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Effects of Polymeric Binders on the RDX-based Explosive Response Character under Slow Cook-off Conditions

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Abstract: Due to safety requirements, insensitive behaviour under slow thermal heating (cook-off) conditions is a desirable behaviour for today's munitions. In this paper a cook-off device is designed to test two groups of RDX-based PBX explosives. In the first group the binder type was varied and in the second group the binder content of the RDX-based explosive was changed. Eleven samples were examined in order to evaluate the influence of four different binders and seven different binder contents on the shell deformation and the degree of the involved reaction. The test results showed that the degree of the reaction can be improved by changing the binder content, but not by the binder type. This phenomenon was explained by the thermal-conduction theory.

Keywords: RDX-based explosive, slow cook-off experiment, binder content, binder type

1 Introduction

RDX (1,3,5-trinitroperhydro-1,3,5-triazine) is a high-energy nitramine explosive, with a high detonation velocity, high heat of detonation and detonation stability characteristics. Although it has been widely used in high-energy composite explosives [1-4], the thermal stability of RDX explosives is still the focus of current research. Many researchers have conducted slow cook-off experiments [5-8] and simulations [9, 10] on RDX-based explosives. In particular, Sandusky and Chambers [11] presented a device to measure the sample expansion and performed slow cook-off tests for both PBXN-109 (67% RDX, 20% aluminum, 13% HTPB/DOA binder) and PBXN-5. They developed a model to simulate the pre-ignition and post-ignition behaviour of the PBXN-109 and verified the measured cook-off time and temperature. To validate their cook-off process models, researchers from Sandia National Laboratories [12] have performed a series of experiments on PBXN-109 and PBX-9501 and have indicated that detailed thermal properties and chemical parameters for the explosives are required in order to predict more accurately the reaction violence. Zhi and Hu [13] chose an RDX-based booster for a slow cook-off test and obtained its response characteristics by varying the density of the booster explosives and by using different restriction materials for the shell. Feng and Rui [14] studied the cook-off test and the numerical simulation of RDX under different temperature conditions. In order to understand the violence of fluid/melting explosives under external heat sources, Nichols [15, 16] changed the model's coupled physics code of ALE3D to handle reacting explosive fluids, and made an experiment for Comp-B (39.4% TNT, 59.5% RDX and 1% wax) using the modified model. None of the above work has fundamentally improved the thermal stability of RDX-based explosives.

From the application of cook-off experiments on energetic materials [17-20], it was found that the binder has a significant influence on the violence of the response. For instance, Cook [21] performed cook-off tests for HMX/HTPB composite explosives and obtained their response characteristics by varying the HTPB content and heating rate. Chaves and Góis [22] simulated the slow cook-off process for an RDX-based explosive and demonstrated that the addition of HTPB, DOS or IPDI binder reduces the ignition delay time as well as the ignition temperature.

In the present paper, a series of slow cook-off tests were performed for RDX-based explosives to investigate their response characteristics, by varying the binder type and binder content. Through these tests, the relationships between binder type and violence or binder content and violence were obtained. The test results could help to reduce the thermal sensitivity of RDX-based explosives in practical applications.

2 Experimental

2.1 Slow Cook-off Tests

A schematic diagram of the cook-off bomb is shown in Figure 1, and consists of an RDX/Estane explosive, retaining bolts, top and end plates, plus two steel and one aluminum sleeves. The top and end plates were made of Q 235 steel. The three sleeves, the inner, the outer, and the aluminum one, had dimensions Φ 22 mm × 64 mm, Φ 33 mm × 78 mm and Φ 28 mm × 72 mm respectively,

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and were firmly connected by four retaining bolts. A groove with a diameter of Φ 33 mm × 1 mm at the center of the two plates was used to fix these sleeves.

