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A Field Study of an Extinguishing Material for use in Forest and Wildland-Urban Interface Fires

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Abstract

The fire extinguishing performance, in a simulation with field experiment of wildland fire, of liquid BONPET and pure water was studied. The results show that 6% BONPET liquid has better performance than pure water. The fire extinguishing simulation shows that the extinguishing performance of liquid BONPET 6% reduces the temperature at the burning area more quickly, showing a better cooling effect than water. Furthermore, shows that achieved 80% water saving and 60% faster extinguishing with the use of 6% BONPET liquid. Moreover, it has been observed that the utilization of BONPET liquid for fire suppression leads to reduced collateral damage. This is attributed to the unique properties of BONPET liquid, as its non-decomposed components persist on the surface following extinguishment. These residual components possess the capability to disintegrate and facilitate surface cooling in the event of a minor temperature rise.

Keywords: Suppression systems, BONPET liquid, Water, Wildland fire, Fire extinguishing properties.

1. Introduction

In recent years, the study of combustion chemistry has advanced. Specialists working with combustion processes and fire suppression systems should be well-versed in the chemistry of fire, extinguishing theory, classification of fires, and characteristics of various fuels. Scientists will be better able to comprehend fire, the dangers it may face how different firefighting products behave, and theoretically how they suppress fire as a result of this crucial knowledge.

The broad and multidisciplinary nature of fire safety science manifests in a variety of scientific, technological, and regulatory aspects. This complex domain includes numerous sub-disciplines such as combustion science, material science, thermodynamics, fluid dynamics, and risk assessment, among others. One of the most pivotal areas in this field pertains to the use and development of chemical fire retardants.

Since the 1930s, a wide range of chemicals have been used to extinguish wildfires. These compounds have shown to be an excellent firefighting technique in slowing the spread and decreasing the severity of wildfires. Chemicals are used to attack fires in both direct and indirect ways (in advance of a fire front to create control lines or to reinforce constructed fire lines in unburned fuel); they are also used in fire prevention and the safe conduct of prescribed burning [1]. Understanding the role of chemical fire retardants is an exploration into the heart of fire safety. These chemicals are predominantly used in the manufacturing industry to reduce the flammability of combustible materials, such as textiles, plastics, and wood. The inclusion of fire retardants in these materials can significantly reduce the rate of ignition, thereby preventing or slowing the spread of fire. While some retardants work by cooling and stopping the combustion process, others react chemically to inhibit the fire. The final outcome is a 35% reduction in overall heat production and a substantial reduction in the zone where new ignitions occur [2].

Long-term fire retardants (which impede burning even after the loss of their watery matrix) and short-term retardants (whose efficacy fades with evaporation) are examples of fire suppression chemicals. Firefighting foams (when combined with water, they create microscopic bubbles) and wetting agents (lower the surface tension of water and enhance its spreading ability) that may be applied from the air by air tankers and helicopters or from the ground using engine-powered pumps [3,4,5].

Fire retardants play a vital part in firefighting [6]. Long-term (chemical) and short-term (suppressant) fire retardants are distinguished. Long-term fire retardants are used ahead of a large fire front to slow the spread or severity of the fire. When heated, sodium bicarbonate (NaHCO3) produces carbon dioxide (CO_2) and water (H_2O), making it one of the most efficient fire retardants [7]. A multi-step method can be used to simulate the thermal breakdown of sodium bicarbonate [8, 9].

The following stages provide the total global decomposition:$Na_2CO_3(s) + CO_2(g) + H_2O(l) = 2NaHCO_3(s)$.Sodium carbonate breaks down into sodium oxide and carbon dioxide.$CO_2(g) + Na_2CO_3(s) + Na_2O(s)$The sodium oxide combines with water vapor to generate alkaline sodium hydroxide, which may interact with the flame's homogeneous chemistry.$2NaOH(s) = Na_2O(s) + H_2O(g)$.Despite the fact that the specific processes are unknown, the NaOH produced may encourage catalytic recombination of the radical species required for flame growth, leading the flames to perish.

Historically, fire retardants have been integral to mitigating fire hazards in a wide array of applications, from

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construction to transportation and consumer goods. Nevertheless, these advancements are not devoid of challenges, which commonly revolve around issues related to health, environment, and effectiveness. Fire retardants have been the subject of significant scrutiny due to concerns about their potential toxicity, environmental persistence, and bioaccumulation. In spite of these concerns, the implementation of safer, more effective fire retardants continues to evolve, considering both the fundamental science behind their operation and the real-world implications of their use.

