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Effect of Aluminum Fiber Content on the Underwater Explosion Performance of RDX-based Explosives

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Abstract: In order to analyze the effect of aluminum fiber contents on the underwater explosion performance of RDX-based explosives, the pressure-time curves of composite explosives with different aluminum fiber contents are measured by underwater explosion experiments. Peak pressure, impulse, shock energy, and bubble energy were obtained by analyzing the curves. The results show that the peak pressures of composite explosives decrease with increasing aluminum fiber contents. The shock impulse of the 30% aluminum fiber composite explosive is the highest in all composite explosives. The effects of the 20% and 40% composite explosives are nearly equal to that of the 30% explosive, and the different values of shock impulse among them do not exceed 5%. The specific shock energy of the 20% aluminum fiber composite explosive is the highest in all composite explosives. The bubble energy and explosion energy of composite explosives increase with increasing aluminum fiber contents.

Keywords: Aluminum fiber explosive · Aluminized explosive · Aluminum fiber content · Explosion energy

1 Introduction

Aluminum is incorporated in composite explosives for a sustained blast effect, due to the potential of secondary reactions of aluminum and detonation production. Aluminized explosives have been used widespread and the effects of the aluminum particle size and aluminum contents on performance parameters (velocity of detonation, etc.) are widely reported, but the precise reaction of aluminum and detonation products has not been fully understood yet. Vadhe reviewed the current status and future trend of aluminized explosives [1]. Extensive studies have been carried out to evaluate the effect of the aluminum contents on the characteristics of composite explosives [2]. Tao et al. analyzed the effect of the particle size on the heat release rate using a Fabry-Perot laser interferometer [3]. Gogulya et al. discussed the effect of variation in the aluminum contents and particle size on the temperature and pressure profiles of the HMX/aluminum compositions [4]. Extensive studies have been carried out to evaluate the effect of the aluminum particle size on the thermal decomposition of RDX [5]. Stromsoe concluded that the bubble energy of aluminized explosives is greater than that of non-aluminized explosives [6]. Explosives are subjected to all kinds of loading under different environment, such as productive process, packing, handing, transportation, launch, and so on. Low vulnerability and insensitivity of explosives become increasingly significant. Aluminized RDX and HMX based compositions with TNT as a binder find wide application in today's scenario because they meet the insensitivity criteria, but insensitive munitions utilize a polymeric binder in place of TNT in the compositions in recent years. PBX is immune to the impact of high-velocity fragments or a bullet, and mainly cast plastic bonded with higher solid loading and better mechanical properties. A series of aluminized PBX compositions have been evaluated. The results of the study given by Rumchik indicate that, under a high strain rate loading, the decrease of the spherical aluminum particle size in a polymer bonded explosive result in increasing peak stress [7]. Traditionally, aluminum is incorporated in the composite explosives in the form of powder, which leads to an improved blast performance due to superior heat of formation. However, impact sensitivity is improved due to aluminum powder becomes hot spots in composite explosives. In addition, the aluminum particle size ranges from nanometer to micrometer, which may lead to the problems of environmental pollution, complex production process, and dust explosion during the production process. The activity of aluminum powder decreases with an increase of storage time. A new non-ideal composite explosive is proposed by replacing aluminum powder in tradition aluminized explosives with aluminum fiber that have not been reported. The disadvantage of traditional aluminized explosives may be solved by using aluminum fiber in composite explosive and the better mechanical properties may be obtained because aluminum fiber is used in the new composite explosive.

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Preliminary studies showed that the underwater explosion performance of the 20% aluminum fiber explosive is almost equal to that of the 20% aluminum powder explosive. In this paper, the pressure-time curves of different aluminum fiber contents composite explosives are measured by underwater explosion experiments, and then the peak pressure, impulse, shock energy, and bubble energy are obtained by analyzing the curves. The effect of aluminum fiber contents on underwater explosion performance of composite explosives will be carried out by exhaustive studies, which provide a reference for the development of aluminized explosives.

