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Electrostatic Hazards Assessment of Nitramine Explosives: Resistivity, Charge Accumulation and Discharge Sensitivity

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Abstract: The electrostatic hazards of nitramine explosives (RDX, HMX) were assessed in this paper. The resistivities of different particle-size RDX and HMX were tested by a device designed and manufactured according to the standard ISO/IEC 80079-20-2:2016. This work shows that the resistivities of uncompact RDX and HMX increase as the particle size decreases. Charging characteristics test experiments were also carried out using a so-called sieve method. Using this method, the influence of aperture size on charge accumulation of RDX was studied, and the characteristics of electrostatic accumulation of different particle-size RDX and HMX sieved with 50 mesh standard sieve were compared. The results show that the absolute value of the charge accumulation increases as the mesh number increases (*i.e.* the aperture size decreases), and increases as the particle size is decreased, indicating that nano-sized RDX and nano-sized HMX accumulate static electricity more easily than conventional micron-sized ones. Finally, the electrostatic discharge (ESD) sensitivity of nano-sized RDX and nano-sized HMX was investigated. Nano-sized nitramine explosives were found to have a higher ESD sensitivity than micron-sized ones.

Keywords: nitramine explosives, electrostatic hazards, resistivity, charging characteristics, electrostatic discharge sensitivity

1 Introduction

Electrostatic charges often accumulate in bulk explosives and equipment during handling and processing procedures due to tribocharging. If the charge buildup becomes high enough to initiate a so-called discharge by ionization of the surrounding atmosphere [1], the hot plasma within the discharge channel may initiate the explosives.

In general, there are two parameters that are used to characterize electrostatic hazards of bulk explosives: the charging characteristic and the electrostatic discharge (ESD) sensitivity [2]. The charging characteristic is the ability of explosive powders to generate and accumulate charge while rubbing against other materials. The ESD sensitivity is the probability of an explosive being initiated by electrostatic discharge. Many studies have been performed in the past to investigate the charging characteristics of explosive powders. In Ref. [3], the electrostatic charging characteristics of three different particle-size (0.167 mm, 0.14 mm and 0.108 mm) desensitized RDX was studied using an inclined isolated metal chute. It was found that charge accumulation increased as the particle size was decreased. In Ref. [4], a similar device was used to explore the influence of aluminite powder on the charging characteristics of RDX. The charging characteristics of normal industrial RDX (half-content diameter $D_{50} \approx 120 \mu\text{m}$) mixed with 20%~30% extra fine RDX ($D_{50} \approx 90 \mu\text{m}$) were also reported. It was suggested that aluminite powder could reduce the charge accumulation of RDX while rubbing against other materials and the extra fine RDX would also reduce the charge accumulation of the mixture. Studies of ESD sensitivity are also fruitful. ESD has been shown to have the ability of igniting many kinds of powdered materials such as powdered food [5], dust [6, 7], textiles [8] and explosives [9-11]. All these studies suggested the same conclusion, namely that charging of explosive powders makes them very dangerous. In order to predict the ESD sensitivity of explosives, some authors have tried to find suitable correlations between detonation parameters (*e.g.* detonation velocity, detonation pressure) and electric spark sensitivity [12-16]. The ESD sensitivity of energetic materials has been confirmed to be influenced by various parameters, including the chemical micro-mechanism [17], moisture content [18], granularity [18-21], particle shape [19, 22], temperature [23], electrodes form, composition of the discharging circuit [18], thermal reactivity [9, 18, 24], and impact reactivity [25-27]. Up to the present time, the experimental test is still the most direct and effective method to ascertain the ESD sensitivity of explosives.

