**The Safety Properties of a Potential Kind of Novel Green Primary Explosive: Al/Fe\textsubscript{2}O\textsubscript{3}/RDX Nanocomposite**

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**Abstract:** Green primary explosives have gained wide attention for environmental protection. A potential novel lead-free primary explosive, Al/Fe\textsubscript{2}O\textsubscript{3}/RDX hybrid nanocomposite was prepared by ultrasonic mixing, and its safety properties are discussed in detail. Results showed that their sensitivity and safety properties were a function of the specific surface area and proportions of their ingredients. Their impact sensitivity fell and their static discharge, flame, and hot bridge wire sensitivities rose as the specific surface area of nano-Fe\textsubscript{2}O\textsubscript{3} increased. As the amount of Al/Fe\textsubscript{2}O\textsubscript{3} nanothermite was increased, its impact sensitivity fell and its flame sensitivity rose; their static discharge and hot bridge wire sensitivities, however, followed an inverted “U” type change trend and were determined by both the particle size of the ingredients and the resistance of the nanocomposite. Their firing properties in an electric detonator depended on the proportion of the constituents. Thus, green nanoscale primary explosives are appropriate for a range of initiatory applications and can be created by adjusting their specific surface area and the amount of their constituents.

**Keywords:** green primary explosives; Al/Fe\textsubscript{2}O\textsubscript{3}/RDX nanocomposite; sensitivity

**1. Introduction**

Initiating explosives are sensitive explosives widely used in military munitions and civilian applications that deflagrate or detonate with low external stimuli, e.g., a flame, pinprick, friction, static discharge, or moderate heat, and release enough energy to initiate other explosives. Traditional initiating explosives, that contain toxic metallic elements such as mercury fulminate, lead azide, or lead styphnate, have inherent drawbacks, such as hydrolytic instability or environmental pollution, and so, their military and civilian uses are limited for the sake of environmental protection [1–3]. Consequently, new green initiating explosives have attracted much attention from researchers in the field of primary explosives [4,5]. Some studies have explored particular green initiating explosives, such as tetrazoles, and their derivatives, furazans [6–13]. However, their synthesis is very complicated, and their production generates pollutants [6,8,10–13]. In addition, in the past decade some nano-energetic materials (for example, metastable intermolecular composites, MIC), with the potential to be used as primary explosives, have also excited great interest from military experts [14,15].

Due to their remarkable ignition and energy release properties, one of the nano-energetic materials, nanothermite, has been gaining increasing attention from researchers in the fields of propellants, explosives, and pyrotechnics [16–20]. Nanothermites, however, do not produce gas during the thermite reaction and they cannot self-detonate, which reduces their usefulness in military and
civilian industry. Secondary explosives like hexogen (RDX) or cyclotetramethylene-trinitramine (HMX) do evolve massive amounts of gas during their chemical reactions, but their volume energy densities are lower than those of nanothermites. Therefore, it appears that nanothermites, mixed with secondary explosives, might perform better than either nanothermites or secondary explosives. Based on this idea, some studies of hybrid nanocomposites have been conducted [21–23], and their combustion characteristics show that they could cause a rapid deflagration-to-detonation transition (DDT) that can be accelerated to the primary explosive level [22] and therefore used to initiate the detonation of a high explosive [23]. In addition, their preparation, by mixing, is simple and generates no pollutants. Therefore, these explosives might be a kind of novel green nanoscale substitute for existing initiating explosives, thanks to their high thermal stabilities and controllable velocities of detonation. Furthermore, due to the absence of lead, and if used as primary explosives, they would escape some of the shortcomings of current primary explosives.

The sensitivity of initiating explosives to external stimuli makes them a potential safety hazard. It is for this reason that their safety properties are crucial to their use in both military munitions and civilian industry. Few systematic evaluations of the safety properties of hybrid nanocomposites have been conducted, however. In this paper, the safety properties of Al/Fe$_2$O$_3$/RDX hybrid nanocomposites, a novel lead-free nanoscale initiatory compound prepared by mixing Al/Fe$_2$O$_3$ nanothermite with RDX, are studied in detail.

