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# Thermal Analysis and Stability of Boron/Potassium Nitrate Pyrotechnic Composition at 180 °C

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**Featured Application: This research aims to obtain the decomposition process of boron/potassium nitrate pyrotechnic composition, and verify its high temperature stability to meet the charge requirements of the separation device such as the cutter for the lunar probe.**

**Abstract:** Aerospace missions require that pyrotechnic compositions are able to withstand 180 °C. Therefore, this paper studies the thermal stability and output performance of boron/potassium nitrate (abbreviated BPN) used in pyrotechnic devices. Firstly, differential scanning calorimetry (DSC) and thermogravimetric (TG) tests are used to analyze the thermal reaction process of $KNO_3$, boron, and BPN to qualitatively judge their thermal stability. Then, apparent morphology analysis, component analysis, and the p-t curve test, which is the closed bomb test to measure the output power of the pyrotechnic composition, are carried out with BPN samples before and after the high-temperature test to verify BPN stability at 180 °C. The weight change of boron powder caused by chemical reactions occurs above 500 °C. When the temperature is lower than the peak exothermic temperature of decomposition, no obvious chemical reaction occurs with $KNO_3$, and only physical changes (crystal transformation and melting) occur. Combined with a verification test at 180 °C for two days, it is concluded that boron and $KNO_3$ components are stable at 180 °C. With an increase in boron content, the thermal stability of BPN is improved, with the best performance achieved when the ratio is 25:75 (B:$KNO_3$). BPN samples without binder have the best thermal stability. In a test at 180 °C for five days, the binder affects the weight loss and p-t curve of BPN, and BPN with fluororubber binder is better than BPN with unsaturated polyester binder.

**Keywords:** boron/potassium nitrate; thermal analysis; high temperature stability; energetic material

## 1. Introduction

Boron/potassium nitrate (B/$KNO_3$; abbreviated BPN) can be used for the output charge of an engine igniter, a fire transfer charge, a small thrust dynamite output charge, a high temperature projectile charge, etc. BPN has the significant characteristics of high combustion heat and low moisture absorption per unit weight. [1] BPN is also listed as a linear reference for the security of pyrotechnic agents [2].

At present, aerospace missions require that BPN composition is thermally stable. In some special launch missions [3], such as of deep space spacecraft, pyrotechnic devices must withstand a large temperature range, usually from −100 to +130 °C [4,5]. Considering that there is a certain safety

margin for temperature, it is of great significance to test and evaluate the thermal stability and output performance of BPN after exposure to the temperature of 180°C, providing a basis for its application in the aerospace field. This research aims to obtain the decomposition process of boron/potassium nitrate pyrotechnic composition, and verify its high temperature stability to meet the charge requirements of the separation device such as the cutter for the lunar probe.

K.R. Rani Krishnan et al. studied the effect on the ignition behavior of potassium boron nitrate pyrotechnic powder of adding RDX and HMX components which are two commonly used high energy explosives. In their paper, thermogravimetric (TG) and differential scanning calorimetry (DSC) analyses which use Perkin Elmer TGA 7 and DSC 7 in flowing argon medium (30 mL min) at 5 °C/min, were carried out on the mixture of potassium boron nitrate and explosive components [6], which provided some inspiration for the present paper. R. Turcotte et al. researched the thermal analysis of black gunpowder in which $KNO_3$ had a pre-ignition reaction under the action of sulfur and charcoal. The pre-ignition reaction occurred at a lower temperature than the decomposition temperature of $KNO_3$ itself, and the decomposition temperature of $KNO_3$ drifted under a complex system [7,8]. ES. Freeman, Seyed Ghorban Hosseini et al. [9,10] studied the thermal decomposition process of $KNO_3$ by the TG-TDA method, and obtained the transformation, melting and decomposition process of $KNO_3$. A. Eslami et al. [11] studied the thermal reaction characteristics of B+$KNO_3$, B+$Ba(NO_3)_2$, B+$PbO_2$ and other mixed systems, and the reaction process of a B+$KNO_3$ mixed system was analyzed in stages.