As the successful preparation of nano-sized nitramine explosives (RDX, HMX), the properties of the explosives have been greatly improved [28-30], and the application of nano-sized explosives is also expanding. However,

previous studies have shown that charge accumulation is inversely proportional to the particle size of explosives [3]. Thus the electrostatic hazards of nano-sized explosives should be always kept in mind. Testing and analyzing the electrostatic hazards of nano-sized nitramine explosives will be helpful to the safety in producing and using them. Unfortunately, until now research on the electrostatic hazards of nano-sized explosives is lacking. Furthermore, the existing powder charging test method (the chute method) is difficult to use on nano-sized explosives due to their high adhesiveness [4]. In this paper, the electrostatic hazards of nano-sized nitramine explosives were assessed. The charging characteristics of nano-sized explosives were tested by sieves. The main content of this paper consists of three sections: the resistivity test, the charging characteristics test, and the ESD sensitivity test.

2 Experimental

2.1 Sample preparation

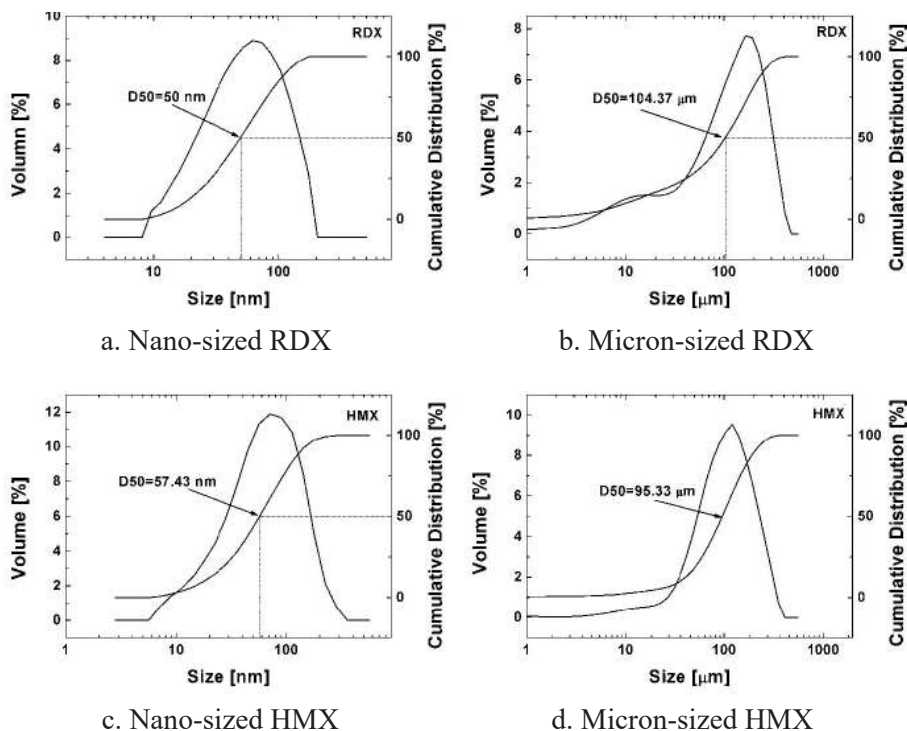


Figure 1. Particle size distributions of RDX and HMX.

Micron-sized RDX (China military standard GJB296A-1995 with purity of 99.5%) and micron-sized HMX (China military standard GJB2335-1995 with purity of 99.5%), produced by Gansu Yinguang Chemical Industry Group Co., Ltd. of China, were ground into several different particle sizes by the National Special Superfine Powder Engineering Research Center of China using a bi-directional rotation mill [30]. We neglected the influence of antistatic agents (if they existed in the impurities) on the samples.

Four typical particle size distributions of RDX and HMX, measured using a Malvern Mastersizer Micro laser particle size analyzer, are shown in Figure 1.