2. Materials and Methods

2.1. Preparation of the Materials

Superfine RDX with a particle size of 1–5 µm was prepared in our lab by spraying RDX solution into deionized water at high-pressure and then recrystallized and freeze-dried. The result of this is shown in Figure 1. Nano-Fe$_2$O$_3$, with specific surface areas of 10.3 m$^2$/g, 43.2 m$^2$/g, and 230 m$^2$/g, was synthesized by the sol-gel method and by a low temperature CO$_2$ supercritical process as described by Luo et al. [24]. The specific surface area was measured using an American Quantachrome ADSORP gas adsorption analyzer and BET theory and five data points between relative pressures 0.05 and 0.3 at 77 K [25]. Passivated nano-Al powder, with an average particle size of 40 nm, a ~5 nm oxide shell, and an active metal content of 52 wt % was obtained from a commercial technology company (Figure 2). The Al/Fe$_2$O$_3$/RDX nanocomposites were prepared by mixing RDX with Al/Fe$_2$O$_3$ nanothermite composed of nano-Fe$_2$O$_3$ and nano-Al powders according to Equation (1) and an equivalence ratio $\Phi$ of 1.1 (Al-rich) in the solvent cyclohexane or cyclohexane plus acetone. The resulting mixtures were treated using an ultrasonification process for 3 h to ensure more homogeneous mixing. Al/Fe$_2$O$_3$/RDX hybrid nanocomposites were then obtained by drying at 55 °C for 48 h in a vacuum drying cabinet to evaporate the solvents. The prepared nanocomposites were labelled with their RDX content (for example, 30 wt % (Al/Fe$_2$O$_3$)/70 wt % RDX = R − 70).

$$\Phi = \frac{(active \ Al/Fe\_2\_O\_3)_{Actual}}{(active \ Al/Fe\_2\_O\_3)_{Stoichiometric}}$$ (1)
2.2. Sensitivity Tests of the Al/Fe$_2$O$_3$/RDX Nanocomposites

The impact sensitivities of the Al/Fe$_2$O$_3$/RDX nanocomposites were determined by the Fall Hammer Method using a 2.0 kg drop weight, 25 cm height, and 30 mg quantity. Their friction sensitivities were assessed using a 1.5 kg hammer weight, a 66° switch angle, 2.45 MPa, and a 20 mg quantity. Twenty-five samples were tested, and the firing percent was calculated for the various impact and friction sensitivities. The static discharge sensitivity of each sample was measured by an electric spark sensitivity analyzer with an electrode gap of 0.5 mm, an electrical capacity of 30.5 pF, and a 20 mg quantity. The firing energy $E_{50}$ was calculated using the formula, $E_{50} = 0.5C(V_{50})^2$, where $V_{50}$ is the 50% firing voltage and $C$ is the electrical capacity of the electrode [26]. The flame sensitivity of each sample was determined using the fuse method with a fuse length of 7 cm and a 20 mg quantity, and the jetting distance of the fuse flame at 50% firing was made for flame sensitivity [27]. For the safety evaluation, 0.1 g of Al/Fe$_2$O$_3$/RDX nanocomposite was placed in an electric detonator with a diameter of 6.3 mm and pressed at 802 kPa; the loading density was 0.48 g/cm$^3$. The electrostatic safety of each sample was measured at 25 kV/500 pF/5 kΩ, its hot bridge wire sensitivity was measured by heating the bridge wire at different voltages to simulate firing conditions in an electric detonator, and the firing energy was calculated using the formula, $E = I^2Rt$, where $I$ is the intensity of the current, $R$ is the electrical resistance of the hot bridge wire, and $t$ is the firing time.
3. Results and Discussion

3.1. Mechanical Sensitivity Analysis

The mechanical sensitivity of Al/Fe$_2$O$_3$/RDX nanocomposites containing various amounts of RDX and nano-Fe$_2$O$_3$ with various specific surface areas were measured using the test criteria for high-sensitivity explosives. The results are given in Table 1.

