LASER ATTENUATION AND OBSCURANT EFFICIENCY OF SCREENING SMOKE

Dinh Thang Pham[1], Duc Nhan Phan[1], Trung Toan Nguyen[1,*]

[1]*Faculty of Special Equipment, Le Quy Don Technical University*

Abstract

The concealment capability is one of the most important characteristics of smoke screens used in military camouflage. In this article, the influence of several factors (i.e., the formulation, sample mass, and environmental conditions) on the obscurant capabilities (including the degree of the 1.064 µm laser attenuation, the mass extinction coefficient, the Yield factor, and the Figure of Merit) was investigated and evaluated. The findings indicate that red phosphorus-based smoke compositions exhibit higher obscurant characteristics, providing superior laser attenuation to traditional anthracene-based formulations. The research findings can be used to develop a method for determining the laser attenuation capability of smoke screens.

Keywords: *Smoke composition; camouflage; laser; transmittance measurements.*

1. Introduction

In modern warfare, the use of laser observation and navigation devices with increasingly perfect target detection and discrimination capabilities will help improve the accuracy of weapons, thus laser-guided weapons would pose a direct and potential threat to military targets [1]-[3]. Therefore, finding solutions to effectively limit or even neutralize enemy laser devices is being considered and researched [4]-[6]. There are many methods to limit the performance of laser-guided devices, of which the use of smoke screens (i.e., aerosols) is one of the most effective and feasible measures. Smoke screens typically have high laser absorption and scattering capabilities and significantly attenuate the laser energy transmitted through it, this conceals the target from electro-optical observation and rangefinders using a guiding laser [7]-[10].

Many smoke mixtures have been used for camouflage purposes, including smoke screens created by dispersing liquids into the air as mist or burning smoke compositions [11]. Typical liquid smoke compositions include vaporized condensed oils with smoke generators, hygroscopic liquids such as mixtures of oleum/chlorosulfonic acid, metal chlorides (i.e., $TiCl_4$, $SnCl_4$), etc. [12]-[14]. Meanwhile, pyrotechnic smoke compositions are more commonly used because of its camouflage ability and

[*] Corresponding author, email: trungtoanktqs@lqdtu.edu.vn
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convenience in use, such as the HC smoke formulations (based on a mixture of metal and hexachloroethane, hexachlorobenzene), the phosphorus-based formulations, and the thermal sublimation formulation (i.e., the composition based on terephthalic acid, ammonium chloride) [15]-[22]. Several studies have shown that smoke mixtures using red phosphorus have high attenuation ability, so these mixtures are widely used for military applications such as camouflage for combat vehicles and warships [17], [23]-[27]. L. Klusacek and P. Navratil demonstrated that the screening smoke of smoke composition based on red phosphorus and epoxy resin is highly effective at attenuating infrared radiation at wavelengths of 0.82 µm, 3-5 µm, and 10.6 µm [24]. Similarly, Y. Suzuki *et al.* identified that the absorption of phosphoric acid is a key factor in screening mid-infrared and far-infrared radiation [28]. Due to the important role of smoke screens' covering characteristics, the development of the laser attenuation measurement method for smoke screens has always attracted scientific interest.

This work aims to investigate the effect of several factors (i.e., the smoke formulation, sample mass, and relative humidity (RH)) on the degree of 1.064 µm-laser attenuation of several smoke compounds commonly used in military applications, particularly smoke compositions based on red phosphorus. The laser attenuation was evaluated by the absorption and scattering of screening smoke at 1.064 µm laser radiation. In addition, several obscurant characteristics of the smoke screen (such as the mass extinction coefficient, the Yield factor, and the Figure of Merit) were also determined.

2. Materials and methods

2.1. Materials

Several technical specifications (i.e., purity, mean particle size, manufacturer, etc.) of the used reagents are shown in Tab. 1.

