ผลกระทบจากการใช้ระบบโฟมอัดอากาศแทนน้ำต่อกระบวนการปฏิบัติการผจญเพลิง

The Impacts of Using Compressed-Air Foam System in Place of Water on Some Fireground Tactical Operations

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บทคัดย่อ

การพัฒนาระบบโฟมอัดอากาศ (Compressed-air foam systems, CAFS) ได้เปลี่ยนแปลงกระบวนการผจญเพลิงไปเป็นอย่างมาก ในช่วงแรกนั้นระบบโฟมอัดอากาศถูกพัฒนาขึ้นเพื่อการผจญไฟป่า เนื่องจากประสิทธิภาพของระบบที่ช่วยให้ปริมาณน้ำที่มีอยู่อย่างจำกัดถูกใช้อย่างมีประสิทธิภาพ ในช่วงหลังแม้แต่หน่วยดับเพลิงที่ปฏิบัติการในชุมชนก็เริ่มหันมาใช้ระบบโฟมอัดอากาศมากขึ้น อย่างไรก็ตาม เนื่องจากสภาพการทำงานที่แตกต่างกัน ประสิทธิภาพและความเหมาะสมของระบบโฟมอัดอากาศในการผจญเพลิงอาคารจึงยังคงเป็นหัวข้อศึกษาที่น่าสนใจ ในบทความนี้ ผู้เขียนได้ทำการทบทวนผลการวิจัยศึกษาเปรียบเทียบระหว่างประสิทธิภาพของการใช้ระบบโฟมอัดอากาศแทนการใช้น้ำ ผลงานวิจัยทุกชิ้นที่ผู้เขียนได้ใช้ในบทความนี้ คัดสรรมาเฉพาะงานวิจัยที่มีการวิเคราะห์โดยใช้หลักการทางสถิติ และสามารถทำซ้ำได้ ผู้เขียนเลือกที่จะไม่พิจารณาบทความที่ใช้การยกตัวอย่างจากประสบการณ์ เนื่องจากเป็นผลการศึกษาที่ไม่สามารถทำซ้ำได้ การเปรียบเทียบประสิทธิภาพระหว่างสองระบบ จะอ้างอิงตามลำดับความสำคัญของวัตถุประสงค์ในการผจญเพลิง (RECEO) ถึงแม้ว่าการใช้ระบบโฟมอัดอากาศจะไม่เปลี่ยนลำดับความสำคัญของวัตถุประสงค์ แต่เทคนิคที่ใช้ในการปฏิบัติภารกิจเปลี่ยนไปจากการใช้ระบบใหม่ การใช้ระบบโฟมอัดอากาศช่วยทำให้การเคลื่อนย้ายสายดับเพลิงมีความคล่องตัวมากขึ้น และช่วยเพิ่มความปลอดภัยให้แก่นักดับเพลิง หากเปรียบเทียบความสามารถในการดับเพลิง ระบบโฟมอัดอากาศมีประสิทธิภาพทัดเทียมหรือดีกว่าการใช้น้ำเสมอ ในผลการศึกษาหลายชิ้นระบบโฟมอัดอากาศมีประสิทธิภาพมากกว่าน้ำ 4-5 เท่า อย่างไรก็ตามถึงแม้ว่า CAFS จะมีประสิทธิภาพมากกว่าอย่างเห็นได้ชัด โดยเฉพาะการป้องกันสิ่งปลูกสร้างข้างเคียงและการดับเพลิง แต่ผลการศึกษาในหลาย ๆ ด้าน เช่น ผลกระทบต่อการสืบสวนหาสาเหตุของเพลิงไหม้ สมควรได้รับการศึกษาเพิ่มเติม

คำสำคัญ : compressed-air foam system, การผจญเพลิง, ปฏิบัติการผจญเพลิงในตัวอาคาร, ความปลอดภัยนักดับเพลิง