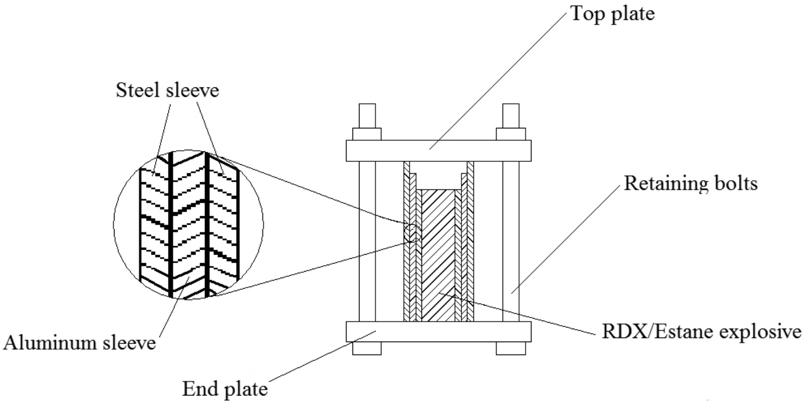

Figure 1. Schematic diagram of the cook-off bomb

Figure 2 illustrates the experimental process, which consisted of an instrument for the thermal response dynamic parameter test of 0.1 degrees (Chengdu Taisite Electronics Information Co. Ltd.), an explosion protection device, the cook-off bomb and a computer with pre-installed analysis software for testing the data. The heating jacket that was placed on the side wall of the shell generated the thermal power for the cook-off bomb.

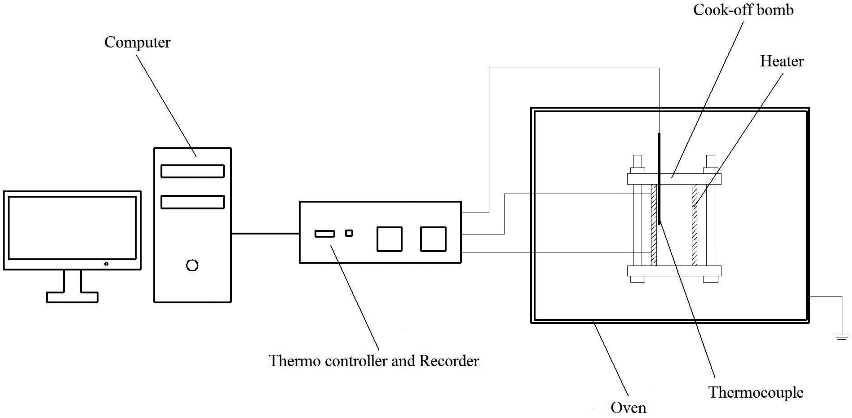

Figure 2. System sketch of the slow cook-off test

An MR13 temperature control device (SHIMADEN MR13 Co., Japan) was used to maintain a temperature increase of 6 ±0.2 °C/min. The temperature

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within the sleeves throughout the heating process was measured by a K-type thermocouple (Beijing Xu Ri Dong Hui Technology Co., Ltd., China) (chromel/alumel, ±1.0 °C) and was fixed in the groove located at the center of the aluminum sleeve exterior.

During the test process, data concerning changes in the surface temperature of the explosive with time, the temperature response time, and the deformation of the shell of the cook-off bomb could be obtained to analyze the severity of the explosive reaction.

2.2 Samples and experimental conditions

The RDX was provided by Gansu Yinguang Chemical Industry Ltd. (Baiyin, China) and its particle size was from 2 μm to 5 μm. Estane 5719, EVA 40W, F 2601 and ACM were purchased from Lubrizal Special Chemical Co. Ltd., E.I. Du Pont Company, Huizhou Hao Yuan Plastic Raw Material Co. Ltd. and Lubrizal Special Chemical Co. Ltd., respectively. Two groups of explosive samples were prepared. The first group consisted of 4 samples and each sample had a fixed RDX content of 95% and 5% of one of the 4 different binders, namely Estane 5719, EVA 40W, F 2601 and ACM. The second group consisted of 7 samples and each sample had the same ingredients, RDX and Estane, but in different ratios. The detailed information is listed in Table 1 and Table 2, respectively.