Tab. 1. Several technical parameters of the reagents

Reagents	**Chemical formula**	**Purity or mean particle size**	**Manufacturer**
Red phosphorus	P	Purity ≥ 99%, 40 µm	Shanghai Macklin Biochemical Co., Ltd.
Mg-Al alloy	Mg_4Al_3	Purity ≥ 98%, 50 µm	
Sodium nitrate	$NaNO_3$	Purity ≥ 99%	
Potassium chlorate	$KClO_3$	Purity ≥ 99%	
Polytetrafluoroethylene	$(C_2F_4)_n$	Purity ≥ 99%, 20 µm	

Reagents	Chemical formula	Purity or mean particle size	Manufacturer
Manganese dioxide	MnO_2	Purity ≥ 85%	
Anthracene	$C_{14}H_{10}$	Purity ≥ 95%	Xilong Scientific Co., Ltd.
Ammonium chloride	NH_4Cl	Purity ≥ 99%	
Acetone	C_3H_6O	Purity ≥ 99.5%	
Viton A rubber	The fluorine content of 66%		Dupont Company

2.2. Methods

2.2.1. Sample preparation

The smoke mixtures based on red phosphorus were prepared as follows: A homogeneous mixture of solids including $NaNO_3$, PTFE, MnO_2, and Mg-Al alloy powders was obtained by mixing on a 0.5 mm sieve. This mixture and red phosphorus powder are slowly mixed into the adhesive solution (a solution of Viton rubber in acetone - 1/15 w/v) at a stirring speed of 600-700 rpm for about 30 minutes. The resulting mixture was dried in a water bath for about 30 minutes and then granulated using a 1.25 mm sieve. Finally, the smoke mixture was vacuum-dried at 60°C for about 3 hours to remove the solvent and moisture. The compositions of these smoke mixtures are expressed in Tab. 2.

Tab. 2. Compositions of the smoke mixtures using red phosphorus

Samples	Content (wt. %)					
	Red phosphorus	Mg-Al alloy	PTFE	$NaNO_3$	MnO_2	Viton
M1	75	-	10	6.5	0.5	8
M2	60	15	10	6.5	0.5	8

The smoke formulations based on anthracene (M3), containing 30% $KClO_3$, 30% anthracene, and 40% NH_4Cl were prepared by mixing using a 1.25 mm sieve until a homogeneous mixture was obtained.

2.2.2. Experimental techniques

The heat of combustion Q_v was determined using a Parr 6200 calorimeter (Parr Instrument Company, USA). The combustion temperature T_f was measured using a 50 μm-thick WRe thermocouple. The two halves of the sample surface were in direct contact with the thermocouple and had a conical shape (Fig. 1). Based on the electromotive force versus time graph, the data were processed to convert into temperature values.

The obscurant characteristics of screening smoke can be evaluated through laser radiation attenuation (i.e., inversely, the degree of transmittance), as well as the mass extinction coefficient and the Yield factor. The design diagram for determining the transmittance of the smoke screen is shown in Fig. 2.

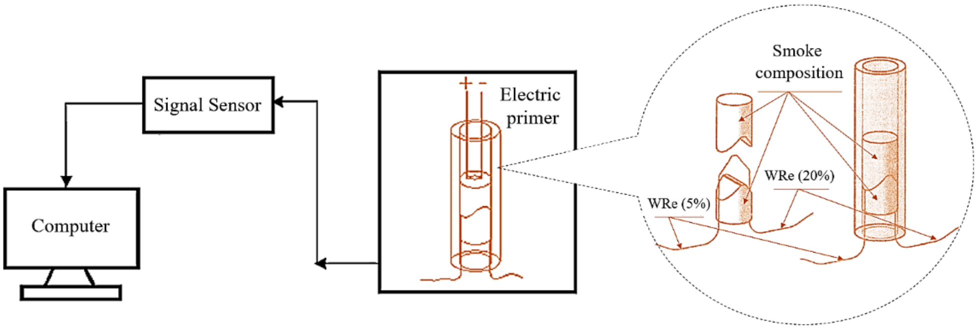

Fig. 1. Experimental setup for measuring the combustion temperature.