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Abstract

Since its development, compressed-air foam systems (CAFS) have changed how fire is extinguished and how firefighters should operate. Initially used in wildland firefighting to conserve water, CAFS can stretch the limited water supply available for firefighting. Recently, many urban fire departments have adapted CAFS for structural firefighting. Because of the differences between a wildland and an urban fire, the success of CAFS in the former type of fire cannot guarantee its successful operation in the latter. We review studies comparing fire attack lines using CAFS and water. The studies included in this review are statistically-based and repeatable. Anecdotal evidence is excluded because of their inability to be repeated and studied in a statistically meaningful manner. The comparison was carried out with respect to CAFS' impacts on relevant tactical priorities on fireground (RECEO). While CAFS does not change the priorities on fireground, some tactics to achieve the objectives are changed by using CAFS in place of water. We found that a CAFS line can improve maneuverability of the attack line and, in turn, increase the safety of personnel on fireground compared to water. For extinguishing fire in controlled burn experiments, a CAFS line is at least as efficient as a water line. In many cases, CAFS can be as much as 4-5 times more efficient than water. Despite the clear advantage of CAFS, especially in exposure protection and extinguishment, there are some aspects that need further studies. For example, the interference of CAFS with fire investigation is unclear and needs further research.

Keywords : compressed-air foam system, fire suppression, interior fire operations, firefighter safety

Introduction

Fire has been one of the most devastating disaster for urban environment. In fact, Records stretch all the way back to antiquity of armies using fire as a weapon because of its destructive power (see Bunting, 2018., for example). The destructive power of fire is amplified in urban settings where buildings are close to one another, providing more fuel to the flame. Because of the destructive power of fire, methods have been devised to stop its spread. One of the earliest records comes from the ancient Roman. Rather than extinguishing the fire, the Romans razed adjacent buildings to stop the fire from spreading instead (Dillon & Garland, 2005). While water has been recognized as an effective agent in extinguishing fire, it did not become a pre-dominant way of putting out fire until Jan Vanderheyden invented the fire pump and hose lines that allow water to be transported over long distance and reach the fire (Lambert, 2013).

Since those early days, many different inventions and methods of application have been developed to increase the efficiency and safety of firefighting. Typically, one thinks of an improvement as a linear process in which better technology and technique supplant old ones. This is not the case in firefighting. Due to the uniqueness of each fire incident, it is frequently unclear which technology is better. This makes new technology adoption process in firefighting far from linear. For example, there has been a general trend of shifting back and forth between a fog nozzle and a smooth-bore nozzle as the main nozzle for firefighting, even though both types of nozzles have been developed more than a century ago (Clark, 1995). Compounding to the problem, the unwillingness of firefighters to deviate from traditions and their dependency on existing technology pose a problem in promoting new technology, even if new technology is objectively better. Changing firefighters' away from bad habits poses such a challenging problem that the International Associations of Fire Chiefs (IAFC) devote their resource to specifically study and promote culture change among firefighters (IAFC, 2015).

In the last decades, a new technology has emerged as an alternative to water, the oldest known extinguishing agent. Compressed air foam system (CAFS) employs three main components for extinguishing a fire: water, compressed air, and fire-retardant foam. Due to the non-linear nature of technology adoption in fire service, much debate is still going on about the pros and cons of using CAFS over water. Numerous studies have been conducted in recent years comparing the two extinguishing agents, but there has not been a review study that summarizes and synthesizes all the results in one place.

We aim to provide a comprehensive comparison between the two extinguishing agents in this study. While there is numerous anecdotal evidence that can be used to support either agent, we will only focus on reviewing studies that are well-controlled and replicable. We define a well-controlled study as a study that has at least one control group and shows meaningful statistical differences between the control and the experiment groups. This is not to discount anecdotal evidence, but to emphasize that each fire is unique with multitude of variables that can affect its development. Therefore, we choose to include only studies that can be replicated again if the replications are also done in a well-controlled manner.