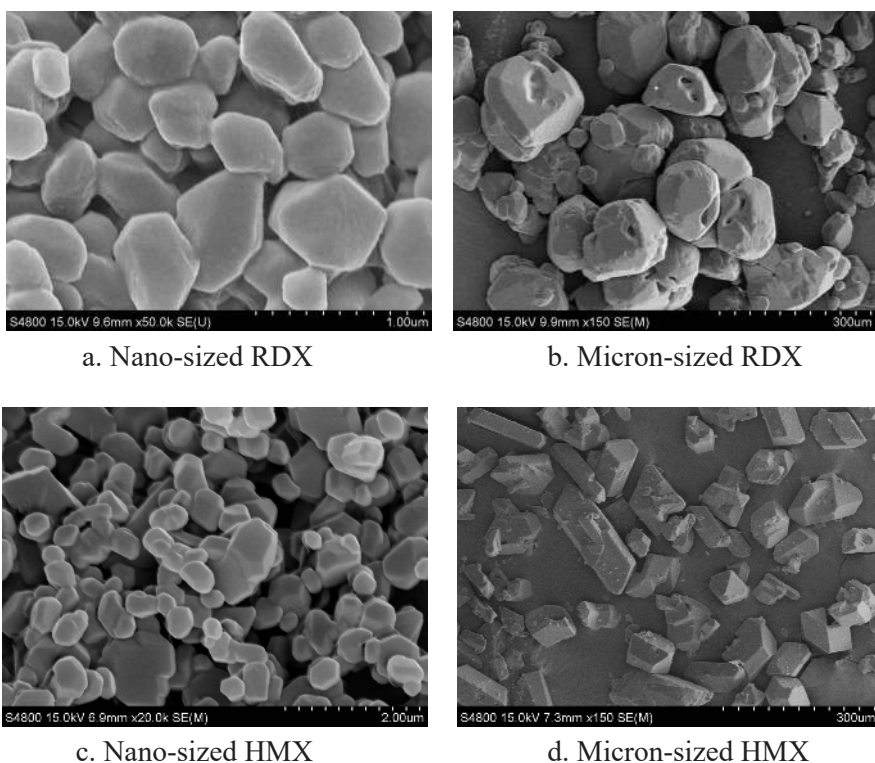


Figure 2. SEM images of RDX and HMX.

As shown in Figure 1, the half-content diameters of nano-sized RDX, micron-sized RDX, nano-sized HMX, and micron-sized HMX were 50 nm, 104.37 μm , 57.43 nm, and 95.33 μm , respectively. In addition, the samples used in the following experiments also included particles of sizes 24.03 μm , 18.45 μm , 640 nm and 80 nm for RDX and 5 μm , 240 nm and 80 nm for HMX.

Four typical explosive particle sizes and morphologies were characterized

using an S-4800II Scanning Electron Microscope (SEM) made by Hitachi High-Technologies Corporation. Images are shown in Figure 2.

As shown in Figure 2, the micron-sized RDX particles (b) are porous and heterogeneous, the micron-sized HMX particles (d) are polyhedral and irregular, while the nano-sized RDX (a) and nano-sized HMX (c) particles are near-spherical and homogeneous.

All of the samples were put into a water bath oven for more than three hours until their weight changes were less than 0.1% before tests. The temperature inside the water bath oven was 60 °C. The dried samples were put into a desiccator.

2.2 Measuring instrument and apparatus

2.2.1 Resistivity test

The powder resistivity test device was designed and manufactured according to the standard ISO/IEC 80079-20-2:2016. It should be noted that the test device described in ISO/IEC 80079-20-2:2016 is not suitable for explosive powders since it may not reflect the powders' explosive property. However, in these studies we only used this device to obtain the resistivity of the powders and did not consider their explosive properties. Thus, this powder resistivity test device was applicable to our research. The test device consists of three parts: a high resistance and micro current measuring instrument, a shielding box and a test cell. The high resistance and micro current measuring instrument was manufactured by Beijing Labor Protection Science Research Institute of China. It provides six testing voltage values: 10, 50, 100, 250, 500 and 1000 V. It can be used to measure resistance ranging from 10^2 to $10^{18} \Omega$, and current ranges from 2×10^{-4} to 1×10^{-16} A. The shielding box was made of steel in order to shield the explosive powders from electromagnetic interference during the test process. The test cell consists of two stainless steel electrodes, two insulating terminal strips and an insulating plate. A sketch of the test cell is shown in Figure 3.