2 Preparation of Pressed Charges and Experimental Facilities

The investigation into the detonation performance of aluminized explosives has revealed that the influence of aluminum on performance of the composite explosives depends mainly on the nature of the high explosive and the aluminum particle size [8]. RDX is used in composite explosives in this paper because aluminum fiber explosive will be compared with RDX-based traditional aluminized explosives below. Aluminum fiber is produced by rolled method and the cross section is non-circular. The thickness of aluminum fiber is in the range of 8 μm to 10 μm. The explosive charges of 19.28 mm in diameter are pressed under the same pressure to achieve the same density of RDX in composite explosives. Mass fractions of aluminum fiber varied from 0% to 40% while the total mass of composite explosives is kept constant at 10 g. Contents in composite explosives are summarized in Table 1.

Barnes concluded that steel tank was ideal as a teaching aid for demonstrating the effects of an underwater explosion [9]. In this paper, the diameter of the steel tank used for underwater explosion is 5 m, and the high of tank filled with water is 5 m. Experimental facilities include an oscilloscope (Agilent 5000A), a current source (482A22, PCB) and pressure transducer (ICP W138A25, PCB Piezotronics Inc, USA). The sensing element of pressure transducer is tourmaline, whose diameter is 4 mm. The pressure transducer is calibrated dynamically using a drop weight tester. The sensitivity is 30.05 mV MPa^{-1} from calibration certificate, which provides a level of confidence of approximately 95%. To meet the measurement requirements of underwater explosion, composite explosives and sensors are located in position of 2 m under water surface. To study the effect of the aluminum fiber contents on underwater explosion performance of the aluminum fiber explosive, the pressure transducers are located in four different positions where vary from 70 cm to 150 cm at the same depth of composite explosives. The pressure-time curves are obtained in different positions by underwater explosion experiments. Two pressure transducers are placed at two different positions in an experiment. Each condition is repeated three times. Experimental system of underwater explosion is shown in Figure 1.

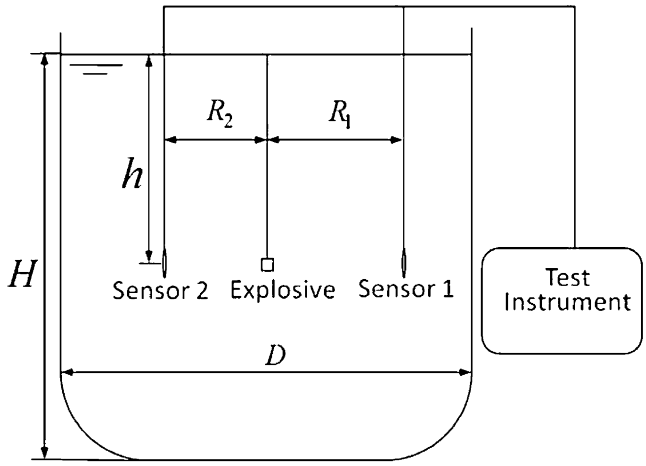

Figure 1. Schematic diagram of the underwater explosion experimental system.

3 Result and Analysis

3.1 Result of Underwater Explosion

Due to secondary reactions and the size effect of aluminized explosives, it is difficult to directly measure heat of explosion. Heat of explosion is equal to the explosion energy, which is made up of the initial shock wave energy and the bubble energy. The shock wave energy and the bubble energy can be calculated from the pressure-time curves of explosives. The underwater explosion experiment is used to determine the explosion energy of non-ideal explosive. The pressure-time curves of different aluminum fiber contents composite explosives are measured by un-

Table 1. Formulations of composite explosives.

Contents in the composite explosives [%]					
Charges number	1	2	3	4	5
RDX	95	85.5	76	66.5	57
Wax	5	4.5	4	3.5	3
Al fiber	0	10	20	30	40
Density [g cm^{-3}]	1.60–1.61	1.64–1.66	1.72–1.74	1.78–1.80	1.84–1.87
Theoretical density [g cm^{-3}]	1.816	1.875	1.938	2.005	2.077