| Sample | Specific Surface Area of Fe$_2$O$_3$ (m$^2$/g) | Impact Sensitivity (%) | Friction Sensitivity (%) |
|--------|---------------------------------------------|------------------------|-------------------------|
| R-100  | -                                           | 8                      | 8                       |
| R-70   | 43.2                                        | 16                     | 100                     |
| R-70   | 230                                         | 12                     | 100                     |
| R-50   | 10.3                                        | 16                     | 100                     |
| R-50   | 43.2                                        | 12                     | 100                     |
| R-50   | 230                                         | 8                      | 100                     |
| R-30   | 43.2                                        | 8                      | 100                     |
| R-30   | 230                                         | 8                      | 100                     |
| R-0    | 230                                         | 0                      | 100                     |

As Table 1 shows, the mechanical sensitivity of Al/Fe$_2$O$_3$/RDX nanocomposites depended heavily on their RDX content and the specific surface area of the nano-Fe$_2$O$_3$ in them. Their impact sensitivity decreased slightly as their RDX content decreased and also decreased as the specific surface area of the nano-Fe$_2$O$_3$ in them increased. In the light of hot spot theory, this may be due to the nano-Fe$_2$O$_3$ particles with low specific surface areas and large particle sizes forming local-center hot-stress regions at impact, which would readily cause the nanocomposites to fire, thereby increasing their impact sensitivity. The friction sensitivity of nanocomposites increased dramatically and then remained the same once Al/Fe$_2$O$_3$ nanothermite was added to RDX. This might be due to breakage of the Al$_2$O$_3$ crust on the surface of the nano-Al particles at the blade load, bringing highly reactive nano-Al into direct contact with nano-Fe$_2$O$_3$, with the resulting thermite reaction between nano-Al and nano-Fe$_2$O$_3$ releasing a large amount of heat, and forming a partial high-temperature zone, which accelerated the thermite reaction and the decomposition of RDX, leading to the firing of the Al/Fe$_2$O$_3$/RDX nanocomposite. Therefore, the nanocomposites had high friction sensitivity, much higher than that of RDX. A loud explosion and a geyser of sparks resulted when testing the samples for friction sensitivity. However, it is difficult to break the Al$_2$O$_3$ crust of nano-Al particles at the percussive force. On the contrary, some of the impact energy was absorbed by the Al and Fe$_2$O$_3$ particles, causing the nanocomposites to be much more sensitive to friction than to impact.

3.2. Static Discharges Sensitivity Analysis

The static discharge sensitivity of Al/Fe$_2$O$_3$/RDX nanocomposites was measured at voltage $(V_{50})$ and firing energy $(E_{50})$ at 50% firing when the samples were put between two electrodes. The static discharge sensitivity of nanocomposites with different RDX content, specific surface areas of nano-Fe$_2$O$_3$, and solvents used in the mixing process are given in Table 2.

As Table 2 shows, the RDX content, the specific surface area of Fe$_2$O$_3$, and the solvent used in the mixing process greatly affected the $V_{50}$ and $E_{50}$ of Al/Fe$_2$O$_3$/RDX nanocomposites. The $V_{50}$ and $E_{50}$—i.e., the static discharge sensitivities of most of the Al/Fe$_2$O$_3$/RDX nanocomposites were much lower than that of pure RDX or Al/Fe$_2$O$_3$ nanothermite. As the amount of Al/Fe$_2$O$_3$ nanothermite increased, the static discharge sensitivity of the nanocomposites first increased, however, and then decreased, following an inverted “U” type change trend. This may be due to changes in particle size and resistance when Al/Fe$_2$O$_3$ nanothermite was added to RDX [28,29]. As the amount of Al/Fe$_2$O$_3$ nanothermite increased, the average particle size of the nanocomposite fell and the specific surface area increased, adding to the effective friction area and thereby making electric charges accumulate easily on the surfaces of the nanocomposites, leading to firing at a low electrostatic voltage [30]. In addition,
the increased amount of Al/Fe₂O₃ nanothermite reduced the resistance of the nanocomposite due to the metal, aluminum, being a conductor. The resistance of Al/Fe₂O₃ nanothermite was far less than that of RDX, and so electrical charges accumulated less on its surfaces, increasing its firing energy and decreasing its static discharge sensitivity. The inverted “U” type change trend for the static discharge sensitivity of the nanocomposites was the result of the interaction of the particle sizes and the resistance of their ingredients.