One of the primary functions of chemical fire retardants is to interfere with the combustion at various stages, thus making them an integral part of comprehensive fire safety strategies. The combustion process consists of three key stages: ignition, growth, and fully developed fire. Retardants function by intervening in one or more of these stages, either through physical or chemical means. For instance, retardants such as aluminum hydroxide and magnesium hydroxide act by releasing water and endothermic decomposition, respectively, which cools the material and slows down or stops the combustion process [3].

However, chemical fire retardants are not a one-size-fits-all solution. Their effectiveness is subject to several factors, including their compatibility with the material, their concentration within the material, and the conditions under which the material is exposed to heat or flame. The selection of an ap-propriate retardant is critical and should consider these factors to ensure the retardant's effectiveness in slowing or stopping a fire.

While evaluating fire retardants, a balanced approach is necessary, recognizing the potential trade-offs between fire safety and health and environ-mental implications. Certain classes of retardants, particularly halogenated flame retardants (HFRs), have raised significant environmental and health concerns due to their persistence, potential for bioaccumulation, and toxicity. These concerns have instigated research into alternatives, leading to the development of newer retardants such as nanocomposites, intumescent, and phosphorus-based compounds that aim to offer similar or improved fire protection with a lesser environmental footprint [3, 10].

The dynamics of fire retardants are not confined to the realm of chemistry alone. The role and impact of these substances extend into the societal domain, shaping regulations and policies governing their use. From the European Union's Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) regulation to the United States' Toxic Substances Control Act (TSCA), the management of fire retardants is heavily influenced by regulatory decisions made in light of the available scientific evidence. These regulations set the standards for safety, effectiveness, and environmental responsibility that fire retardants must meet.

The study of fire retardants is a quintessential illustration of the multi-faceted nature of fire safety science. This domain requires a comprehensive understanding of the complexities of combustion, the subtleties of material interactions, the intricacies of chemical behavior under different conditions, and the balance between safety and sustainability. Simultaneously, it demands a perspective that goes beyond the scientific and technical aspects, factoring in regulatory constraints, societal needs, and environmental considerations.

From a research perspective, the continuous development and refinement of fire retardants is an essential area of focus. With ongoing advancements in material science, there is a growing need to develop new retardants that are both effective and compatible with a broader range of materials. Moreover, with the increasing global emphasis on sustainability and health, the future of fire retardants lies in the development of solutions that are not only effective in mitigating fire risks but also respectful of human health and the environment.

Furthermore, new suppressants are developed that are more effective than those already in use. The purpose of this paper is to present the BONPET suppressant, thanks to a greater understanding of the chemistry of fire. This raises the bar for fire suppression. BONPET yields substantial benefits. Its most notable advantage is reducing extinguishing times due to its enhanced extinguishing capabilities, resulting in less CO_2 emissions from the fire and a smaller burned area to restore. Its cost-effectiveness is notable, with the liquid able to be premixed with water for optimal ratios for various fire types, including larger ones. This reduction in cost, paired with sustained extinguishing effect, amplifies its appeal. Lastly, its environmentally friendly design negates harm when extinguishing and post-extinguishing. It poses no risk to wildlife or plant life, underscoring its eco-friendly status. The incorporation of BONPET in fire management strategies can, therefore, contribute to significant advancements in fire safety.

2. Materials and Methods

2.1. The BONPET extinguishing material.

BONPET is a proprietary fire extinguishing material, that is designed to extinguish fires quickly and efficiently. It is a non-toxic, non-corrosive, and eco-friendly product that is suitable for use in a wide range of environments, including residential, commercial, and industrial settings. The exact composition is not publicly disclosed. However, it is known that BONPET is a mixture of dry powder and foam, and it contains several active ingredients that work together to extinguish fires. The fire-extinguishing liquid BONPET is a mixture of non-hazardous additives and substances listed in Tab. 1(information obtained from BONPET's Safety Data Sheet).

Table 1. Composition/information on ingredients.