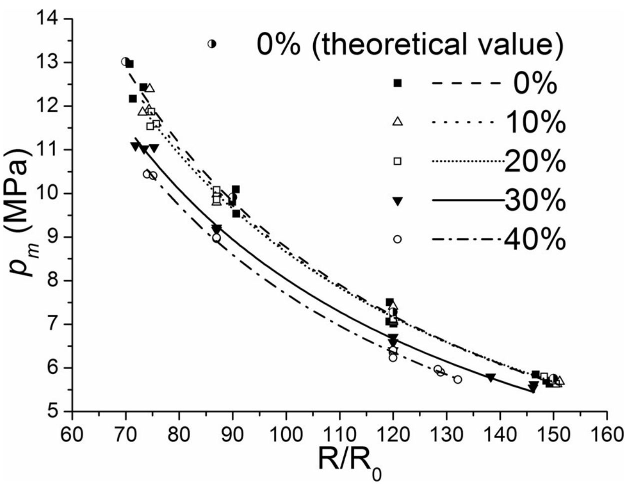

Figure 2. Peak pressure – R/R_0 curves of composite explosives with different aluminum fiber contents.

derwater explosion experiments, and then the peak pressures are obtained by analyzing the curves. In order to analyze the differences of peak pressure, the peak pressures of different aluminum fiber contents composite explosives at different positions are shown in Figure 2.

It can be seen from Figure 2 that the theoretical peak pressure of RDX in different positions (calculated by the equation in Ref. [10]) locates on the curve, which is fitted by the experimental peak pressure data of RDX. It indicates that the sensitivity of pressure transducer is credible and the experimental data are reliable. The peak pressures of different Al fiber contents composite explosives are inferior to RDX at same position. The peak pressures of 10% and 20% Al fiber composite explosives are close to that of RDX. It indicates that the peak pressures of composite explosives with low Al fiber contents do not significantly decrease by the addition of aluminum fibers. The peak pressures of composite explosives with 30% Al fiber content are lower than that of RDX when $60 < R/R_0 < 150$, and the effect of 40% are lower than that of 30%. It indicates that the peak pressures of composite explosives with high Al fiber contents significantly decrease by the addition of aluminum fibers.

The following simple form has been found adequate for many types of explosives [11]:

$$p_m = A\ (R/R_0)^{\alpha} \tag{1}$$

where p_m is the peak pressure in primary shock wave (MPa), R_0 is the charge radius (m), R is the distance between explosives and sensor (m), A and α are coefficients, which are obtained by fitting the experimental data. The peak pressures of composite explosives with different Al fiber contents are fitted respectively according to Equation (1), and the fitted effect are quite good in Figure 2. The coefficients are summarized in Table 2. In addition, these expressions could estimate the peak pressures of composite explosives with different Al fiber contents at different positions.

Table 2. Fitted coefficient of pressure peak for composite explosives with different aluminum fiber contents.

Number	1 (0%)	2 (10%)	3 (20%)	4 (30%)	5 (40%)
A [MPa]	1269.3	1160.7	1018.9	919.5	896.8
A	−1.081	−1.063	−1.036	−1.027	−1.034

3.2 Analysis of Underwater Performance

3.2.1 Shock Impulse

The shock wave impulse is defined as the integral of the pressure, which is given as follows [12]:

$$i = \int_0^{6.7\theta} \Delta p(t)\, dt \tag{2}$$

where i stands as impulse (MPa s), $\Delta p(t)$ is pressure of shock wave and is given as a time function (MPa), θ is time constant in primary shock wave (time for pressure in shock wave to decay from p_m to p_m/e) (s). θ is difficult to calculate because the pressure-time curves are not ideal. Therefore, 300 μs are assigned to upper limit on time in this paper. The shock wave impulses of composite explosives with different Al fiber contents at different positions are shown in Figure 3.

It can be seen from Figure 3 that the obtained experimental data are in good repeatability. The shock impulses of composite explosives with different aluminum fiber contents are decreased with increasing R/R_0, and they all exceed that of RDX at different position due to the potential of secondary reaction of aluminum fiber and detonation

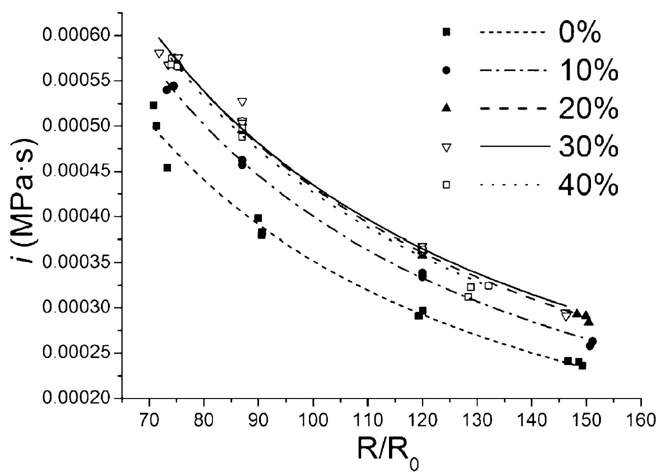

Figure 3. Impulse – R/R_0 curves of composite explosives with different aluminum fiber contents.