How is fire extinguished

It is beneficial for us to discuss how fire is extinguished. To understand extinguishment, we must understand what causes fire. While there are more complete models (such as the fire tetrahedron), for our purposes, we will use the fire triangle concept. The fire triangle describes the three ingredients necessary for fire to persist. These are fuel, heat, and oxygen. Through chemical reactions, the fuel combines with oxygen to release energy. The energy released can then vaporize more fuel for combustion or can be converted to heat to maintain the high temperature (Quintiere, 2016).

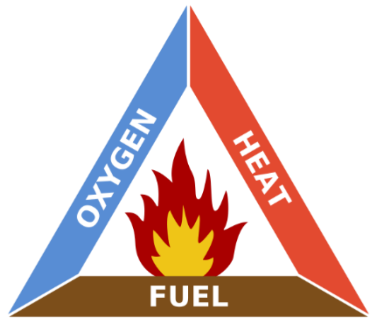

Figure 1 Fire triangle showing the three ingredients of fire (Gustavb, 2006)

To extinguish a fire, one must take away one or more ingredients from the fire triangle. For example, digging a fire line, a gap in vegetation created by hand tools or machinery typically used in wildland firefighting to act as a barrier in stopping a wildfire, removes fuel from the fire triangle. Burying a campfire under sand suffocates the fire from oxygen.

Understanding the fire triangle allows us to understand how water extinguishes fire. Water extinguishes fire through reducing the temperature of the heated environment. The exchange of heat is carried out between the environment and water. Since the environment is hotter than water, heat flows from the fire to water and causes water to gain temperature, vaporize to steam. The exchange of heat continues even after the steam conversion if the environment is still above the boiling point of water (100°C) (Lambert, 2013). Because of the heat exchange, the environment cools down. Once the temperature is low enough, the chemical reaction sustaining the fire is reduced to a level that extinguishes the fire.

CAFS and its use in structural firefighting

1. CAFS working principle

Brief discussion of how CAFS works is given here. Readers who are interested in more details can consult the multitude of literature already exists (see (Foam task group, 1993; Brooks, 2005; Mitchell, 2013), for examples).

Even though water has proven to be an effective extinguishing agent, CAFS was developed to improve the efficiency of a fire stream, the term used to describe extinguishing product flowing out of a nozzle. As mentioned before, CAFS consists of three ingredients: water, foam, and compressed air (Brooks, 2005). Water still acts as a heat exchanger to reduce the temperature of the fire. It is the inclusion of the other two ingredients that potentially make CAFS a better extinguishing agent compared to water.

The inclusion of foam has many effects. The most important one is the reduction of water's surface tension, similar to how soap and detergent are used. Water with less surface tension can penetrate deeper into porous surfaces such as building walls, ceilings, or pieces of furniture (Nave, 2017). Deeper penetration allows the applied water to stay in the heated environment longer, which results in more heat exchanged for the same amount of water (Foam task group, 1993). Therefore, less water is needed to extinguish the same fire when CAFS is used. In fact, in a water-only fire stream, only 11% of the applied water participates in heat exchanging. The rest of the water simply flows away from the area, which causes further water damage to the structure (Lambert, 2013). The better penetration of CAFS can especially be seen on vertical surfaces. CAFS stream will adhere better to such surfaces, whereas water stream would simply run off. This is shown in Figure 2.

Figure 2 U.S. Air Force firefighters train with a compressed air foam firestream. (Stidham, 2014)

Note that the combination of water with foam is nothing new. It has been used extensively, especially in wildland firefighting (Foam task group, 1993). The addition of the third ingredient, compressed air, distinguishes CAFS from the water/foam predecessor. Adding compressed air has two immediate effects. First, due to the pressurized air, the fire stream travels further with more force, which allows firefighters to be further away from the heated environment, increasing their safety. Second, the combination of all three ingredients breaks water stream apart into small bubbles. Thus, for the same amount of water, the surface area of the extinguishing agent is increased in the bubble form. In the simplest model, the rate of heat exchanging between the environment and the agent can be described by Newton's cooling law

$$\frac{dQ}{dt} = h \cdot A\Delta T \tag{1}$$

where the left-hand side gives the rate of thermal energy exchanged, h is the heat transfer coefficient, A is the heat transfer surface area, and ΔT is the difference in the temperature between the applied fire stream and the heated environment. Since the rate of thermal energy exchanged is directly proportional to the surface area, CAFS's bubbles improves the rate of extinguishing significantly compared to water-only application.