Substance	CAS no.	ECC no.	Conc %
Ammonium carbonate (CH_2O_3-xH_3N)	10361-29-2	233-786-0	3
Ammonium hydrogen carbonate (CH_2O_3-H_3N)	1066-33-7	213-911-5	3
Towalex AFFF 3% UL			2

One of the main active ingredients in BONPET is ammonium carbonate, which is a common flame retardant. It is often used in fire extinguishers and other fire suppression systems because it can help to smother fires and prevent them from spreading. BONPET also contains surfactants, which are compounds that help to reduce the surface tension of liquids. This allows the foam component of BONPET to spread quickly and evenly over the surface of the fire, helping to extinguish it more effectively.In addition, BONPET may contain other proprietary ingredients that are designed to enhance its performance and make it more effective at extinguishing fires (Tab. 2). However, the exact composition of BONPET is not publicly disclosed, as it is a closely guarded trade secret.

Table 2. Information on basic physical and chemical properties of BONPET.

Physical state	Liquid
Colour	Slightly coloured liquid
Smell	Slight ammonia smell
pH	8.0 -8.5
Density	1100 kg/m^3
Flammability	Non-flammable
Solubility in water at 20 ºC in g/L	Completely soluble in water
Freezing point	<0ºC
Boiling point	103ºC
Flashpoint	Non-existent
Explosion point	Non-existent
Ignition temperature	Non-existent
Decomposition temperature	> 300ºC
Decomposition products	N_2, CO_2, H_2O

The BONPET liquid works by releasing a mixture of dry powder and foam when it encounters heat or flames. The powder component of BONPET helps to cool down the fire and smother it, while the foam helps to prevent re-ignition by creating a barrier between the fire and the surrounding air.

The exact working of various fire extinguishing chemicals when a fire breaks out is as follows:

• production of carbon dioxide and ammonia (cooling effect) by heating urea and adding water:

$$CO(NH_2)_2 + H_2O \rightarrow CO_2 + 2NH_3$$

• ammonia (cooling effect) and hydrochloric acid are formed by heating ammonium chloride:

$$NH_4Cl \rightarrow NH_3 + HCl$$

• ammonium sulfate changes into ammonia (cooling effect) and sulfate acid:

$$(NH_4)_2SO_4 \rightarrow 2NH_3 + H_2SO_4$$

• sodium carbonate reacts with hydrochloric acid to form table salt and water (cooling effect) and carbon dioxide (fire extinguishing chemical):

$$Na_2CO_3 + 2HCl \rightarrow 2NaCl + H_2O + CO_2$$

• in addition, sodium carbonate reacts with sulfate acid to form sodium sulfate and carbon acid. Carbonic acid becomes water and sodium carbonate (powder - fire extinguishing chemical) and has a cooling effect together with sodium sulfate and water:

$$Na_2CO_3 + H_2SO_4 \rightarrow Na_2SO_4 + H_2CO_3$$

$$H_2CO_3 \rightarrow CO_2 + H_2O$$

A schematic representation of the reactions of fire extinguishing chemicals is presented in Figure 1.

When the components of the BONPET liquid get in contact with a hot surface, they result in fast absorption of heat due to water evaporation. As mentioned above, large amounts of ammonia and carbon dioxide are produced and, in synergy with the cooling effect of the water from the solution that is converted to water vapour by the heat of the fire, the fire is extinguished very fast. Also, when sodium sulphate reacts with the burnt stubble, dehydrated aluminium sulphate is formed, this has excellent spreading characteristics. In turn, the sulfate forms an extremely thin coating preventing a second ignition.

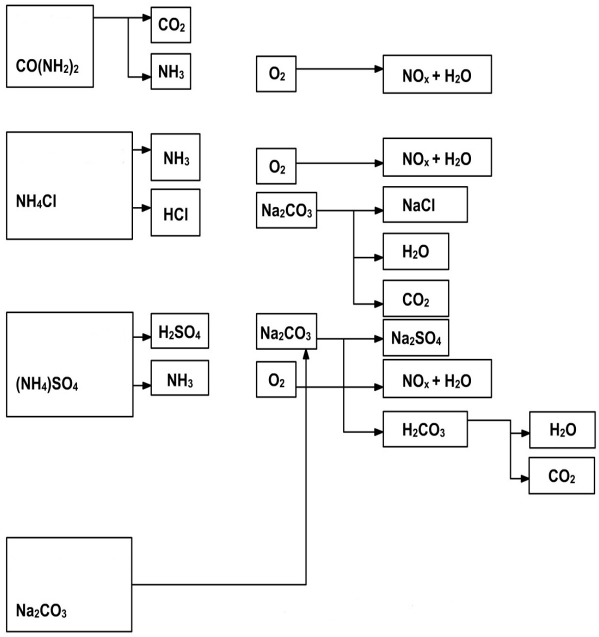

Fig. 1. Typical reactions occurring in fire extinguishing chemicals.