Table 1. The sample compositions with 4 different binders for the slow cook-off tests

Name	Composition
es-RDX	RDX 95%, Estane 5719 5%
e-RDX	RDX 95%, EVA 40W 5%
f-RDX	RDX 95%, F 2601 5%
a-RDX	RDX 95%, ACM5%

Table 2. The sample compositions with different binder contents for the slow cook-off tests

Sl. No.	Composition
1	RDX 99%, Estane 5719 1%
2	RDX 97%, Estane 5719 3%
3	RDX 95%, Estane 5719 5%
4	RDX 94%, Estane 5719 6%
5	RDX 93%, Estane 5719 7%
6	RDX 92%, Estane 5719 8%
7	RDX 90%, Estane 5719 10%

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In this paper, all explosive particles were prepared by the water suspension method and pressed into an explosive column with a size of Φ 16 mm × 32 mm based on 90% of the theoretical maximum density (TMD). A constant heating rate of 6 °C/min was applied in each experiment until reaction occurred.

2.3 DSC tests

The four different plastic binders listed in Table 1 were analyzed using a DSC-131 differential scanning calorimeter (France Setaram Corporation, Shanghai, China). The conditions for the DSC tests were as follows: sample mass 0.7 mg, heating rate 6 °C/min, nitrogen atmosphere flowing at 30 mL/min.

3 Results and Discussion

3.1 Slow Cook-off Test results

3.1.1 Slow Cook-off Tests for different binders

The results from the slow cook-off tests for the PBX explosives with the four different binders are shown in Figure 3 and the corresponding response results are listed in Table 3. It may be observed from Table 3 and Figure 3 that the reaction degrees of the slow cook-off tests remained the same, regardless of the binder types.

Table 3. Results for the 4 different samples in the cook-off tests

Name	Reaction temperature [°C]	Degree of shell deformation	The degree of reaction
es-RDX	220.4	The end plate was perforated and the shell was broken into 154 pieces	Detonation
e-RDX	222.4	The end plate was perforated and the shell was broken into 134 pieces	Detonation
f-RDX	222	The end plate was perforated and the shell was broken into 101 pieces	Detonation
a-RDX	223.5	The end plate was perforated and the shell was broken into 119 pieces	Detonation

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a. RDX/Estane 5719 **b. RDX/EVA 40W**

c. RDX/F 2601 **d. RDX/ACM**

Figure 3. Photographs of fragments from the Slow Cook-off Test of the 4 different explosive components: a – RDX/Estane 5719, b – RDX/EVA 40W, c – RDX/F 2601, d – RDX/ACM

Figure 4 shows the DSC curves of the 4 different binders, namely, Estane 5719, EVA 40W, F 2601 and ACM. The heating rate was 6 °C/min, the same as the heating rate in the slow cook-off tests. IIt may be observed from Figure 4 that after the temperature passes 450 °C, the 4 different binders exhibit different degrees of endothermic reaction.

As listed in Table 3, the response temperatures for the 4 explosive samples were almost identical, around 220 °C. However, their DSC curves revealed that the 4 different binders have no notable endothermic or exothermic reactions. These phenomena indicate that once the percentage of the binder is fixed in a PBX explosive, it remains unchanged until the explosive reaction occurs.

The density of 4 different binders was in the order F 2601 > Estane 5719 > ACM > EVA 40W. When the binder's mass percentage was 5%, a higher density and thus a lower volume percentage in the composite explosive gave an increase in the volume percentage of RDX. When the explosive column volume

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is fixed, an increase in the volume percentage of RDX means an increase in the RDX mass, and this leads to a larger energy output. It may be observed from Table 3 and Figure 3 that the reaction degrees of these 4 composite explosives in the slow cook-off test remained the same. To some extent, this explains why F 2601 is better than the other binders on the basis of a fixed volume percentage of RDX and explosive column volume. However, this experiment cannot fully explain this conclusion and needs further research.