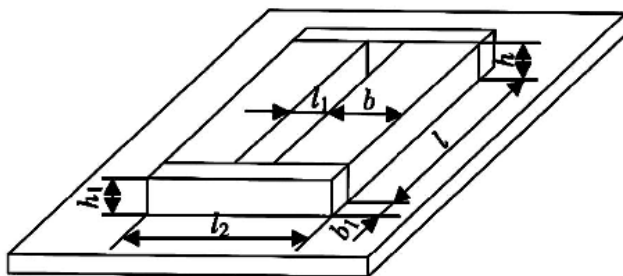


Figure 3. Sketch of test cell for resistivity measurement.

As shown in Figure 3, the length of the stainless steel electrodes l is 100 mm, their width b 25 mm and their height h 10 mm. The gap between two electrodes l_1 was 10 mm. The length of the insulating terminal strip l_2 was 60 mm, the width b_1 10 mm, and the height h_1 10 mm. The insulating plate was made of 3 mm thick glass.

The calculation of the resistivity ρ can be divided into two cases. When the resistance of the empty test cell R_0 is ten times larger than the resistance R_s when it contains a sample, the formula is:

$$\rho = 0.1R_s \quad (1)$$

if no, the formula is:

$$\rho = 0.1R_sR_0 / (R_0 - R_s) \quad (2)$$

The test cell was cleaned and dried using an electric hot air blower before each test. The test cell is uniformly filled with a dried loose test sample with no compaction (a small piece of glass was pushed onto the surface of the sample in the test cell and the surfaces of the two plate electrodes in order to make those surfaces the same level). The ambient relative humidity (RH) was set between 45% and 50% during a test.

2.2.2 Charging characteristics test

The electrostatic charging characteristics test apparatus includes four parts: a sample cup, a standard sieve, a Faraday cage and a digital charge meter [31]. The experimental setup is shown in Figure 4.

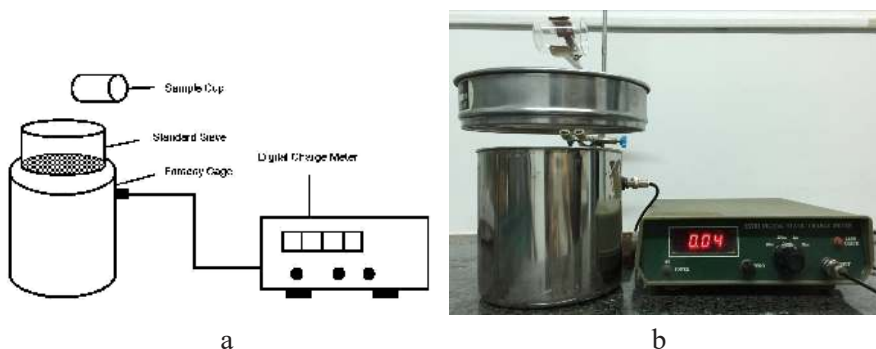


Figure 4. Electrostatic charging characteristics test apparatus: (a) schematic diagram; (b) experimental stand.

The sample cup is used to weigh the sample. In this experiment, it was a 100 mL glass beaker. The standard sieves were designed and manufactured according to standard ISO 565:1990 and GB/T 6003.1-2012 of China. All of these sieves' diameters were 100 mm, the mesh material was stainless steel, and the aperture sizes were 0.6 mm (30 mesh), 0.355 mm (50 mesh), 0.22 mm (70 mesh), and 0.16 mm (90 mesh). The Faraday cage was designed following the principle of electrostatic induction and was dedicated to the measurement of electrostatic charge in insulating materials. The measuring range of the digital charge meter (EST111), produced by Beijing Labor Protection Science Research Institute of China, was $\pm 10 \text{ pC} \sim \pm 20 \text{ }\mu\text{C}$.

The sample cup, standard sieve and Faraday cage were cleaned and dried using an electric hot air blower before each test. The ambient relative humidity (RH) was set between 45% and 50% during each test.