Table 3. Fitted coefficient of impulse for composite explosives with different aluminum fiber contents.

Number	1 (0%)	2 (10%)	3 (20%)	4 (30%)	5 (40%)
e [MPa s]	0.0378	0.042	0.0402	0.035	0.0395
G	−1.013	−1.01	−0.984	−0.953	−0.984

products. The shock impulse of 30% aluminum fiber composite explosive is 1.14 to 1.21 times as much as that of RDX at different positions and is the highest in all composite explosives. The effects of 20% and 40% are nearly equal to that of 30%, and the difference values of shock impulse among them do not exceed 5%. The shock impulses of 10% Al fiber composite explosives are 1.08 to 1.11 times as much as that of RDX at different positions. The difference values of shock impulse between different content aluminum fiber explosive and RDX is nearly constant with increasing R/R_0.

The relationship between the shock impulse and R/R_0 may be described by

$$i = \mathrm{e}\ (R/R_0)^{\mathrm{g}} \tag{3}$$

where e and g are coefficients, which are obtained by fitting the experimental data. The shock impulses of different Al fiber contents composite explosives are fitted respectively according to Equation (3), and the fitted effects are quite good in Figure 3. The coefficients are summarized in Table 3. In addition, these expressions could estimate the shock impulse of different Al fiber contents composite explosives at different positions.

3.2.2 Specific Shock Energy and Specific Bubble Energy

The equations of specific shock energy and specific bubble energy are given as follows [12]:

$$E_s = \frac{4\pi R^2}{W\rho_w C_w}\int_0^{6.7\theta} \Delta p^2(t)dt \tag{4}$$

$$E_b = (\sqrt{1+4CT_b} - 1)^3 / 8C^3 k_1{}^3 W \tag{5}$$

$$k_1 = 1.135\rho_w{}^{1/2} / P_h{}^{5/6} \tag{6}$$

$$T_b = aW^{\frac{1}{3}} + bW^{\frac{2}{3}} \tag{7}$$

$$C = \frac{b}{a^2} \tag{8}$$

where E_s is the specific shock energy (MJ kg^{-1}), W is charge weight of explosive (kg), ρ_w is the density of water (kg m^{-3}), C_w is the sound speed of water (m s^{-1}), θ is the time constant in the recorded shock wave (ms). E_b is the specific

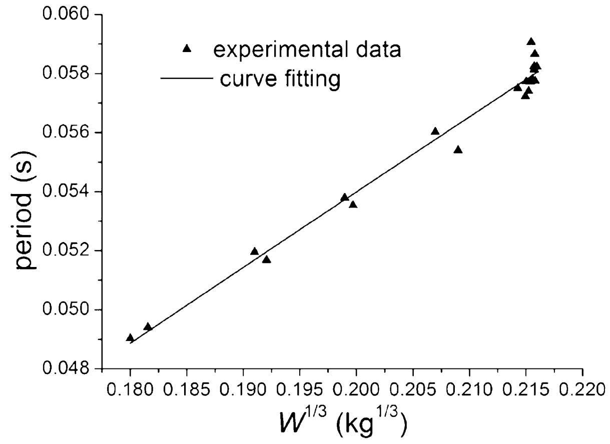

Figure 4. The fitted curve of T_b–$W^{1/3}$.

bubble energy (MJ kg^{-1}), T_b is the first pulsation period (s), P_h is the total hydrostatic pressure at the charge depth (including atmospheric pressure) (Pa). The inherent constants a and b characterizes the influence of the boundaries on the bubble period, such as used pools and a certain hydrostatic pressure, and they are determined by making a least square fit to the (T_b, $W^{1/3}$) data. C is the adjustable parameter of boundary effects, which is calculated according to Equation (8). In order to obtain C, the RDX with different mass (6 g to 10 g) are tested in the same condition and the experimental data are fitted according to Equation (7). The fitted result is shown in Figure 4.