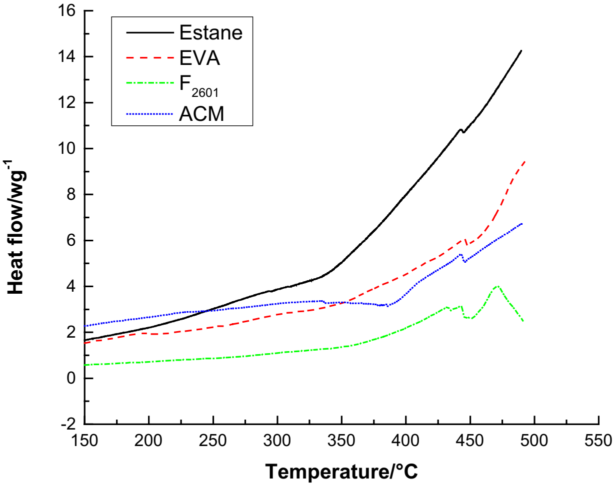


Figure 4. DSC curves of crude Estane 5719, EVA 40W, F2601 and ACM

Although these tests cannot establish which binder is the best, these experiments showed that changing the type of binder does not improve the thermal stability of an RDX-based PBX explosive. Estane was chosen as the binder in further studies for its good cohesiveness.

3.1.2 Slow Cook-off Tests for different binder contents

The slow cook-off tests were also performed for the second group of 7 explosive samples, corresponding to 7 different ratios of RDX and Estane (see Table 2). The images of the fragments after the slow cook-off tests are shown in Figure 5 and the corresponding response results are listed in Table 4. From both Table 4 and Figure 5, it may be observed that the response characteristics of the slow cook-off tests increase with a decrease in the binder content in the RDX-based PBX explosives. Further inspection of the results revealed that the slow cook-off test underwent a deflagration-to-detonation transition (DDT) at 5%, as the binder content was decreased from 10% to 1%. Both the top and end plates displayed noticeable brown and white residues when the binder content was greater than 6%.

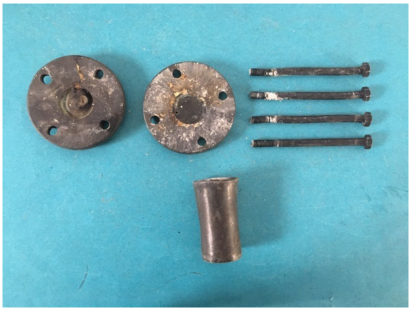
a. RDX/Estane 1%

b. RDX/Estane 3%

c. RDX/Estane 5%

d. RDX/Estane 6%

e. RDX/Estane 7%



f. RDX/Estane 8%

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g. RDX/Estane 10%

Figure 5. Photographs of fragments from the slow cook-off test of the 7 different explosive compositions: a – RDX/Estane 1%, b – RDX/Estane 3%, c – RDX/Estane 5%, d – RDX/Estane 6%, e – RDX/Estane 7%, g – RDX/Estane 8%

Table 4. Results for the 7 different samples in the cook-off tests

Sample No.	Reaction temperature [°C]	Degree of shell deformation	The degree of reaction
1	226.2	The top plate had a crack, the end plate was perforated and the shell was broken into 313 pieces	Detonation
2	221.1	The top and end plates were perforated and the shell was broken into 215 pieces	Detonation
3	220.4	The end plate was perforated and the shell was broken into 154 pieces	Detonation
4	216.8	The end plate was perforated and the shell was split into two	Pressure rupture
5	220.5	The end plate was bent and the shell became a drum	Burn
6	225.8	The shell became a drum	Burn
7	217.2	The shell became a drum	Burn

The response mechanism of a nonhomogeneous explosive detonation is explained by the two-stage theory [13]; that is, hot ignition and hot spots cause chemical reactions to transform to detonation. The main factors of the hot ignition stage are the sizes of the holes between the explosive particles and the porosity. As the density of an explosive decreases, its porosity increases. Then the high-temperature gases decompose at the explosive centres and easily penetrate the surrounding area, leading to the temperature increasing and more hot spots being

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formed [23]. As the number of hot spots increases, the burning area likewise grows exponentially with its burning rate triggering a detonation. A partial detonation wave produces a superposition effect, leading to a violent reaction.