Table 2. Static discharge sensitivity of Al/Fe₂O₃/RDX nanocomposites.

| Sample | Specific Surface Area of Fe₂O₃ (m²/g) | Solvent | V₅₀ (kV) | E₅₀ (mJ) |
|--------|-------------------------------------|---------|-----------|----------|
| R-100  | -                                   | cyclohexane | 4.824     | 355.1    |
| R-70   | 43.2                                | cyclohexane | 3.367     | 173      |
| R-70   | 230                                 | cyclohexane | 3.1       | 147      |
| R-70   | 230                                 | acetone + cyclohexane | 2.5     | 95.3     |
| R-50   | 230                                 | cyclohexane | 1.9       | 55.05    |
| R-50   | 230                                 | acetone + cyclohexane | <1.8   | <49.41   |
| R-30   | 230                                 | acetone + cyclohexane | 2.8     | 119.6    |
| R-0    | 230                                 | cyclohexane | 6.04      | 560      |

The V₅₀ and E₅₀ for the nanocomposites decreased as the specific surface area of the nano-Fe₂O₃ increased, and their V₅₀ and E₅₀ also decreased when both cyclohexane and acetone were used instead of cyclohexane alone. This may be because the effective friction area increased with the increase in the specific surface area, causing more static discharges to accumulate on the surfaces of the sample, which resulted in a decrease in the sample’s V₅₀ and E₅₀ and an increase in its static discharge sensitivity. When cyclohexane plus acetone was used as the solvent, the average particle size in the resulting nanocomposite was smaller than when cyclohexane alone was used, leading to an increase in static discharge sensitivity.

Figure 3 gives SEM images of Al/Fe₂O₃/RDX nanocomposites prepared using different solvents. As shown in Figure 3a, the use of cyclohexane produced large, 1 μm particles and small, <100 nm particles. The large particles are super fine RDX, and the small particles are nano-Al/Fe₂O₃ composite. When both cyclohexane and acetone were used, the particle sizes of the nanocomposite were less than 100 nm, and the granularity distribution was more uniform because RDX dissolves in acetone. Therefore, a hybrid nanocomposite prepared using both cyclohexane and acetone will have smaller RDX particles and a higher static discharge sensitivity than nanocomposite prepared using cyclohexane alone. Nanocomposite’s static discharge sensitivity was greatest when the amount of Al/Fe₂O₃ nanothermite was 50 wt % and both cyclohexane and acetone were used. Thus, Al/Fe₂O₃/RDX nanocomposites with different static discharge sensitivities can be produced by adjusting the RDX content and the particle sizes of the constituents.

Figure 3. SEM images of Al/Fe₂O₃/RDX nanocomposites prepared using (a) cyclohexane or (b) both cyclohexane and acetone.
3.3. Flame Sensitivity Analysis

As stated, the flame sensitivity of Al/Fe$_2$O$_3$/RDX nanocomposites was determined using the fuse method. The results are given in Table 3.

| Sample | Specific Surface Area of Fe$_2$O$_3$ (m$^2$/g) | Solvent | Ignition Distance (mm) |
|--------|-----------------------------------------------|---------|------------------------|
| R-100  | -                                             | -       | <1.2 mm                |
| R-70   | 43.2                                          | Cyclohexane | 9.0                   |
| R-70   | 230                                           | Cyclohexane | 15                    |
| R-70   | 230                                           | acetone + cyclohexane | 30           |
| R-50   | 230                                           | Cyclohexane | 35                    |
| R-50   | 230                                           | acetone + cyclohexane | 70                    |
| R-30   | 230                                           | acetone + cyclohexane | >80                |
| R-0    | 230                                           | Cyclohexane | >80                    |