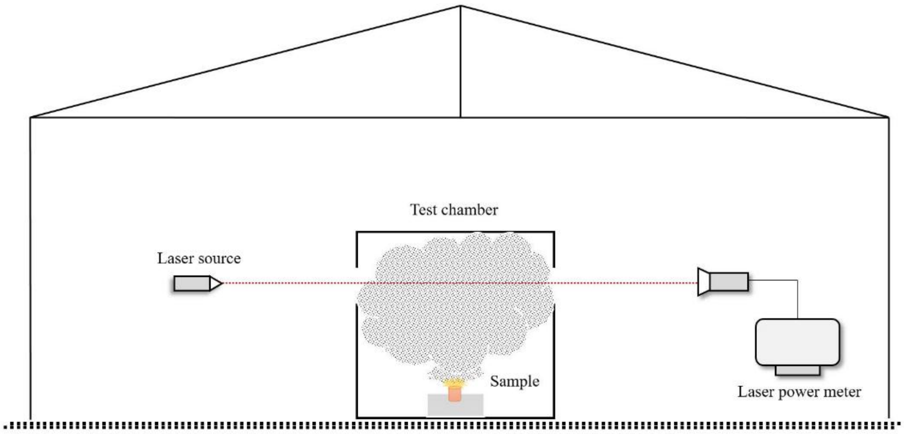

Fig. 2. The design diagram for determining the transmittance of the smoke screen.

The degree of transmittance was determined by burning a specified quantity of smoke mixture within a test chamber and assessing the smoke screen's ability to absorb and scatter laser beams. The test chamber has a volume of 0.216 m^3 and the path length of the laser beam through the smoke screen is 600 mm. A laser source with a wavelength of 1.064 μm and a power of about 11.0 mW was passed through two small windows placed on two opposite walls of the test chamber, and recorded by a laser power meter. To avoid environmental influences, especially wind, the system is covered by a tent.

The transmission T of the smoke screen was calculated by [9], [26]:

$$T = \frac{E_t}{E_0} \tag{1}$$

where E_0 and E_t are the laser power received at the laser power meter without smoke and with smoke in the test chamber at any time *t*, respectively. The percentage attenuation (A_T) can be calculated using the following formula:

$$A_T = 1 - T \tag{2}$$

According to the Lambert-Beer law, the mass extinction coefficient α_λ ($m^2 \cdot g^{-1}$) can be calculated using the formula [5], [26]:

$$\alpha_\lambda = -\frac{\ln T}{c \cdot L} \tag{3}$$

where *c* is the smoke concentration ($g \cdot m^{-3}$) and *L* is the thickness of the smoke screen (m).

The Yield factor Y_f of the smoke composition is a parameter that characterizes its smoke production capability, indicating the change in the mass of the aerosol m_s to the initial mass of the smoke composition m_p [26]:

$$Y_f = \frac{m_s}{m_p} \tag{4}$$

To comprehensively assess the camouflage capability of a smoke composition, the concept of the Figure of Merit (F_m) is commonly used, which is the product of the Yield factor and the mass extinction coefficient [5], [26]:

$$F_m = \alpha_\lambda \cdot Y_f \tag{5}$$

3. Results and discussion

3.1. Combustion characteristics

Before conducting the main experiments, several combustion characteristics of the smoke formulations (e.g., the combustion temperature T_f, the heat of combustion Q_v, the composition of combustion products, etc.) were calculated based on chemical equilibrium according to the free energy minimization principle [29]. The calculated results were compared with the experimental results and presented in Tab. 3.

Tab. 3. Several combustion characteristics of smoke formulations

No.	**Main component of smoke clouds ($mol \cdot kg^{-1}$)**	**T_f (K)**		**Q_v ($Kcal \cdot kg^{-1}$)**	
		Theory	**Exp.**	**Theory**	**Exp.**
M1	P_4 - 5.3, P_2 - 0.15, C - 4.1	1040	1018 ± 8	4410	4230 ± 16
M2	P_4 - 0.5, P_2 - 8.5, C - 4.0, MgF_2 - 1.8	1813	1710 ± 14	4620	4510 ± 21
M3	NH_4Cl - 7.2, C - 17.8, KCl - 2.4	650	610 ± 10	290	280 ± 20

For the smoke mixtures using red phosphorus, soot particles (C), H_3PO_4 particles (formed by the reaction of phosphorus with oxygen and moisture in the atmosphere) and MgF_2 particles are considered the main components of the smoke clouds. On the other hand, the main components of anthracene-based smoke screens are C, KCl (formed by the decomposition reaction of $KClO_3$), and NH_4Cl [7].

The experimental values of T_f and Q_v obtained are similar to those of theoretical calculations, demonstrating the validity of the calculation program. Additionally, the presence of metal powders in the mixtures significantly increases the combustion temperature and heat of combustion for the smoke formulation based on red phosphorus. It should be noted that the heat of combustion of the two mixtures based on red phosphorus is relatively high due to both calculations and experimental measurements under excess oxygen conditions, whereas the combustion heat of the mixture based on anthracene is quite low.