Firstly, as the binder content increases, the density of the composite explosive decreases, and the decrease in density leads to a continuous increase in porosity. Secondly, as the binder content increases, the RDX content in the composite explosive is reduced. Due to these two factors, the amount of explosive per unit volume is decreased and the release rate of gaseous products is reduced. There is insufficient pressure inside the explosive pellet, so the energy loss in the burned area is too large to lead to the formation of detonation.

The thermal expansion and decomposition [11] due to the temperature increasing lead to pressure accumulation in the RDX-based PBX explosive. Since the amount of explosive per unit volume is decreased, a spray occurs after the pressure burst. Some unreacted or post-combustion traces adhere to the top plate as residue. A similar ejection of unreacted material after the pressure burst was also observed in the HMX/HTPB and RDX/TNT experiments [21, 24].

4 Conclusions

1. At a fixed content, the four binders cannot improve the thermal stability of a PBX explosive based on RDX.
2. Under slow heating conditions, the binder content has a significant effect on the response violence. When the binder content is less than 5%, DDT occurs. In order to reduce the thermal sensitivity of RDX-based explosives under slow cook-off conditions, the binder content should be greater than 5%.

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5 References

[1] Stepanov, V.; Anglade, V.; Balas Hummers, W. A.; Bezmelnitsyn, A. V.; Krasnoperov, L. N. Production and Sensitivity Evaluation of Nanocrystalline RDX-based Explosive Compositions. *Propellants Explos. Pyrotech*. **2011**, *36*(3): 240-246.

[2] Stepanov, V.; Willey, T. M.; Ilavsky, J.; Gelb, J.; Qiu, H. Structural Characterization

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of RDX-Based Explosive Nanocomposites. *Propellants Explos. Pyrotech*. **2013**, *38*(3): 386-393.

[3] Qu, K. P.; Shen, F.; Wang, S. Y.; Xiao, W.; Li, L. L. Research on Impact Safety of a RDX-based PBX Explosive at Different Stress Rate. *Chinese Journal of Explosives & Propellants* **2014**, *37*(6): 40-43.

[4] Qiu, H.; Stepanov, V.; Di, S. A.; Chou, T.; Lee, W. Y. RDX-based Nanocomposite Microparticles for Significantly Reduced Shock Sensitivity. *J. Hazard. Mater.* **2011**, *185*(1): 489-493.

[5] *Slow Heating Tests for Munitions*. STANAG 4382 (Ed. 1), Military Agency for Standardization, AC/3 10-D/100, June **1992**.

[6] Brousseau, P.; Brochu, S.; Brassard, M.; Ampleman, G.; Thiboutot, S.; Côté, F. RIGHTTRAC Technology Demonstration Program: Preliminary IM Tests. *2010 Insensitive Munitions & Energetic Materials Technical Symposium*, Munich **2010**, 11-14.

[7] Talawar, M. B.; Agrawal, A. P.; Anniyappan, M.; Wani, D. S.; Bansode, M. K.; Gore, G. M. Primary Explosives: Electrostatic Discharge Initiation, Additive Effect and Its Relation to Thermal and Explosive Characteristics. *J. Hazard. Mater.* **2006**, *137*(2): 1074-1078.

[8] Kondrikov, B. N. Investigation of Cook-off-type Test Methods. *11th Int. Detonation Symposium*, Colorado **1998**, 135-142.