The fitted results are as follows: $a = 0.28489$, $b = -0.07463$, $C = -0.9195$ s^{-1}.

3.2.3 Explosion Energy

The calculative equations of explosion energy are as follows [12]:

$$E_t = K_f\ (\mu E_s + E_b) \tag{9}$$

$$\mu = 1 + 1.3328 \times 10^{-1} p_{CJ} - 6.5775 \times 10^{-3} p_{CJ}{}^2 + 1.2594 \times 10^{-4} p_{CJ}{}^3 \tag{10}$$

$$p_{CJ} = {}^1/_4\ \rho_0\ D^2 \tag{11}$$

where E_t is the specific explosion energy (MJ kg^{-1}). μ is the shock loss factor, which has been shown to be a function of the detonation pressure of explosive. K_f is the charge geometry factor, $K_f = 1.00$ for the shape is spherical, $K_f = 1.02$ to 1.10 for the shape is non-spherical. The height of explosive are nearly close to their diameter in this paper, and the shape of charges are treated as sphere in the calculation of explosion energy. ρ_0 is the density of explosives (kg m^{-3}), D is the velocity of denotation (m s^{-1}), p_{CJ} is Chapman-Jouguet pressure [Pa in Equation (10) and GPa in Equation (11)]. Equation (11) is appropriate for calculating

p_{CJ} of single explosive, and the calculative equations of traditional aluminized explosives are as follows [13]:

$$p_{CJ} = {}^{1}\!/_{4}\ \beta\ \rho_{e,w}\ D^{2} \tag{12}$$

where β is the coefficient (ρ_0/ρ_t), ρ_t is the density of aluminized explosives in theory ($kg\,m^{-3}$), $\rho_{e,w}$ is the density of based explosive ($kg\,m^{-3}$). In this paper, it assumes that Equation (12) is appropriate for aluminum fiber explosive.

The detonation velocities of explosives are measured by detonation velocity measuring instrument (2BS-110), the time-base is 0.1 μs. The distances between neighboring probes are the heights of explosives. The charges are located in a plastic pipe. The detonation velocity experiment is shown in Figure 5.

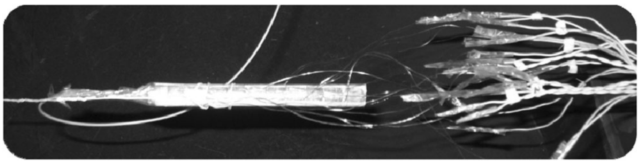

Figure 5. Detonation velocity experiment.

Table 4. Detonation velocities of composite explosives with different aluminum fiber contents.

Number	1 (0%)	2 (10%)	3 (20%)	4 (30%)	5 (40%)
D [$m\,s^{-1}$]	7986	7846	7803	7639	7432

The detonation velocities of composite explosives with different aluminum fiber contents are summarized in Table 4.

It can be seen from Table 4 that the detonation velocities of composite explosives decrease with increasing aluminum fiber contents. It indicates that the potential of secondary reaction of aluminum fiber and detonation products does not support the detonation propagation.

Energy output parameters of composite explosives with different aluminum fiber contents on underwater explosion are summarized in Table 5. The heats of explosion of aluminum fiber explosives are equivalent to those of aluminum powder explosives theoretically containing a corresponding aluminum content. Therefore, it is assumed that the heats of explosion of aluminum powder explosives from Ref. [13] are treated as that of aluminum fiber explosive.

It can be seen from Table 5 that the incorporation of aluminum fibers leads to an increase in the pulse periods, it indicate that the specific bubble energies of aluminized explosives increase with increasing aluminum fiber contents. The specific shock energy of different aluminum fiber contents composite explosives decrease with an increase of R/R_0, but the specific bubble energies are unchanged with an increase of R/R_0. The specific shock energy of the 20% aluminum fiber composite explosive is 1.0956 to 1.15 times as much as that of RDX at different positions and is the highest in all composite explosives, which is similar to the traditional aluminized explosives. The explosion energy and bubble energy of composite explosives are increased with increasing aluminum fiber contents, due to the potential of secondary reaction of aluminum fiber and detonation products. The E_t/Q_v of composite explosives with different aluminum fiber contents are close to the theoretical value