2.2.3 ESD sensitivity test

Figure 5 shows the ESD sensitivity test device designed according to US military standard MIL-STD-1751A. It is composed of five parts: a high voltage generator, a spherical switch controller, an electrostatic sensitivity test box, a capacitor, and a resistor.

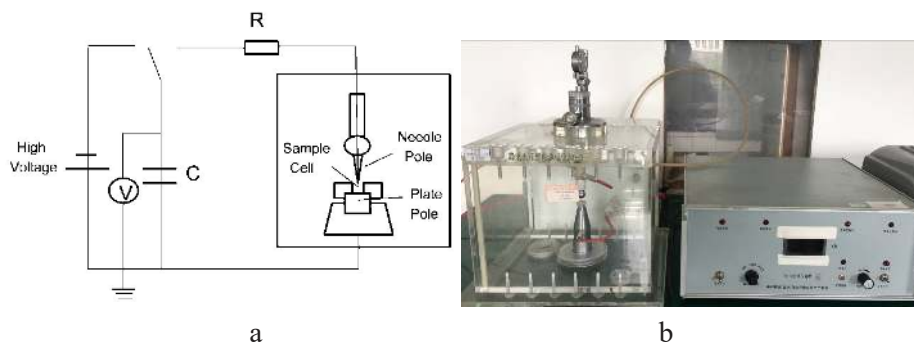


Figure 5. ESD sensitivity test device: (a) schematic diagram, (b) experimental stand.

The spherical switch controller controls the capacitor which is charged by the high voltage generator and then discharged through the needle pole and plate pole inside the electrostatic sensitivity test box. Both the needle pole (top diameter = 1 mm, length = 15 mm, the diameter decreasing towards the ends) and cylindrical plate pole (diameter = 10 mm, height = 16 mm) were made of stainless steel. The sample cell was made from a polyethylene ring and mounted on the

edge of the plate pole. The mass of the samples in each test was 20 mg. The ESD sensitivity of nitramine explosives was measured under a relatively high electric discharge energy stimulus [9], the discharge voltage of the capacitor being 50 kV, the capacitance of the capacitor 2 nF, the gap width of the electrodes 0.2 mm, and the resistor value 0 Ω . The ambient relative humidity (RH) was set between 45% and 50% during each test.

3 Results and Discussion

3.1 Resistivity of nitramine explosives

The measured sample resistivities for different voltages were much the same. The voltage used here was 500 V, and the resistivities of different particle-size uncompact RDX and HMX powders are listed in Table 1. The values shown in Table 1 are the average values of two or more repeated tests.

Table 1. The resistivities of different particle-size uncompact RDX and HMX powders

RDX		HMX	
D50 [μm]	Resistivity [$\Omega\cdot\text{m}$]	D50 [μm]	Resistivity [$\Omega\cdot\text{m}$]
104.37	3.2×10^{10}	95.33	2.2×10^9
24.03	2.8×10^{11}	5.64	4.6×10^{10}
18.45	1.6×10^{11}	0.24	1.1×10^{11}
0.64	6.2×10^{12}	0.057	6.3×10^{11}
0.05	8.1×10^{12}	—	—

As listed in Table 1, the resistivities of uncompact RDX and HMX increase with decreasing particle size down to nanoscale, although the increase is modest. The main reason for this phenomenon is that the loose density of nano-sized samples is smaller than that for micro-sized samples. This is due to the fact that a micro-sized particle can be divided into thousands of nano-sized particles that are not compacted and hence occupy more volume. The resistivity minima of nano-sized RDX and nano-sized HMX are 6.2×10^{12} $\Omega\cdot\text{m}$ and 1.1×10^{11} $\Omega\cdot\text{m}$ respectively, which indicates that they will have a potential for discharging due to the generally held view that, for bulk materials, 10^{10} $\Omega\cdot\text{m}$ is the lower limit at which cone discharges are likely to occur [1].

3.2 Charging characteristics

3.2.1 Charge accumulation of different masses

The charge accumulations of micron-sized RDX (D50 is 104.37 μm) with different masses are listed in Table 2, where Q is the measure value of charge accumulation, \bar{Q} is the average value of charge accumulation, and \bar{q} is the average value of specific charge accumulation. The micron-sized RDX was sieved using a 50 mesh standard sieve. The relationship between mass and charge accumulation is shown in Figure 6.