[9] Li, W.; Yu, Y.; Rui, Y.; Yang, H. Simulation of Cook-off for AP/HTPB Composition Propellant in Base Bleed Unit at Different Heating Rates. *Explosion & Shock Waves* **2017**, *37*(1): 46-52.

[10] Nassim, B.; Zhang, Q. Thermal Stability of Explosive Mixture with Additives at Different Ambient Temperatures. *Propellants Explos. Pyrotech.* **2018**, *43*(2): 177-187.

[11] Sandusky, H. W.; Chambers, G. P.; Erikson, W. W.; Schmitt, R. G. Validation Experiments for Modeling Slow Cook-off. *12th Int. Detonation Symposium* **2002**, 863-872.

[12] Kaneshige, M. J.; Renlund, A. M.; Schmitt, R. G.; Erikson, W. W. Cook-off Experiments for Model Validation at Sandia National Laboratories. *Albuquerque NM* **2002**, 87185.

[13] Zhi, X. Q.; Hu, S. Q.; Li, J. J.; Xu, S. P.; Li, Y. RDX-based Booster Explosive Response Character under Slow Cook-off Conditions. *J. Energ. Mater.* **2011**, *29*(2): 75-87.

[14] Feng, C. G.; Zhang, R.; Chen, L. The Cook-off Test and Its Numerical Simulation of RDX. *J. Energ. Mater*. **2004**, *12*: 193-198.

[15] Nichols, A. L. *Improved Cook-off Modeling of Multi-component Cast Explosives*. Report No. LLNL-CONF-737694, **2017**.

[16] Nichols, A. L.; Schofield, S. Modeling the Response of Fluid/Melt Explosives to Slow Cook-off. *15th Int. Detonation Symposium* **2014**, *18*(7): 881-900.

[17] Xu, W.; An, C.; Wang, J.; Dong, J.; Geng, X. Preparation and Properties of an Insensitive Booster Explosive Based on LLM-105. *Propellants Explos. Pyrotech.*

2013, *38*(1): 136-141.

[18] Dickson, P. M.; Asay, B. W.; Henson, B. F.; Smilowitz, L. B. Thermal Cook-off Response of Confined PBX 9501. *Proc. Royal Soc. London A: Mathematical, Physical and Engineering Sciences*, The Royal Society **2004**, *460*(2052): 3447-3455.

[19] Hsu, P. C.; Strout, S.; Mcclelland, M.; Ellsworth, F. E. *One-dimensional Time to Explosion (Thermal Sensitivity) Tests on PETN, PBX-9407, LX-10, and LX-17*, Report No. LLNL-TR-681467, **2016**.

[20] Lee, K. E.; Braithwaite, P. C.; Sanderson, A. J.; Child, D. R. An Insensitive Alternative to the Pressed Explosive LX-14. *NDLA 2000, Insensitive Munitions and Energetic Materials Technology Symposium* **2000**, 384-391.

[21] Cook, M. D.; Stennett, C.; Haskins, P. J.; Briggs, R. I.; Wood, A. D.; Cheese, P. J. *The Role of Binders in Controlling the Cook-off Violence of HMX/HTPB Compositions*. *Shock Compression of Condensed Matter.* American Institute of Physics, **2006**, 952-955.

[22] Chaves, F. R.; Góis, J. C. Slow Cook-Off Simulation of PBX Based on RDX. *Journal of Aerospace Technology and Management* **2017**, *9*(2): 225-230.

[23] Yan, S. H. *Explosives Theory*. Beijing Institute of Technology Press, **2016**, pp. 168-170; ISBN 9787568225588.

[24] Cook, M. D.; Briggs, R. I.; Stennett, C.; Haskins, P. J.; Fellows, J. Direct Observation of Cook-off Events Using a Novel Glass-windowed Vehicle and Pipe Bombs. *12th Int. Detonation Symposium*, **2002**, 11-16.

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