3.2. Obscurant characteristics

3.2.1. The degree of laser attenuation

To determine the effect of the smoke composition's mass on the coverage and camouflage capability of the smoke screen, the varying masses of smoke samples are burned in a test chamber. Based on the laser energy values obtained after passing through the smoke screen, the degree of laser attenuation was calculated, and the results are presented in Fig. 3. The RH in the air during the tests was 65%.

It can be observed from Fig. 3 that smoke compositions based on red phosphorus exhibit higher laser energy attenuation than those based on anthracene. Specifically, red phosphorus-based smoke samples weighing 0.3 g or more produce high camouflage smoke clouds and maintain this effect for a long duration (up to 200 seconds or even longer). In contrast, anthracene-based smoke samples require higher sample mass (i.e., 0.7 g and more) but provide lower camouflage, with the effective coverage duration being significantly shorter (around 50-60 seconds).

Figure 3 also indicates that, for smoke compositions based on red phosphorus, the sample without the Mg-Al alloy achieves a higher degree of laser attenuation than the one with the alloy. This difference is attributed to the higher H_3PO_4 content in the main components of the smoke clouds of sample M1 compared to sample M2. The trend is particularly evident when the smoke agent weights are 0.3 g and 0.5 g. Specifically, with a 0.5 g sample, the smoke cloud from the composition without the Mg-Al alloy achieves a high level of laser attenuation (over 90%) and maintains this effect for more than 200 seconds. Meanwhile, the sample containing the Mg-Al alloy achieves laser attenuation mainly within the range of 80-90%. Additionally, with a sample weight of 0.1 g, the smoke concentration is insufficient, and the smoke screen is unstable. Besides, with a sample weight of 0.7 g or more, the smoke screens generated by both M1 and M2 become excessive, leading to concentration saturation. As a result, the smoke screen's coverage capability of the 1.064 μm laser is considered complete. Therefore, the appropriate mass of smoke composition for studying the change in laser energy attenuation is 0.3-0.5 g for a 0.216 m^3-test-chamber (i.e., from 1.38 g/m^3 to 2.31 g/m^3).