As shown in Table 3, superfine RDX was very stable and did not fire even when the fuse’s combustion flame was as close as 1.2 mm, indicating that the flame sensitivity of superfine RDX is very low. As the proportion of Al/Fe$_2$O$_3$ nanothermite increased, the ignition distance and the flame sensitivity of the nanocomposites also increased—i.e., the larger the amount of Al/Fe$_2$O$_3$ nanothermite, the longer the ignition distance of the Al/Fe$_2$O$_3$/RDX nanocomposite, and the greater its flame sensitivity. This may be due to the good thermal conductivity of the nano-Al and the high reactivity of the Al/Fe$_2$O$_3$ nanothermite in the nanocomposite. When the fuse’s combustion flame contacted the surface of the nanocomposite, the nano-Al on the surface of the nanocomposite presumably adsorbed enough heat from the flame to make the Al/Fe$_2$O$_3$ nanothermite react, releasing abundant heat that formed a local high-temperature region in which the surface of the RDX generated a hot spot that made the RDX decompose. It was this process that produced the voluminous smoke that was seen during testing. The Al/Fe$_2$O$_3$ nanothermite around the high-temperature region also fired, and finally the nanocomposite fired as a whole.

Due to this chain of events, hybrid nanocomposites containing Al/Fe$_2$O$_3$ nanothermite were more sensitive to heat than RDX, and the nanocomposites containing a large amount of Al/Fe$_2$O$_3$ nanothermite showed high flame sensitivity. As the specific surface area of Fe$_2$O$_3$ increased, the firing distance and flame sensitivity of the Al/Fe$_2$O$_3$/RDX nanocomposite also increased. If both cyclohexane and acetone were used as the solvent during mixing, the flame sensitivity of the nanocomposite also increased because RDX dissolves in the acetone, reducing its particle size and increasing the specific surface area of the particles. Thus, the particle size of the ingredients in the nanocomposites had a large effect on their flame sensitivity.

3.4. Hot Bridge Wire Sensitivity Analysis

The static discharge safety properties of Al/Fe$_2$O$_3$/RDX nanocomposites in an electric detonator were measured using the angle–crust connection mode and the angle–angle connection mode. The results are given in Table 4. The firing pictures of nanocomposites with different RDX content at the angle–angle connection mode are shown in Figure 4.

| Sample | Specific Surface Area of Fe$_2$O$_3$ (m$^2$/g) | Solvent | Firing Property at Static Discharge |
|--------|-----------------------------------------------|---------|------------------------------------|
|        |                                               |         | Angle–Crust                        |
|        |                                               |         | Angle–Angle                         |
| R-100  | -                                             | -       | no                                 |
| R-70/50/30/0 | 10.3/43.2/230 | cyclohexane/acetone + cyclohexane | no | yes |
The properties of Al/Fe hot bridge wire sensitivity. The increase in the specific surface area of Fe
and then increased, following a "U" type change trend that is the reverse of the change trend for
amperage. This is because the addition of Al/Fe nanothermite improved the firing properties of
nanocomposites with different specific surface areas of Fe
mixing, and RDX content through heating the bridge wire at 5 A in an electric detonator. The results
the firing properties of nanocomposites. Different firing properties were achieved by adjusting the proportion of RDX in
the nanocomposites.
As Table 4 shows, pure RDX in an electric detonator was very stable and did not fire at the
angle–crust connection or at the angle–angle connection in the static discharge safety test (Figure 4a).
In contrast, the different connection circuit modes considerably affected the static discharge safety
properties of Al/Fe/RDX nanocomposites in electric detonators. The fact that the nanocomposites
did not fire completely at the angle–crust connection may be due to the good conductivity of the metal
crust of the electric detonator, which impeded electrostatic accumulation on its surface. As a result,
the nanocomposites did not fire at the angle–crust connection, indicating that they were very safe in
that connection mode. They did fire at the angle–angle connection (Figure 4), however, with their
firing strength decreasing as the proportion of RDX decreased. Some nanocomposites with a high
RDX content (>50 wt % RDX) exploded in the static discharge safety test, and the metal crusts of
the electric detonators disappeared (Figure 4b). When the RDX content was 30 wt % (Figure 4c),
the nanocomposite also exploded, splitting and deforming the metal crusts. Al/Fe nanothermite
also fired at the angle–angle connection, but only combustion occurred, and the metal crust was only
burned through, not destroyed or deformed (Figure 4d). The specific surface area and the solvent used
during mixing had little effect on the static discharge safety properties of the nanocomposites in an
electric detonator. Different firing properties were achieved by adjusting the proportion of RDX in
the nanocomposites.