Table 5. Energy output parameters of composite explosives with different aluminum fiber contents at underwater explosion.[a]

	R/R_0	T_b [ms]	E_s [$MJ\,kg^{-1}$]	μ	μE_s [$MJ\,kg^{-1}$]	E_b [$MJ\,kg^{-1}$]	E_t [$MJ\,kg^{-1}$]	E_b/E_t [%]	Q_v [13] [$MJ\,kg^{-1}$]	E_t/Q_v [%]
1 (0%)	70	58.040	1.169	2.209	2.583	2.551	5.135	49.69	5.378	95.47%
	90	58.653	1.102	2.202	2.426	2.636	5.062	52.07	5.378	94.13%
	120	58.653	1.044	2.202	2.300	2.629	4.929	53.34	5.378	91.64%
	150	58.040	1.027	2.209	2.268	2.548	4.817	52.91	5.378	89.56%
2 (10%)	70	61.332	1.180	2.086	2.461	3.066	5.527	55.47	–	–
	90	61.728	1.146	2.088	2.393	3.081	5.473	56.29	–	–
	120	61.328	1.122	2.086	2.340	3.066	5.406	56.71	–	–
	150	61.719	1.059	2.088	2.211	3.079	5.290	58.21	–	–
3 (20%)	70	65.050	1.256	2.085	2.618	3.759	6.377	58.94	6.443	98.98%
	90	65.776	1.235	2.088	2.579	3.796	6.375	59.54	6.443	98.95%
	120	65.050	1.205	2.085	2.512	3.759	6.271	59.94	6.443	97.33%
	150	65.776	1.161	2.088	2.425	3.796	6.221	61.02	6.443	96.55%
4 (30%)	70	67.999	1.147	2.056	2.359	4.331	6.690	64.74	7.046	94.95%
	90	69.031	1.161	2.062	2.394	4.411	6.805	64.81	7.046	96.58%
	120	67.999	1.150	2.056	2.366	4.337	6.702	64.70	7.046	95.12%
	150	69.031	1.096	2.062	2.261	4.416	6.677	66.13	7.046	94.76%
5 (40%)	70	69.877	1.065	2.039	2.171	4.606	6.777	67.96	–	–
	90	70.662	1.045	2.041	2.133	4.762	6.895	69.06	–	–
	120	69.883	1.071	2.039	2.183	4.608	6.791	67.85	–	–
	135	70.676	0.977	2.041	1.995	4.760	6.755	70.47	–	–

a) The data are average values of experimental results.

(100%), which proves that the extent of aluminum fiber reaction in detonation products is almost equal to that of aluminum powder and the method to estimate the explosion heat of aluminized explosives by underwater explosion is feasible.

4 Conclusions

An analysis of experimental data for composite explosives with different aluminum fiber contents shows that the effect of aluminum fiber contents on the underwater explosion performance is similar to that of traditional aluminized explosives. The peak pressures of composite explosives decrease with an increase in the aluminum fiber content. The shock impulse of the 30% aluminum fiber composite explosive is the highest in all composite explosives. The effects of the 20% and 40% composite explosives are similar to that of the 30% composite explosive, and their shock impulse different values do not exceed 5%. The specific shock energy of the 20% aluminum fiber composite explosive is the highest in all composite explosives. The specific bubble energy and explosion energy of the composite explosives increase with an increase in the aluminum fiber content. The detonation velocities of composite explosives decrease with increasing aluminum fiber contents, which indicates that the potential of a secondary reaction of aluminum fibers and detonation products do not support the detonation propagation.

Aluminum fiber explosives are proposed to replace aluminum powder in traditional aluminized explosives with aluminum fiber. They might be able to solve several problems of traditional aluminum powder explosives, such as environmental pollution, dust explosion, among others. The impact sensitivity of the aluminum fiber explosive may be decreased because aluminum powder is not used and aluminum fiber explosives may have better mechanical properties, which needs to be proved by experiment in the future. This approach can also be applied to cast aluminized explosives, which encompass both the melt-cast trinitrotoluene (TNT)-based and the slurry cast polymer-based explosives (PBX), which could provide a reference for the development of aluminized explosives.

Acknowledgments

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