Wet chemicals undergo decomposition, resulting in the generation of gases such as carbon dioxide (CO_2) and nitrogen (N_2). These gases effectively suffocate the fire by impeding the access of oxygen to the burning surface. The direct suffocation of the fire on the burning surface is achieved through intensive cooling and a substantially larger volume (approximately 60 times larger) compared to the size of a single drop. Consequently, the utilization of a relatively small quantity of these chemicals proves highly efficient in extinguishing fires.

The non-decomposed constituents of BONPET liquid, which persist on the surface following fire extinguishment, possess the capacity to disintegrate and induce surface cooling upon a slight temperature rise. When a water solution comes into contact with a fire, the energy from the fire is utilized for heating and evaporating water, as well as for the endothermic decomposition of chemicals present in the fire extinguishing agent. This endothermic reaction, accompanied by the release of gases, effectively suppresses the fire on its surface. Moreover, the application of BONPET liquid serves as a preventive measure against fire re-ignition. The non-decomposed elements of BONPET liquid that remain on the surface after extinguishing the fire exhibit the ability to disintegrate and cool the surface in the event of a slight temperature in-crease.

BONPET is often used as an alternative to traditional fire extinguishers, especially in areas where traditional fire extinguishers are not practical or where they may cause damage to property or equipment. It can be used to extinguish fires in a variety of materials, including wood, paper, textiles, plastics, and even flammable liquids.The BONPET liquid is suitable for fire class A, B in F and the consequences from the fire class C.

Overall, BONPET is a highly effective and reliable fire extinguishing material that can help to prevent fires from spreading and causing serious damage.

2.2. Experimental fire tests

In order to assess the effectiveness of the BONPET-WATER mixture as a wildland firefighting agent, two field experiments were conducted. In each of those experiments, two similar forest fuel stacks were constructed and ignited in an open field (c.f. Figure 2), where after their ignition, the fire in the one stack was attempted to be extinguished with the BONPET-WATER mixture while the other, with "conventional" water. The process was recorded with both visual and thermal cameras. Both experiments were carried out at the Military Shooting Field of Corinth, Peloponnese, Greece the first one took place on February 4, 2022, and the second one on November 5, 2022.

Fig. 2. Indicative photo of the first field experiment, prior to initiation of fire suppression efforts.

Fig. 3. Indicative photo of the second field experiment.

The main difference between the two experiments was the stage of ignition. In the first experiment, the flame was allowed to spread to the entire fuel mass, while in the second experiment a more "localized" flame was investigated (Fig. 3), this was done in order to assess how the fire propagates in "wetted" fuel. Concerning the fuel characteristics, for the first experiment, the fuel stacks were constructed from a random mixture of live forest material in 15 m^2 rectangular areas and a fuel mass of {3.200,00} kg, yielding a fuel load of {3200/15} kg/m^2. For the second experiment, again, a random mixture of live fuel material was stacked in circular areas of roughly 12 m^2 and a fuel mass of {4.600,00} kg ({4600/12} kg/m^2 fuel load). Concerning the atmospheric characteristics, the mean atmospheric wind was {5,00} and {7,00} km/h measured at {1,80} and {1,60} m height, respectively for the first and second experiment. Lastly, concerning the characteristics of the extinguishing agents, for the first experiment a mixture of 6 % BONPET – 94% WATER (by mass) was delivered with an average flow of 80 L/min on the one stack, were on the other stack, "conventional" suppression water was delivered with an average flow of 190 L/min. In the second experiment we followed the same process.

It is noted that the ignition of the fuel was assisted by wetting them with a small amount of gasoline.

3. Results

The experimental measurements, obtained by using both optical and thermal cameras, from the two fire tests are presented. For the first experiment, visual and thermal images for various times after the initiation of the suppression attempt (at 15, 30, 60, and 120 s) are presented, thus depicting the temporal evolution of the two fires. Additionally, the maximum temperatures, estimated from the thermal camera, are presented as a function of time. For the second experiment, visual and thermal image pairs are presented for various times after the initiation of the suppression attempt (at 15, 30, 60, and 180 s). During the application of BONPET-WATER mixture the fire's temperature spanned from 837.2 to 315.7 °C, and the investigation revealed distinct variations in temperature relative to the duration of the fire events.