The hot bridge wire sensitivity of Al/Fe/RDX nanocomposites was measured by determining
the firing properties of nanocomposites with different specific surface areas of Fe, solvents used in
mixing, and RDX content through heating the bridge wire at 5 A in an electric detonator. The results
are given in Table 5.
As Table 5 shows, pure RDX was very stable and did not fire when the bridge wire was heated at
5 A, but as Al/Fe nanothermite was added to the RDX, the resulting nanocomposite did fire at that
amperage. This is because the addition of Al/Fe nanothermite improved the firing properties of
RDX. As the proportion of RDX decreased, the firing energy of the nanocomposites first decreased
and then increased, following a "U" type change trend that is the reverse of the change trend for
their hot bridge wire sensitivity. The increase in the specific surface area of Fe and the use of
both cyclohexane and acetone increased their hot bridge wire sensitivity, because these two factors
increased the specific surface area of the nanocomposites, leading to an increase in their reactivity and

**Figure 4.** Firing pictures at the angle–angle connection for Al/Fe/RDX nanocomposites with RDX
content of (a) R-100, (b) >50 wt % RDX, (c) R-30, (d) R-0.
a decrease in their firing energy. The nanocomposite had the lowest firing energy (87.9 mJ) when the proportion of Al/Fe$_2$O$_3$ nanothermite was 50 wt %, and both cyclohexane and acetone were used as the solvent. The hot bridge wire sensitivity of the nanocomposites depended heavily on their RDX content and specific surface area.

| Sample | Specific Surface Area of Fe$_2$O$_3$ (m$^2$/g) | Solvent                  | Firing Conditions | Electrical Resistance of Bridge Wire (Ω) | Firing Energy (mJ) |
|--------|-----------------------------------------------|--------------------------|------------------|------------------------------------------|-------------------|
| R-100  | -                                             | -                        | -                | 0.995                                    | -                 |
| R-70   | 43.2                                          | cyclohexane              | 5 A/14.8 ms      | 1.082                                    | 400.3             |
| R-70   | 230                                           | cyclohexane              | 5 A/10.2 ms      | 0.965                                    | 245.3             |
| R-70   | 230                                           | Acetone + cyclohexane    | 5 A/4.5 ms       | 1.001                                    | 112.6             |
| R-50   | 230                                           | cyclohexane              | 5 A/3.9 ms       | 1.040                                    | 101.4             |
| R-50   | 230                                           | Acetone + cyclohexane    | 5 A/3.5 ms       | 1.005                                    | 87.9              |
| R-30   | 230                                           | cyclohexane              | 5 A/9.3 ms       | 0.975                                    | 226.7             |
| R-30   | 230                                           | Acetone + cyclohexane    | 5 A/6.6 ms       | 0.946                                    | 156.1             |
| R-0    | 280                                           | cyclohexane              | 5 A/17.8 ms      | 1.002                                    | 445.9             |

4. Conclusions
The safety properties of one potential kind of novel green nanoscale primary explosive were evaluated by measuring its sensitivities. These were greatly affected by the RDX content and the particle sizes of its ingredients, and they were heavily dependent on its specific surface area and its ingredients. As the specific surface area of nano-Fe$_2$O$_3$ increased, the impact sensitivity of Al/Fe$_2$O$_3$/RDX nanocomposite fell, but the static discharge, flame, and hot bridge wire sensitivities all increased. When both cyclohexane and acetone were used as the solvent during mixing, the sensitivity of the nanocomposite also increased, due to the decrease in the RDX particle size. As the content of Al/Fe$_2$O$_3$ nanothermite increased, impact sensitivity fell, and flame sensitivity rose. However, the static discharge and hot bridge wire sensitivities of the nanocomposite followed an inverted “U” type change trend and were determined by both the particle size of the ingredients and the resistance of the nanocomposite. Nanoscale primary explosives with different sensitivities and firing properties can be obtained by adjusting their RDX content and the specific surface area of their ingredients.