2. Brief history of CAFS

CAFS is not a new concept. Similar system was used by the British Navy during World War II (Brooks, 2005). By 1968, because of its recognized efficiency, the idea of using CAFS for firefighting has been experimented with numerous times. However, due to many technical difficulties and the high cost of using foam, the experiments did not lead to any significant progress toward adopting CAFS (Foam task group, 1993). Modern day CAFS was made possible because of three inventions. First, a system to deliver CAFS product using separate foam and water tanks with two pumps and one compressor. Second, the development of synthetic hydrocarbon surfactant foaming agent, which allows the extinguishing agent to use less foam in application, a discovery that reduces the use of expensive foam significantly (Foam task group, 1993). Third, an automatic metering system that automatically mixes the three ingredients of CAFS in the right proportion, reducing the complexity of using CAFS (Brooks, 2005). The three inventions help CAFS gain acceptance among firefighters. Today, many established fire departments have begun to accept CAFS. For example, in the state of Texas, using CAFS can reduce the ISO rating, the measure of how effective an area's fire service is, by 1.5 points. Developing nations, such as Thailand, also begin to import and train on CAFS technology (College of Disaster Prevention and Mitigation, Phuket, Thailand, 2017).

Given the theoretically more efficient performance of CAFS, why do many fire departments still use water-only fire streams? There are many reasons. A system to deliver CAFS is expensive. Misconceptions about how CAFS work play some roles. One of the biggest factors is still the resistance to cultural change (Jerrard, 2012). The most well-known departments such as the New York City Fire Department, USA, and the Chicago Fire Department, USA are still using only water. While there are many research, demonstrations, and studies that aim at dispelling misconceptions, they are not universally known by firefighters.

3. Comparison of CAFS and water for fireground operations

The goal of this review article is to collect and discuss studies comparing the effectiveness of CAFS and water in urban environment structural firefighting. While CAFS can be used in many settings, it is only heatedly debated in the case of urban structure fires because of the possibility of high-economic damage and safety risks associated with fighting fire in that setting. Because of the type of fire interested, we will only discuss CAFS product made with Class A foam (firefighting foam for ordinary combustion). As mentioned earlier, anecdotal examples are not included in our discussion because of the difficulty in replicating their specific circumstances for testing purposes.

We will divide our discussion into 4 categories. The four categories are classified according to the acronym used to order tactical priorities on fireground, RECEO (FireRescue1, 2018). Each of the letter stands for an activity that must be done on fireground to ensure successful operations. In order of importance, they are rescuing, exposure protection, confinement of fire, extinguishment, and overhauling. We are leaving out two letters from the tactical priorities: V (ventilation) and S (salvage). The last two priorities are the same regardless of the type of extinguishing agent used. The choice of an extinguishing agent does not affect the tactical priorities presented by RECEO. However, choosing CAFS in place of water affects various tactics used to achieve the objectives of RECEO, as will be presented in the following sections.

3.1 Rescue (Safety of firefighters)

The first priority on fireground is the life safety of everyone, including that of firefighters. Since this priority typically focuses on the search and rescue of victims, nature of which does not change whether CAFS or water is used, we will instead discuss how using CAFS could affect the safety of firefighters performing interior fire attack.