3.1. First experiment

Visual and thermal images from various times after the ignition are presented in Figure 4. As it is evident from Figure 4a, 15s after the initiation of the extinguishing attempt, the fire quenched with the BONPET-WATER mixture exhibited significantly lower temperatures, since the thermal camera measurements indicate a temperature difference of approximately 100^0C between the two cases. In Figure 4b, where 30 s have passed, the two fires exhibit similar temperatures; however, significantly lower amounts of smoke are emitted from the fire quenched by the BONPET-WATER mixture. When 1 and 2 mins since the fire suppression initiation have elapsed (Figures 4c and 4d, respectively) the two fires again exhibit a temperature difference of roughly $100b^0$C, with the BONPET-WATER mixture estimated to be around 350^0C, a value close to the ignition temperature of woody fuels.

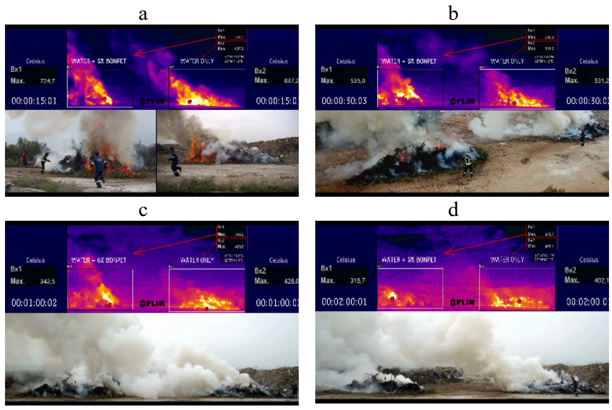

Fig. 4. Visual evolution from thermal and visual cameras of the two fires after 15 s (top, left), 30 s (top, right), 60 s (bottom, left) and 120 s (bottom, right) from the suppression attempt initiation; in each image, the "water-BONPET mixture" fire is depicted on the left, while the "water only" fire is depicted on the right.

The maximum flame temperatures as a function of time, estimated by analyzing the obtained thermal images, are presented in Figure 5. It is evident that the time-temperature profiles of the two fires exhibit a similar behavior for roughly the first minute of the quenching attempt. However, after the first minute, the fire suppressed with the BONPET-WATER mixture exhibits significantly lower temperatures, thus demonstrating a higher sensitivity to the extinguishing agent, while the fire suppressed with water exhibits a more stable response, since its maximum temperature is roughly constant. Finally, roughly 2 mins after the quenching initiation, the BONPET-WATER quenched fire temperature is below 150 ^{0}C; at this point, the fuel pyrolysis process has ended.

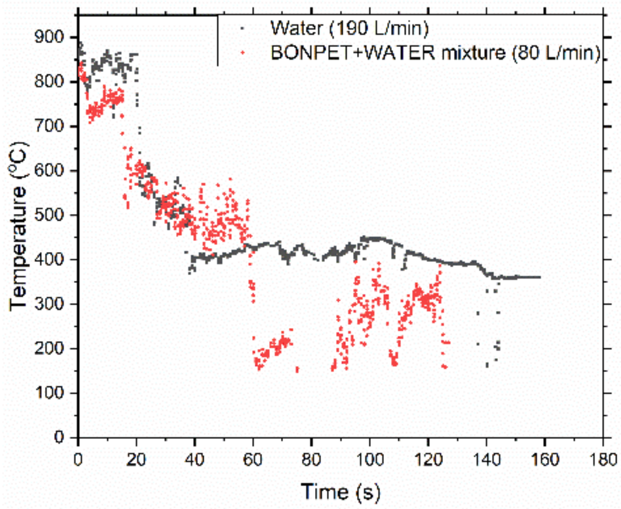

Fig. 5. Estimated maximum temperature from the thermal camera.

3.2. Second experiment

Indicative visual and thermal camera images, recorded during the second experiment, are presented in Figure 6. Fifteen seconds after the fire suppression initiation, the fires exhibit a similar size (Figure 6a); however, the emitted smoke is significantly higher in the stack suppressed by water (Figure 6b). Thirty seconds after the suppression initiation, the fires have not managed to significantly spread (Figures 6c and 6d). The fire suppressed with the BON-PET-WATER mixture decreases in size after 60 s of the suppression initiation (Figure 6e), and finally, after 155 s, the same fire is almost extinguished (Figure 6g).