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References
1. Danilov, Y.N.; Ilyushin, M.A.; Tselinsky, I.V. Industrial Explosives: Primary Explosives; State Inst. of Technol. (Technic. Univ.): St. Petersburg, Russia, 2004.
2. Baev, V.I.; Lvov, C.N.; Shugalei, I.V. Influence of the Environment Internal Factors on Warm-blooded Organisms. In Proceedings of the Problems of Military and Emergency Medicine, St. Petersburg, Russia, 1998; pp. 62–63.
3. Tsvetkova, O.B.; Shatrova, N.M.; Scheglov, A.N. Storage of radio-nucleases and heavy metals by basidiomycetes of forest ecosystems. Bull. Inst. Nucl. Invest. Kiev 2001, 3, 171–176.
References

4. Talawar, M.B.; Sivabalan, R.; Mukundan, T.; Muthurajan, H.; Sikder, A.K.; Gandhe, B.R.; Rao, A.S. Environmentally compatible next generation green energetic materials (GEMs). J. Hazard. Mater. 2009, 161, 589–607. [CrossRef] [PubMed]

5. Ilyushin, M.A.; Tselinsky, I.V.; Shugalei, I.V. Environmentally friendly energetic materials for initiation devices. Cent. Eur. J. Energ. Mater. 2012, 9, 293–327.

6. Huynh, M.H.V.; Coburn, M.D.; Meyer, T.J.; Wetzler, M. Green primary explosives: 5-Nitrotetrazolato-N2-ferrate hierarchies. PNAS 2006, 103, 10322–10327. [CrossRef] [PubMed]

7. Klapötke, T.M.; Stierstorfer, J.; Weber, B. New energetic materials: Synthesis and characterization of copper 5-nitriminotetrazolates. Inorg. Chem. Acta 2009, 362, 2311–2320. [CrossRef]

8. Klapötke, T.M.; Mehta, N. Lead-Free primary explosives. Propellants Explos. Pyrotech. 2014, 39, 7–8. [CrossRef]

9. Li, Z.M.; Zhang, J.G.; Zhang, T.L.; Shu, Y.J. Nitro-tetrazole and its high nitrogen-contented compounds. Prog. Chem. 2010, 22, 639–647.

10. Fronabarger, J.W.; Williams, M.D.; Sanborn, W.B.; Bragg, J.G.; Parrish, D.A.; Bichay, M. DBX-1-A Lead-free replacement for lead azide. Propellants Explos. Pyrot. 2011, 36, 541–550. [CrossRef]

11. Fischer, N.; Klapoetke, T.M.; Stierstorfer, J. Calcium 5-Nitriminotetrazolate—A green replacement for lead azide in priming charges. J. Energ. Mater. 2011, 29, 61–74. [CrossRef]

12. Zhu, S.G.; Sun, Y.L.; Zhang, L.; Li, Y. A new green primary explosive: Zinc 5,5’-azotetrazole. In Proceedings of the 38th International Pyrotechnics Seminar and Symposium, Littleton, CO, USA, 10–15 June 2012; pp. 696–704.

13. Fronabarger, J.; Williams, M.; Sanborn, W.; Sitzmann, M.; Bichay, M.; Gilardi, R. Characterization and output testing of the novel primary explosive, bis(furoxano)nitrophenol, potassium salt. In Proceedings of the 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Tucson, AZ, USA, 10–13 July 2005.