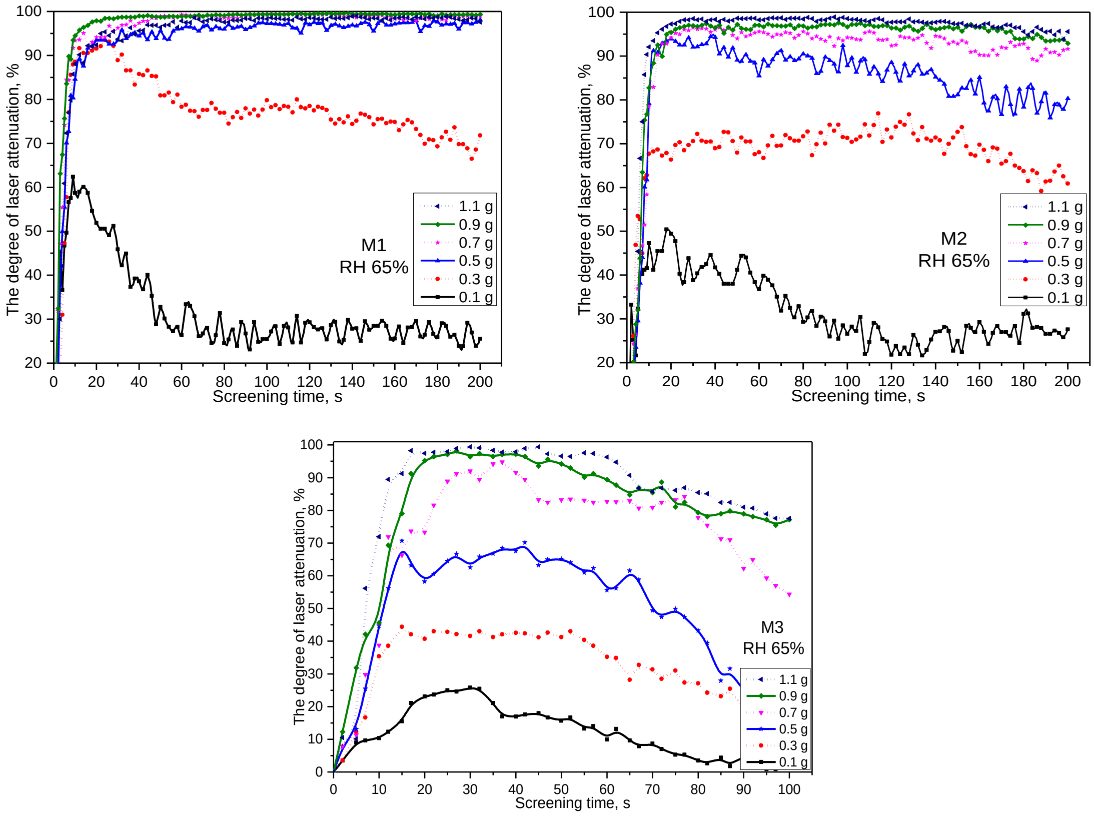

Fig. 3. The degree of laser attenuation at different smoke composition masses.

Unlike traditional smoke mixtures such as composition based on anthracene (M3), the obscurant red phosphorus-based aerosols are formed by the reaction of phosphorus with atmospheric oxygen to produce phosphorus pentoxide, which then interacts with moisture in the air to form o-phosphoric acid, creating small liquid droplets (condensed phase) in the atmosphere. Therefore, the obscuration capability of red phosphorus-based smoke clouds is always dependent on the RH of the air. The effect of RH on smoke generation capability, and thus its influence on the laser energy attenuation of the smoke screen of samples M1 and M2 at different relative humidities, is presented in Fig. 4.

Figure 4 demonstrates that the RH of the air significantly influences the degree of laser attenuation of the smoke screen, with this trend being most evident when burning 0.3 g test samples that produce moderately concentrated smoke screens. This effect occurs because the condensation of atmospheric water on H_3PO_4 liquid droplets increases their size. Under high humidity, water condensation around o-phosphoric acid molecules further enhances aerosol formation, resulting in greater obscuration.

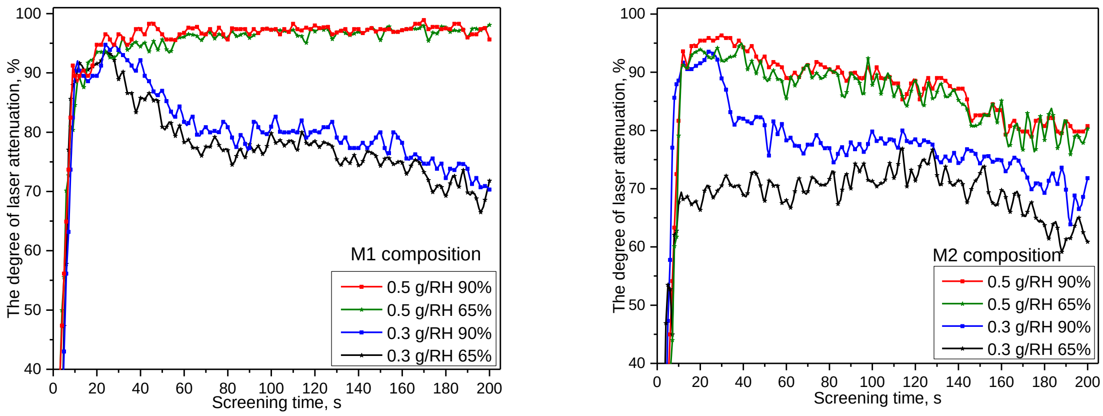

Fig. 4. The degree of laser attenuation at different relative humidities of the air.

For 0.5 g test samples, smoke clouds formed at 90% RH exhibit higher laser energy attenuation than those at 65% RH during the first 60 seconds from the onset of combustion. After that, the difference becomes minimal, and in some cases, the degree of laser attenuation under both conditions is nearly identical. This can be attributed to the fact that in the polydisperse system of the smoke cloud, larger smoke particles (i.e., due to absorbing more moisture) do not remain stable in the air and quickly settle down due to the effect of gravity. As a result, after approximately 60 seconds, the concentration of smoke clouds in the air becomes comparable under both 65% and 90% RH conditions.