The best way to ensure the safety of firefighters is to put personnel further away from the fire compartment. Because of the addition of compressed air in CAFS, a CAFS fire stream can reach further than a water stream, allowing the firefighters extra margin of safety away from the heated environment. Any firefighters that have experienced a CAFS stream and a water stream flowing at the same flow rate can readily see the difference in the reach. Nevertheless, a well-designed and carefully-measured experiment has been carried out by Dicus and Turner (Dicus and Turner, n.d.). In the study, the authors flow a CAFS stream and a water stream through the same apparatus setup on a ground-mounted nozzle at the same pressure and the same flow rate. The nozzle can be locked at different angles above the horizontal. For all of the three angles tested, a CAFS stream reaches up to 1.5 – 2 times further than a water stream. Furthermore, Dicus and Turner measure the mass distribution of the two streams and show that a CAFS stream has most of the extinguishing agent reaches the furthest distance, while a water stream loses a lot of mass on the way to the target zone.

Since the amount of water per volume of CAFS in a hoseline is less than a straight water stream, a hoseline with CAFS could be more susceptible to bursting due to impinging radiant heat condition inside of a heated environment. Intuitively, CAFS line should burst quicker due to its lower heat capacity. A combination of air/water/foam has much less mass than only water, which leads to smaller specific heat capacity. Currently, there is only one evidence suggesting that a CAFS hoseline bursts faster under a heated condition. Current evidence suggests that, in a 200 Celsius heated environment a CAFS hoseline could burst in under two minutes, while a water hoseline could take as long as "several minutes" (De Vries, 2007; Grant, 2012). This is a valid safety concern for CAFS operation. Most studies agree that further studies are needed to compare hose bursting characteristics of a CAFS and a water hoseline to establish a more reliable result (De Vries, 2007; Grant, 2012; LaPolla, Morano, and Luchsinger, 2012).

Another important practice to improve firefighter's safety is to extinguish fire early and quickly. While the speed at which a fire is extinguished (how quickly) will be compared in Section 4.4, how early the fire can be extinguished is also important. In general, how early a fire attack team can reach the fire compartment for interior attack depends on multiple factors including apparatus positioning, available personnel and equipment, and building layout. An important factor in consideration is the maneuverability of the hoseline. The easier it is for the attack hoseline to be moved and deployed, the earlier the fire compartment can be reached by the attack team. Multiple factors affect the maneuverability of a hoseline: weight, hose kinking, and nozzle reaction.

A CAFS line weighs only about 60% of a water line (Grant, 2012). Since CAFS replacing some volume of water with air and foam, which are lighter, this is to be expected. The lighter weight allows a CAFS line to be loaded into a building and advanced into a structure more easily (Stern and Routley, 1996; Grant, 2012). While the hose is being deployed to reach the fire compartment, the fire attack team must ensure that there are no kinks in the hoseline. Kinks prevent the hoseline from delivering the full flow rate required to extinguish the fire and pose a safety hazard to the attack team. An attack hoseline with kinks can reduce the flow enough that the attack team could find themselves without extinguishing agent to protect themselves against unexpected fire. While this is an important concern, there is only one study that fits the well-designed and repeatable criteria by La Polla, Morano, and Luchsinger (2012). They conclude that a CAFS line needs about 25 percent less force to kink compared to a water line when the line is not being flowed (static condition). The opposite happens when the line is flowed (dynamic condition), with roughly 25 percent difference as well.

Once the attack line is in place and extinguishing agent is flowed out of the nozzle, firefighters experience a reaction force from the flow. This is the nozzle reaction. So far, there has been only one measurement on the difference in nozzle reaction between a CAFS line and a water line. While the conclusion of the study is that the reaction force is the same for the flow rate used in firefighting, the authors of the study recommends that more careful measure should be performed (La Polla, Morano, and Luchsinger, 2012).

While some aspects of maneuverability have been studied, studies should be performed to establish a clear result for unstudied areas. We note here that the maneuverability of a hoseline is a crucial consideration for firefighters' safety, as the majority of fireground injuries in the US are caused by "strain, sprain, and muscular pain" (Haynes and Molis, 2017). An easier to handle attack line could reduce such type of injuries.