14. Asay, B.W.; Son, S.F.; Busse, J.R.; Oschwald, D.M. Ignition characteristics of metastable intermolecular composites. Propellants Explos. Pyrot. 2004, 29, 216–219. [CrossRef]

15. Puszynski, J.A.; Bulian, C.J.; Swiatkiewicz, J. The effect of nanopowder attributes on reaction mechanism and ignition sensitivity of nanothermites. MRS Proc. 2005, 896, 0896-H04-01. [CrossRef]

16. Levitas, VI.; Asay, B.W.; Son, S.F.; Pantoya, M. Melt dispersion mechanism for fast reaction of nanothermites. Appl. Phys. Lett. 2006, 89, 071909. [CrossRef]

17. Lafontaine, E.; Comet, M. Nanothermites; John Wiley & Sons: Hoboken, NJ, USA, 2016.

18. Comet, M.; Martin, C.; Schnell, F.; Spitzer, D. Nanothermite foams: From nanopowder to object. Chem. Eng. J. 2017, 316, 807–812. [CrossRef]

19. Zhou, X.; Wang, Y.; Cheng, Z.; Ke, X.; Jiang, W. Facile preparation and energetic characteristics of core-shell Al/CuO metastable intermolecular composite thin film on silicon substrate. Chem. Eng. J. 2017, 328, 585–590. [CrossRef]

20. Zhang, T.; Zhao, N.; Li, J.; Gong, H.; An, T.; Zhao, F.; Ma, H. Thermal behavior of nitrocellulose-based superthermites: Effects of nano-Fe2O3 with three morphologies. RSC Adv. 2017, 7, 23583–23590. [CrossRef]

21. Thiruvengadathan, R.; Bezmelnitsyn, A.; Apperson, S.; Staley, C.; Redner, P.; Balas, W.; Nicolich, S.; Kapoor, D.; Gangopadhyay, K.; Gangopadhyay, S. Combustion characteristics of novel hybrid nanoenergetic formulations. Combust. Flame 2011, 158, 964–978. [CrossRef]

22. Qiao, Z.; Shen, J.; Wang, J.; Wang, J.; Huang, B.; Yang, Z.; Yang, G.; Zhang, K. Fast deflagration to detonation transition of energetic material based on a quasi-core/shell structured nanothermite composite. Compos. Sci. Technol. 2015, 107, 113–119. [CrossRef]

23. Comet, M.; Martin, C.; Klaumünzer, M.; Schnell, F.; Spitzer, D. Energetic nanocomposites for detonation initiation in high explosives without primary explosives. Appl. Phys. Lett. 2015, 107, 113–119. [CrossRef]

24. Luo, Q.; Nie, F.; Long, X.; Qiao, Z.; Yang, G.; Ma, Y. Preparation of nano-Fe2O3 by CO2-supercritical-process-assisted sol-gel method. Curr. Nanosci. 2014, 10, 722–729. [CrossRef]

25. Plantier, K.B.; Pantoya, M.L.; Gash, A.E. Combustion wave speeds of nanocomposite Al/Fe2O3: The effects of Fe2O3 particle synthesis technique. Combust. Flame 2005, 140, 299–309. [CrossRef]

26. Liu, C.L.; Wang, S.P.; Wu, Z.C.; Li, Y.M. Study on the test method of the electrostatic sensitivity of the non-initiating explosive devices. J. Electrost. 2011, 69, 501–503. [CrossRef]

27. Wei, Y.J.; Lu, C.L.; Zhou, D.C.; Geng, X.H.; Zhang, J. Influence of particle size on RDX thermal sensitivity and flame sensitivity. Chem. Propellants Polym. Mater. 2011, 9, 89–91.
28. Yao, L.N.; Feng, X.S.; Zhao, S.X.; Wang, C.L.; Wang, S.P. Influence of nano Al on mechanical sensitivity and flame sensitivity of RDX-based explosive. Chin. J. Explos. Propellants 2012, 35, 15–18.

29. Weir, C.; Pantoya, M.L.; Ramachandran, G.; Dallas, T.; Prentice, D.; Daniels, M. Electrostatic discharge sensitivity and electrical conductivity of composite energetic materials. J. Electrost. 2013, 71, 77–83. [CrossRef]

30. Zeman, S. New aspects of initiation reactivities of energetic materials demonstrated on nitramines. J. Hazard. Mater. 2006, A132, 155–164. [CrossRef] [PubMed]

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