Table 2. Charge accumulation of micron-sized RDX with different masses

m [g]	Q [nC]			\bar{Q} [nC]	\bar{q} [$\mu\text{C}\cdot\text{kg}^{-1}$]
	1	2	3		
5	-29.0	-29.3	-26.7	-28.33	-5.67
8	-44.7	-46.2	-48.3	-46.40	-5.80
10	-57.2	-62.5	-57.5	-59.07	-5.91
12	-67.3	-70.2	-74.0	-70.50	-5.88
15	-88.2	-91.5	-86.6	-88.77	-5.92

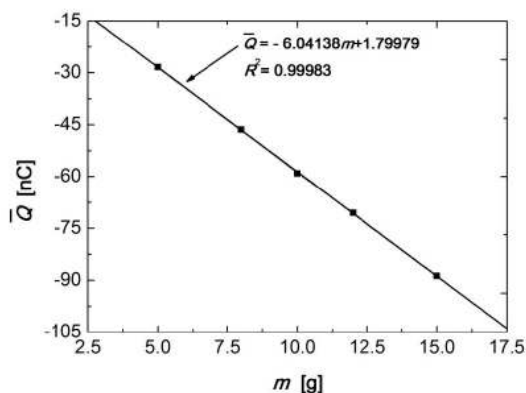


Figure 6. Effects of mass of micron-sized RDX on charge accumulation.

As listed in Table 2, the charge accumulation increases with increasing mass. The specific charge values for different masses generally remain the same. We can see from Figure 6 that, the relationship between charge accumulation and mass follows a linear relationship in our experimental sample mass range (the linear relationship may be invalid for larger sample masses). This result is consistent with the conclusions in Refs. [3, 4] in which the chute method was

used. Thus, our sieve method could be successfully used later to measure the charge accumulation of nano-explosives.

3.2.2 Charge accumulation of different standard mesh sieves

The charge accumulations of nano-sized RDX (D50 is 80 nm) sieved using different standard mesh sieves are listed in Table 3. The mass of the samples in each test was 5 g. The values shown in Table 3 are the average values of two or more repeated tests.

Table 3. Charge accumulation of nano-sized RDX sieved with different standard mesh sieves

Mesh number	30	50	70	90
\bar{Q} [nC]	-23.1	-105.5	-178.2	-236

As listed in Table 3, the charge accumulation (absolute value) increases as the mesh number increases (*i.e.* the aperture size decreases). The charge accumulation of nano-sized RDX sieved using a 90 mesh standard sieve is approximately nine times greater than that sieved with a 30 mesh standard sieve.

3.2.3 Charge accumulation of different particle sizes

The specific charge accumulations of different particle-size RDX and HMX sieved using a 50 mesh sieve are listed in Table 4. The values shown in Table 4 are the average values of two or more repeated tests.

Table 4. The specific charge accumulations of different particle-size RDX and HMX

RDX		HMX	
D50 [μm]	\bar{q} [$\mu\text{C}\cdot\text{kg}^{-1}$]	D50 [μm]	\bar{q} [$\mu\text{C}\cdot\text{kg}^{-1}$]
104.37	-5.8	95.33	-2.2
24.03	-17.9	5.64	-7.1
18.45	-18.1	0.24	-8.1
0.64	-20.8	0.08	-8.1
0.08	-21.1	—	—

As listed in Table 4, the specific charge accumulations (absolute values) of both RDX and HMX increase with decrease of their particle sizes. We think the reasons are as follows. As a result of ultrafine processing, the densities of the explosives decreased greatly. Thus, the looser and finer properties of the

explosive particles will give them more chances to contact the sieve screen during the sieving process. Besides, the ratio of adhesion force to gravity will increase with decrease of particle size. That means that the superfine powder will more easily make contact with the sieve screen due to the force of adhesion. Furthermore, the results presented in Section 3.1 showed that the resistivities of RDX and HMX increase as their particle sizes decrease. And a greater resistivity implies it will be more difficult to leak electrostatic charge.