The stability of chemical agents refers to the ability of a sample to maintain its physical, chemical and explosive properties from changing beyond the permitted range under certain circumstances [12]. Stability analysis of physical properties mainly encompasses apparent morphology, color, weight, crystal shape, phase change (melting point, boiling point, volatilization), moisture absorption, particle size, charge density, crystal crack, volatilization, oil permeability, migration, and dielectric constant. Chemical stability encompasses purity, composition, valence state, oxidation state, slow/rapid thermal decomposition, weight loss, and composition of explosive products. The stability of explosion performance encompasses explosion point, detonation heat, detonation velocity, combustion velocity, p-t curve (which is the closed bomb test to measure the output power of the pyrotechnic composition), detonation pressure, detonation capacity, flame sensitivity, hot wire sensitivity, impact sensitivity, friction sensitivity, static inductance, initiation sensitivity, and shock wave sensitivity. In addition to stability, compatibility is also a consideration. This is particularly true of chemical compatibility, including the internal compatibility between the pyrotechnic charge and contact metal (bridge wire, tube shell, cover sheet, motion mechanism, etc.).

At present, there are few reports on the thermal reaction process and high temperature stability. Existing studies of BPN mainly focus on the influence of the preparation process [13,14], particle size [15], ratio [16] and other factors related to ignition performance.

## 2. Materials and Methods

### 2.1. Materials

Laboratory reagent grade boron and $KNO_3$ powder were all purchased for tests. The particle size of powdered boron was approximately 1 μm, and $KNO_3$ was 99.5% pure. As shown in Table 1, using boron powder and $KNO_3$ as raw materials, BPN samples with different proportions were prepared.

**Table 1.** Samples of pure components and mixtures.

| No. | Component | Composition (%) | Binder |
|---|---|---|---|
| 1 | Boron | 100 | – |
| 2 | $KNO_3$ | 100 | – |
| 3 | 1#BPN | 15:85 | – |
| 4 | 2#BPN | 25:75 | – |
| 5 | 3#BPN | 33:67 | – |
| 6 | 4#BPN | 25:75 | Fluorine rubber |
| 7 | 5#BPN | 25:75 | Unsaturated polyester |

## 2.2. Methods

The thermal stability of BPN after exposure at 180 °C was studied by methods such as thermogravimetric analysis and differential scanning calorimetry, and analysis of appearance morphology, weight loss, content, and output performance. The process scheme is shown in Figure 1.

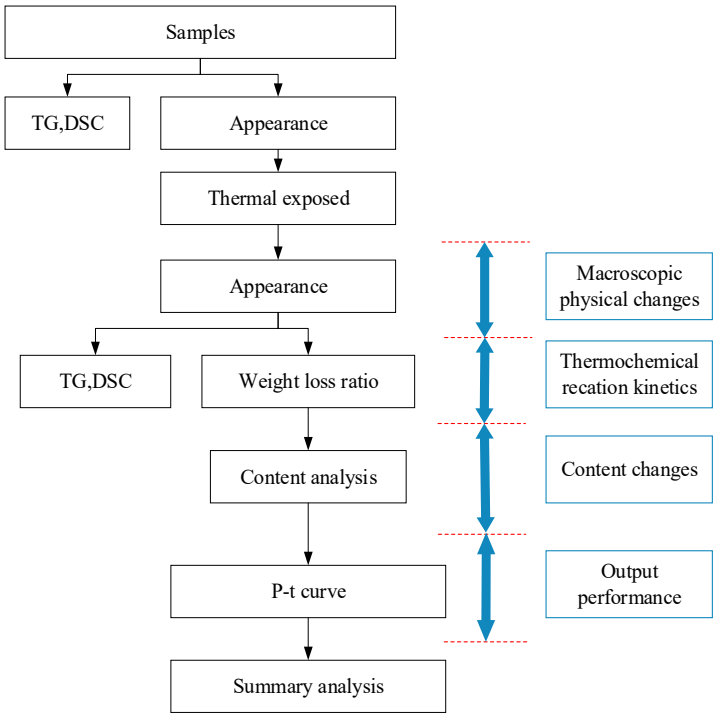



**Figure 1.** Experimental process scheme.

TG and DSC test data were applied to analyze the thermal reaction process of $KNO_3$, boron powder and BPN with different ratios, to qualitatively judge high-temperature stability. The apparent morphology analysis, thermogravimetric (TG) analysis, differential scanning calorimetry (DSC) analysis, and output power test were carried out on BPN samples after the high-temperature test to verify the stability of BPN under a high temperature of 180 °C, thereby providing a basis for its application in the aerospace field. A summary of the analysis method is presented in Table 2.