3.2 Exposure protection

Once the victims are rescued to safety, the fireground priority changes to protecting unburned part of the building and nearby structures, the exposure of the fire. If an exposure is threatened by the heat or the fire, and if it is suitable, it can be coated with a layer of extinguishing agent to cool it down and slow down the impinging heat from the fire.

Since CAFS consists of multiple components, a different proportion of mixing leads to extinguishing agents with vastly different characteristics. Most class A foam requires less than 1 percent mix ratio with water (Foam task group, 1993). By mixing air in different proportion, different CAFS product ranging from Type 1 (very dry) to Type 5 (very wet) can be achieved (Grant, 2012). In theory, for exposure protection, drier CAFS should perform better than water. The thicker foam solution allows the extinguishing agent to cling on surfaces better. Water-only application with no foam results in most of the water simply splash off the surface and runs off. Despite the clear theory, there has been no study that can inarguably proves the fact. Most reports are based on anecdotal evidence or feedback from fireground operations (Boston Fire Department, 1993; Brooks, 2005; Grant, 2012). A better study is needed to prove the theory.

3.3 Confinement of fire

Once the exposures are well protected, the next fireground priority is to confine the fire to the original fire compartment. The objectives for confinement include preparing the fire for extinguishment and preventing it from spreading to already-protected exposures. The most used concept in fire confinement is the process of “resetting the fire”. A water stream is applied indirectly to the fire by bouncing it off the wall or the ceiling. The broken water droplets can cool down the fire significantly prior to a direct attack in the extinguishment step. Due to some notable modern fire behavior research (Kerber, 2014; Silvernail, 2014), the methodology for confinement has changed significantly in the past several years. Currently, a transitional attack is preferred over the more traditional interior attack for fire confinement. Due to the increase surface area and better extinguishment efficiency, CAFS is more suitable for confinement of fire based on modern fire behavior research.

Traditionally, an interior attack is used for fire confinement. In an interior attack, after exposure protection, a fire attack line is immediately deployed inside of the burning structure. The fire is then “reset” by indirectly applying a water stream to the fire from an interior location not in the fire compartment (Madrzykowski, 2013). The process is based on the now-disputed theory that an application of a water stream can push the fire in the application direction (Kerber, 2014; Silvernail, 2014). By applying the water from an unburned compartment inside the building, the fire will then be push out of the structure.

Due to some notable modern fire behavior research (Kerber, 2014; Silvernail, 2014), the methodology for confinement has changed significantly in the past several years. In addition to the rejection of the theory of fire being push by water application, a framework called SLICERS has been proposed to complement RECEO. While RECEO gives an overall look at the priorities of a fireground operation from the incident commander’s perspective, SLICERS was invented specifically for the initial fire attack company, typically the first fire engine to get on the fireground (Albemarle County Dept. of Fire Rescue, 2015; South Brunswick Fire Service, 2017). SLICERS stands for scene sizing up, locating the fire, identifying the flow path, cooling the fire from a safe location, extinguishing the fire, rescuing, and salvaging.

The most notable change after the introduction of SLICERS is the preference for a transitional attack over the more traditional interior attack for confinement. In a transitional attack, the fire is reset indirectly from a safe location. Without the fear of pushing fire into the unburned compartments of the building, the fire can also be reset from outside of the building through a window (Kerber, 2014; Silvernail, 2014; Albemarle County Dept. of Fire

Rescue, 2015). Due to its greater application reach, CAFS could reach and reset fire in taller buildings. Its increased surface area and greater extinguishment efficiency, as will be discussed in the next section, also improve the efficiency at which fire can be reset. Thus, CAFS is more suitable to modern tactic for fire confinement than a water line.

3.4 Extinguishment

After all the exposures, both around the burning structure and the unburned part of the structure, are well protected, the next fireground priority is to extinguish the root cause of the problem, the fire.

