylight)	6,500 (similar to daylight)
Operating time, h	8 h at 100% capacity	2.5 h at 100% capacity

Currently, in many countries around the world (the USA, China, France, Israel, Germany, and Russia) fire departments also use various auxiliary lighting and indicative-light fire equipment, namely: fire light cables; fire hoses with glow effect; fire beacon. It should be noted that there are no European normative documents freely available on the Internet, which define the standards and requirements for auxiliary fire lighting and indicative lighting equipment. Perhaps, this is due to the fact that such equipment is auxiliary because to improve the ability to orient firefighters-rescuers in

smoke and other objects with limited visibility, are quite sufficient technical specifications, which the manufacturer notes in the technical documentation of the products.

Let's take a closer look at the requirements for the last type of auxiliary lighting equipment — the fire beacon. Based on an analysis of existing analogs, their main functional and technical disadvantages were identified. In particular, these are mass-dimensional sizes; artificial light sources, which have a sharp angle of illumination and a rather low energy conversion efficiency; absence of battery charging connectors; in case of an unsuccessful beacon installation or its rollover, fall, etc., the light targeting effect is reduced or absent at all. The mechanical activation of the lighting is also an unfortunate solution. However, a major disadvantage of the existing fire beacon is the lack of lighting requirements for artificial light sources when used in smoky environments with varying optical densities.

Due to the fact that the case of the beacon has a spherical shape with an outer diameter of 55 mm, with a counterweight (weight) placed on the bottom, it always takes the position of the LEDs to the top when in use. The positioning of the four LEDs in the upper hemisphere allows a 360° visual observation of the beacon's luminescence in relation to the vertical axis. Automatic activation of the beacon occurs at the moment of its removal from the mounting case due to the use of a normally closed electromechanical reed switch and neodymium magnets, which are located in the mounting case.

The analysis of literature (Grant et al., 2015; Ivanov, 2020; Volkov et al., 2020) also showed that LED beacons with different color temperatures of 1 W and 3 W power are used most often in fires, their technical parameters are given in Table 7.

Table 7: LED types and their main specifications

Specifications	LED types						
	Warm white		Neutral white		Cold white		Red
	1W	3W	1W	3W	1W	3W	1W
Nominal luminous flux, lm	110.0	220.0	110.0	220.0	110.0	220.0	50.0
Power, W	1.0	3.0	1.0	3.0	1.0	3.0	1.0
Rated current, mA	350.0	700.0	350.0	700.0	350.0	700.0	350.0
Angle of illumination, deg.	120.0	135.0	120.0	135.0	120.0	135.0	120.0
Color temperature of radiation, K	3,500.0	3,500.0	4,500.0	4,500.0	6,500.0	6,500.0	620.0
Size, mm	8.0x5.0	8.0x5.0	8.0x5.0	8.0x5.0	8.0x5.0	8.0x5.0	8.0x5.0
Voltage, V	3.2	3.0	3.2	3.0	3.2	3.0	2.25

The results of the research to determine the efficiency of luminous flux penetration in a high-density smoke environment with different combinations of LEDs showed that the most visible is a fire beacon with a combination of LEDs — 2 pcs red 1 W and 2 pcs cold white 3 W (Grant et al., 2015). Considering the identified shortcomings of the world analogs, as well as the results of the study (Grant et al., 2015), for the effective use of a fire beacon, the necessary technical characteristics of the fire beacon were determined, namely: The number of beacons in a set-3 pcs; the color of glow-white and red; luminous flux-400 lm; operating time-continuous operation at least 4 hours, operating modes-flickering; resistant to mechanical damage; supply voltage-up to 12 V; mass-not more than 0.3 kg.

4. Conclusion

In most cases, the work of firefighting units involved in fighting fires is tough and challenging. It consists of rescuing people and their property from fire, as well as protecting their own lives in the process. Therefore, it is important to have everything one needs to make this job less difficult and more manageable.

Smoke during a fire leads to loss of orientation. The use of lighting and orientation light fire equipment offered by the market today is characterized by sufficient brightness and allows one not to lose orientation in a smoky open area or inside smoky rooms, which makes the process of detecting and rescuing victims of a fire more efficient. It is also usually compact so as not to drag down firefighters and is strong enough to withstand hot, smoky, and harsh environments. The results of the study confirmed the hypothesis that for fire service personnel to efficiently and safely perform their duties, lighting, and orientation of light fire equipment play a significant role in eliminating fires and rescuing victims (both civilians and fire service personnel).

Compliance with ethical standards

Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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