We can also conclude from Table 4 that the specific charge accumulation of RDX is generally much larger than that of HMX for the same particle size. For example, the specific charge accumulation of RDX is 2.6 times that of HMX for a particle size of 0.08 μm . This conclusion means that charge accumulation is much easier to occur for RDX and steel. Generally, the main properties of materials that cause differences in charge accumulation include density, conductivity, viscosity, dispersion and work function. However, the determination of the degree of influence of each property still needs further research.

3.3 ESD sensitivity of different particle sizes

The 50% ignition probabilities of RDX and HMX with different particle sizes were tested by 25-time tests in which the discharge voltage of the capacitor was varied in each case. The results were expressed by the 50% ignition voltage U_{50} gained with the so-called “up and down” method set out in the standard GJB 2178A-2005. The test results are shown in Table 5. The 50% ignition energy E_{50} , which is also shown in Table 5, was calculated by the following formula:

$$E_{50} = \frac{1}{2} C U_{50}^2 \quad (3)$$

where, C is the capacitance of the capacitor (2 nF).

Table 5. The ESD sensitivity of different particle-size RDX and HMX

RDX			HMX		
D50 [μm]	U_{50} [kV]	E_{50} [J]	D50 [μm]	U_{50} [kV]	E_{50} [J]
104.37	47.8	2.285	95.33	43.3	1.875
24.03	46.1	2.125	5.64	42.1	1.772
18.45	45.7	2.088	0.24	38.4	1.475
0.64	44.0	1.936	0.08	35.2	1.239
0.08	41.6	1.731	—	—	—

The data in Table 5 show that the ESD sensitivity decreases as the particle size decreases for both RDX and HMX. This indicates that for the same stimulus, the sensitivity of nano-sized nitramine explosives is higher than that of micron-sized ones. Meanwhile the ESD sensitivity of RDX is higher than that of HMX for the same particle size, which is clearly illustrated in Figure 7.

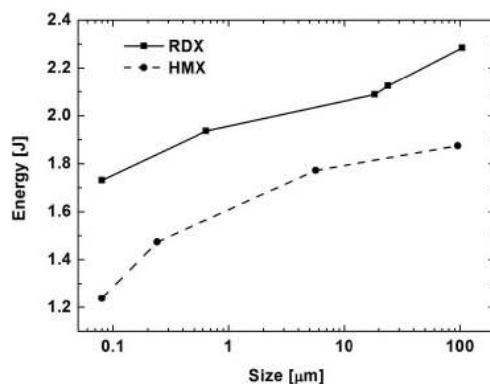


Figure 7. Relationship between the particle size and 50% ignition energy E_{50} of RDX and HMX.

4 Conclusions

The following conclusions can be asserted.

- (1) The resistivities of uncompact RDX and HMX powders increase with decreasing particle size. Thus, the electrostatic hazards of RDX and HMX powders, especially those of nano-sized RDX and nano-sized HMX powders, have to be taken into consideration in all applications.
- (2) The sieve method used in this paper was found to successfully measure the charge accumulation of nano-sized explosives. By this method, the charge accumulations of nano-sized RDX sieved using different standard mesh sieves were measured. We found that the charge accumulation (absolute value) increases as the mesh number increases (*i.e.* the aperture size decreases). A study of the charge accumulations of different particle-size RDX and HMX sieved using 50 mesh standard sieves showed that charge accumulation increases with decreasing particle size. This implies that nano-sized RDX and nano-sized HMX more easily accumulate static electricity. This result will be verified by other techniques and presented in future publications.

- (3) The ESD sensitivity was found to decrease as the particle size decreased for both RDX and HMX. Thus, the sensitivity of nano-sized nitramine explosives is higher than that of micron-sized ones. Meanwhile the ESD sensitivity of RDX is higher than that of HMX for the same particle size.

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