Most of the studies comparing a CAFS line to a water line focus on extinguishing behaviors of the two agents. The extinguishment effectiveness can be compared across many aspects. The three most important ones are temperature drop, knockdown time, and amount of water used. Temperature drop is the difference of the temperature in the fire compartment before and after the application of the extinguishing agent. Knockdown time is the amount of time the fire attack team has to apply the agent to extinguish the fire. Clearly, less knockdown time indicates higher extinguishing rate for the same temperature drop. Lastly, the less water used in achieving a knockdown, the better the extinguishing agent is. Excessive water used in firefighting can cause secondary water damage to the structure. There are multiple anecdotal evidences of the greater extinguishment efficiency of CAFS (Boston Fire Department, 1993; Colletti, 2008). However, in this section, we will only review some of the major studies that fit the criteria suggested in the introduction. The review is presented in chronological order.

In 2005, the Los Angeles County Fire Department (LACoFD) conducted a comparison burn using four single-story structures of identical layout and furnishing (Cavette, 2005). The artificially ignited fire was allowed to burn until the temperature of the fire compartment was above 315°C before a fire attack team tried to extinguish it with either a CAFS line or a water line. The amount of time and water used to reduce the temperature to approximately 90°C were measured using thermocouples. The CAFS line used one-fifth of the amount of water used by the water line and achieved knockdown in a quarter duration (1.5 minutes vs 6 minutes).

In 2012, Andrew Kim from the Institute for Research in Construction, Canada, presented another comparison study (Grant, 2012). In his study, ten burn experiments were conducted inside a specially-designed compartment. Unlike the LACoFD's study, which used real furniture as fuel, Kim used wood pallets. The fire was ignited and allowed to develop into a flashover, indicating a temperature exceeding 500°C (NIST, 2016). In contrary to the prior study of LACoFD, which used a set temperature as a starting signal, Kim used time duration post-flashover to start a measurement. Two minutes post-flashover, the fire attack team extinguished the fire with either a CAFS line or a water line. Again, the CAFS line performed better than the water line. The CAFS line's knockdown time was half of that of the water line. The amount of water needed by the CAFS line was one-fifth of that of the water line.

Mitchell performed a gas cooling experiment in 2013 (Mitchell, 2013). Instead of looking at fire extinguishment, the cooling of smoke caused by a fire that was allowed to develop in an adjacent room by different extinguishing agents was investigated. Once the smoke temperature reached peak value for each measurement, it was attacked by different agents for 15 seconds. The change in the smoke room temperature was measured using arrays of thermocouples at different locations in the smoke room. Eighty-eight measurements were done. Statistically, each agent outperformed one another without a specific agent having clear advantage. Additional analysis of the same data set in 2017 by Weinschenk also has the same conclusion (Weinschenk, Madrzykowski, Stakes, and Willi, 2017). However, both Mitchell and Weinschenk noted that the lack of fire severity might have an impact on their measurements and analysis.

While the gas cooling experiment shows no difference between a CAFS line and a water line, all direct fire attack measurements showed that a CAFS line performs better. In conclusion, a CAFS line is at least as efficient as a water line and is more efficient by a factor of four to five in some situations.

3.5 Overhaul

After the fire has been extinguished, the overhaul process can begin. For overhaul fireground priority, the structure is carefully and thoroughly examined to find any embers that could rekindle or any valuable material worth salvaging from the scene.

In addition to preventing fire rekindling, if there is standing water in the building, firefighters will try to drain it away to prevent water damage to the structure and its content. Since the water causing damage comes from firefighting activities, the less water that is used in extinguishing the fire, the less water damage the firefighting operation incurs. In this regard, the amount of water used by a CAFS line is typically less than that of a water line, as has been discussed in the previous section.