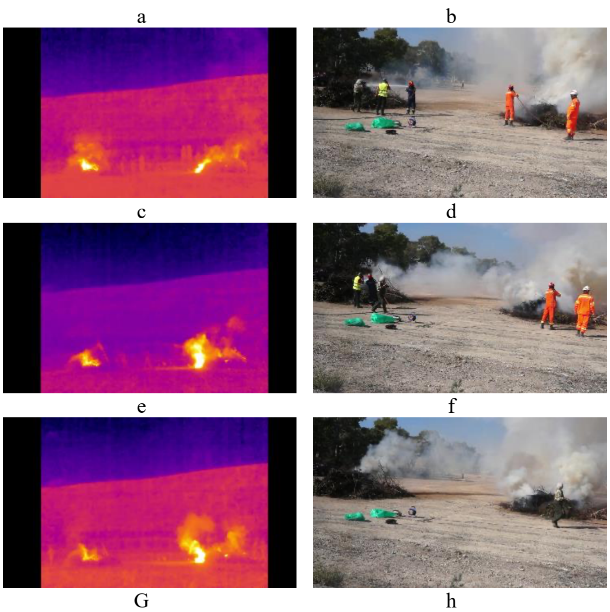

Fig. 6. Visual (right) and thermal (left) images of the time evolution of the two fires after 15 s (a, b), 30 s (c, d), 60 s (e, f), and 155 s (g, h), respectively, in all images, the right stack is quenched with water and the left stack with the BONPET-WATER mixture.

4. Discussion

Judging from the overall results of the first experiment, it is interesting that, although the conventional water flow rate was more than twice that of the BONPET-Water mixture's, the response of the respective fires was com-parable, especially for the first two minutes of the experiment. This is a strong indication of the effectiveness of BONPET, especially if one considers its low proportion in the mixture (6%). The additional effects of BONPET are becoming apparent two minutes after the quenching attempt, where the indicated temperatures (figure 4) begin to diverge. This may be the result of prevention of re-ignition which one of the additional effects of the BONPET. It is noted here that since the ignition temperature for wood rest between the range of 296 to 497^{0}C the indication that the fire quenched by the mixture lies either bellow or roughly above the above-mentioned lower range strengthens the claim for the BONPET effectiveness.

The effectiveness of BONPET may be more profound in the attempt to resist the spread of the fire, as indicated from the results of the second experiment. It seems that the chemical product of BONPET, induced by the heat of the incoming fire, when locally released in the proximity of the fuel, are acting more efficiently, than the case where the BONPET is casted to the fire, and less amount of the products manage to reach the fuel.

5. Conclusions

The utilization of BONPET liquid offers several notable advantages, primarily stemming from its enhanced extinguishing capabilities. One significant benefit is the substantial reduction in extinguishing times, which can be at-tributed to the superior performance of the liquid in suppressing fires. As a result, this leads to a notable decrease in the amount of carbon dioxide (CO_2) emissions generated by the fire, contributing to a more environmentally sustainable approach. Additionally, the reduced time required for extinguishing translates into a smaller burned area that needs to be restored back to its original state, thereby minimizing the overall impact and facilitating post-fire recovery efforts.

Another advantageous aspect of BONPET liquid is its cost-effectiveness. The liquid can be conveniently pre-mixed with water, allowing for the optimal ratio to be achieved for extinguishing various types of fires, including larger ones. This approach significantly lowers the cost of fire suppression operations while still maintaining the desired extinguishing effect. By offering a cost-effective solution, BONPET liquid enables efficient fire management without compromising on effectiveness.

Furthermore, the environmental benefits of BONPET liquid are worth highlighting. The formulation of the liquid is specifically designed to ensure that it does not produce any harm during the extinguishing process and thereafter. It is non-toxic and does not pose a threat to wildlife or plant life, making it environmentally friendly. This characteristic underscores the commitment to environmental stewardship and provides reassurance that the fire suppression efforts do not come at the expense of the ecosystem.

In summary, the utilization of BONPET liquid offers significant advantages, including enhanced extinguishing capabilities leading to reduced extinguishing times and decreased CO_2 emissions. The liquid's cost-effectiveness and its environmentally friendly nature further contribute to its appeal as a valuable tool for fire suppression operations.

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