3.2.2. Evaluation of the camouflage capability

In addition to the laser attenuation capability, other obscurant characteristics of camouflage smoke screens such as α_λ, Y_f, and F_m also play important roles in the comprehensive evaluation of the smoke screen's performance. After passing through the smoke screen, the minimum laser energy value was used to calculate the transmission according to Eq. (1), and the values of α_λ, Y_f, and F_m were determined using Eq. (3) to Eq. (5), respectively. It should be noted that the sample mass for each test is 0.3 g. The results are presented in Tab. 4.

The results in Tab. 4 again demonstrate that smoke-generating formulations based on red phosphorus exhibit superior obscurant characteristics (including the mass extinction coefficient, Yield factor, and Figure of Merit) compared to those based on anthracene. Notably, since the red phosphorus content in sample M1 is higher than that of M2 (i.e., the form of liquid H_3PO_4 droplets is more prevalent in the smoke cloud), the α_λ value of sample M1 is significantly higher than that of sample M2, demonstrating the higher coverage ability of the H_3PO_4-containing smoke screen. In addition, the Yield coefficient values (or smoke-generating capability) of the M1 and M2 samples are significantly higher than those of the M3 sample. This is because the smoke clouds formed from red phosphorus result from the interaction of combustion products with oxygen and moisture in the air, whereas such a process does not occur in anthracene-based smoke clouds. Consequently, the Figure of Merit values for the M1 and M2 samples are considerably higher than those of the M3 sample.

Tab. 4. Obscurant characteristics of smoke formulations

Sample	**Transmittance T (%)**	**Extinction coefficient α_λ ($m^2.g^{-1}$)**	**The Yield factor Y_f**	**The Figure of Merit F_m ($m^2.g^{-1}$)**	**RH (%)**
M1	10	1.28	2.16	2.76	65
M2	22	0.90	2.02	1.82	
M3	58	0.81	0.80	0.65	

The presence of the Mg-Al alloy in the M2 sample also significantly reduces the smoke cloud's coverage characteristics compared to the M1 sample. However, this is compensated by a significant change in the infrared emission spectrum distribution of the M2 smoke cloud compared to the M1 smoke cloud, following the intended use of the smoke mixtures.

4. Conclusion

The smoke formulation, sample mass, and RH of the air significantly affect the degree of 1.064 µm laser attenuation. Smoke mixtures based on red phosphorus exhibit superior attenuation of 1.064 µm laser energy and other obscurant characteristics compared to anthracene-based mixtures. To accurately determine the laser energy attenuation capacity of phosphorus-based smoke screens, the recommended ratio of the smoke sample's mass to the test chamber's volume is about 1.4 to 2.3 g/m^3.

Additionally, higher RH enhances the camouflage ability of red phosphorus-based smoke clouds.

Future research will focus on the relationship between camouflage ability and the particle size distribution of smoke particles based on red phosphorus.

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KHẢ NĂNG SUY GIẢM LAZE VÀ HIỆU QUẢ CHE PHỦ CỦA MÀN KHÓI

Phạm Đình Thắng[1], Phan Đức Nhân[1], Nguyễn Trung Toàn[1]

[1]*Khoa Thiết bị đặc biệt, Trường Đại học Kỹ thuật Lê Quý Đôn*

Tóm tắt: Khả năng che phủ là một trong những đặc trưng quan trọng nhất của các màn khói ngụy trang trong quân sự. Trong nghiên cứu này, ảnh hưởng của một số yếu tố (như thành phần chất tạo khói, khối lượng mẫu và điều kiện môi trường) đến khả năng che phủ (bao gồm khả năng làm suy giảm năng lượng tia laze bước sóng 1,064 µm, hệ số che phủ khối, hệ số hiệu suất) của các màn khói đã được khảo sát và đánh giá. Kết quả nghiên cứu cho thấy các chất tạo khói trên cơ sở photpho đỏ có hệ số hiệu suất và hệ số che phủ khối cao hơn, nên có khả năng suy giảm laze tốt hơn hỗn hợp khói truyền thống trên cơ sở antraxen. Kết quả nghiên cứu có thể được sử dụng để phát triển phương pháp xác định khả năng che phủ năng lượng tia laze của màn khói.

Từ khóa: *Thuốc tạo khói; ngụy trang; laze; phép đo truyền qua.*

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