Another consideration during overhaul is the preservation of evidence. After the building is deemed non-hazardous, fire investigators will enter to examine the cause and the origin of the fire. Since a fire sometimes is caused by criminal or malicious intents, it is crucial that the fire scene is not disturbed or contaminated by extinguishing agent more than necessary. Unlike water, since CAFS uses foam bubbles to extinguish fire, its application leaves foam residue inside the structure. It takes 14-30 days for Class A foam to achieve complete biodegradation (Foam task group, 1993). The period is too long for any meaningful fire investigation. If a fire accelerant is used to start the fire, the chemical residue of the accelerant left on the crime scene could get masked, altered, or destroyed by the foam residue.

There has only been one study that addresses contamination from foam residue in fire investigation. The study was conducted by the Bureau of Alcohol, Tobacco and Firearms and Explosives' Fire Research Laboratory (ATF FRL), United States (Geraci, 2006). Two identical rooms with the same content at ATF FRL were used. Charcoal lighter fluid, approximately three to four US cups, was poured inside each room in a trailer fashion, long lines of fire damage spreading from one point to another (Gorbett *et al*., 2015), to imitate a crime scene. The fire was ignited by a propane torch affixed to a long wand for safety. The fire was allowed to burn until one minute post-flashover, before the fire was suppressed by a CAFS line. The same fire attack team with extensive experience in CAFS operation was deployed for both cases. The amount of extinguishing agent used in test room #1 was judicious, while that of test room #2 was intentionally excessive. After the fire was extinguished, a fire investigator with a certified accelerant detection canine entered each room. Four samples from each room were collected when the canine gave primary alerts of the presence of an accelerant. The canine showed no hesitation entering either room, showing that the presence of excessive foam does not affect the performance of the canine. The samples were sent to an ATF lab for chemical analysis.

Of the four samples from test room #1, three samples were identified to contain the accelerant expected. Only one of test room #2's samples tested positive for the accelerant. All negative samples' chemical chromatographic data were dominated by chemical components from the foam, despite chemical testing carried out approximately 30 days from the burn date. The author suggested that the presence of foam chemical components in the samples could have interfered with the investigation if the accelerant used was a heavy normal-alkane product, such as kerosene or diesel.

Since there was no control group (using only water for extinguishing) for comparison, it is hard to draw significant conclusion from this study. Most discussion on this topic relies on the argument that Class A foam is biodegradable. However, the ATF FRL study has shown that the presence of foam chemical components in the result could mask the presence of some accelerants. More studies need to be carried out to establish reliable data on this topic.

Conclusion

Even though CAFS has been used extensively in wildland firefighting, the adoption of it for structural firefighting is a recent development. Because of the differences between a wildland and an urban fire, the performance of CAFS as an extinguishing agent needs to be examined and compared to established agent, i.e. water. Since CAFS line weighs less than an equivalent water line, it should be easier to deploy and advance the line to the fire compartment. However, since it is easily kinked when not flowed and since its reaction force is larger, further study is needed to establish the effects of the increased difficulty on fire attack team's operations. For exposure protection, CAFS line is theoretically superior to a water line. Nonetheless, there has not been a well-designed study that can verify the theoretical argument. For extinguishment, a CAFS line is at least as efficient as a water line. In some cases, CAFS can be as much as five times more efficient. Further study is required to establish CAFS' interference of fire investigation, preferably with water as a control group in the study.

Despite the amount of work required to compare CAFS' effectiveness against water, many fire departments have already used CAFS as their main attack lines. This is because of the established superior efficiency of the CAFS line. While all the other aspects requiring further study are important, they should not be weighted equally in deciding whether CAFS should be used instead of water. Having a more efficient extinguishing agent allows firefighters to achieve their objectives of saving lives and protecting properties much better.

Some considerations that are not covered in this review paper are worth mentioning. CAFS line requires more training and knowledge to operate than water line. The high costs of outfitting a fire engine with extra equipment for CAFS operation and to keep a constant supply of class A foam are also typically cited as reasons some departments are not using CAFS (Heck, 2012). These aspects should be dealt with at the fire department's level and are beyond the scope of this review paper.

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