**Table 2.** Analysis methods for BPN thermal analysis and high temperature stability analysis.

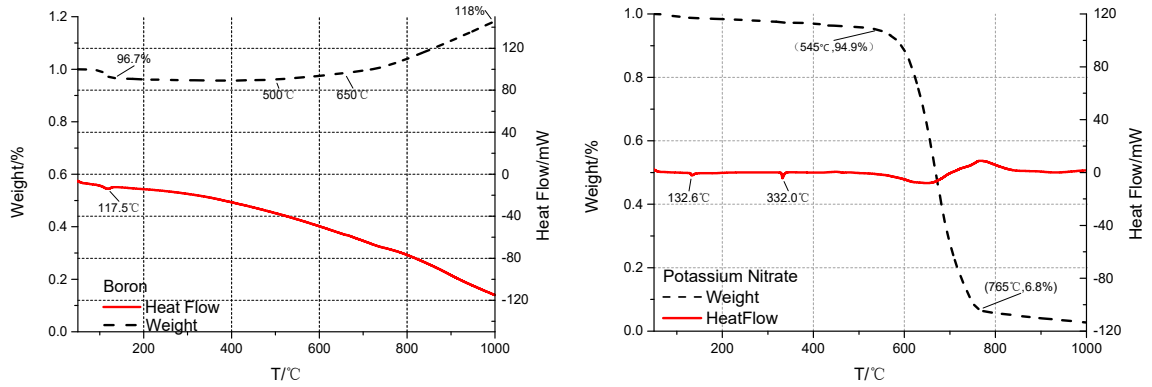
| Analysis Method | Content |
| --- | --- |
| Thermogravimetry | Measure the weight of loose sample before and after high temperature test with precision balance. |
| Appearance | Scanning microscope, optical digital microscope used to observe the color, particle size, etc. |
| DSC analysis | Analyze the initial decomposition temperature and peak decomposition temperature of samples. |
| Content analysis | Ion exchange method for determination of $KNO_3$ contentMannitol complex titration method for determination of boron. |
| output performance | P–t curve pressure peak and rise time to evaluate the power capacity of samples. |

## 3. Results and Discussion

### *3.1. Thermal Analysis of Single Component*

The TG process of boron was studied with a nitrogen atmosphere. As shown in Figure 2, a weight loss of approximately 3.3% is observed from heating to 117.5 °C, which reflects the loss of moisture and volatiles in boron powder. Until 500 °C, the quality of boron powder samples increases gradually, and the speed increases after 650 °C. The total mass increases to approximately 118% at 1000 °C. It is speculated that the reaction in this stage is the slow reaction of boron powder and nitrogen, and the final product is BN. The reaction equation is

$$2B + N_2 = 2BN, \quad (1)$$




(**a**) (**b**)

**Figure 2.** (**a**) Thermogravimetric-Differential Scanning Calorimetry (TG-DSC) curve of boron powder; (**b**) TG-DSC curve of $KNO_3$ (in nitrogen atmosphere).

The DSC curve of $KNO_3$ has two endothermic peaks. The first endothermic peak (peak temperature 132.6 °C) corresponds to the conversion temperature of $KNO_3$, which is the phase transition of $KNO_3$ from rhombic to trigonal. The second endothermic peak (peak temperature 332.0 °C) corresponds to the melting point of $KNO_3$. [9] The DSC curve shows that the decomposition of $KNO_3$ occurs at more than 500 °C. Combined with the TG curve, the mass change of $KNO_3$ is 5.1% at 545 °C, indicating that $KNO_3$ is melting but is not decomposed or gasified from the melting point (332.0 °C) to the temperature of 500 °C. Therefore, the physical stability of $KNO_3$ changes within the temperature range of 332–500 °C, but the chemical stability is not affected.

A weight loss of $KNO_3$ of 88.1% mainly occurred between 545 °C and 765 °C. According to E.S. Freeman [17], the decomposition of $KNO_3$ took place at this stage, generating nitrite, followed by the

decomposition reaction of potassium nitrite, and the product $K_2O$ was reported to evaporate (m.p. 380 °C) [10]. The equation of weightlessness in this stage is [8]

$$2KNO_3 \rightarrow 2KNO_2 + O_2, \quad (2)$$

$$4KNO_2 \rightarrow 2K_2O + 4NO + O_2, \quad (3)$$

Compared with the operating condition of 180 °C, the melting temperature of $KNO_3$ at 336.5 °C is about 156 °C higher. No obvious chemical reaction occurs before the peak temperature of decomposition (i.e., more than 545 °C). It can be qualitatively concluded that the boron powder and $KNO_3$ components are stable at a high temperature of 180 °C. It should be noted that this result is obtained according to the reaction temperature of DSC, and the stability of samples at constant temperature needs to be verified.

### *3.2. Thermal Analysis of BPN with Different Ratios*

TG-DSC analysis of BPN samples with different ratios (heating rate 5 °C/min) were carried out, and the curves are shown in Figure 3. For BPN samples with different ratios, the thermal reaction process is similar to that of $KNO_3$ before 500 °C.

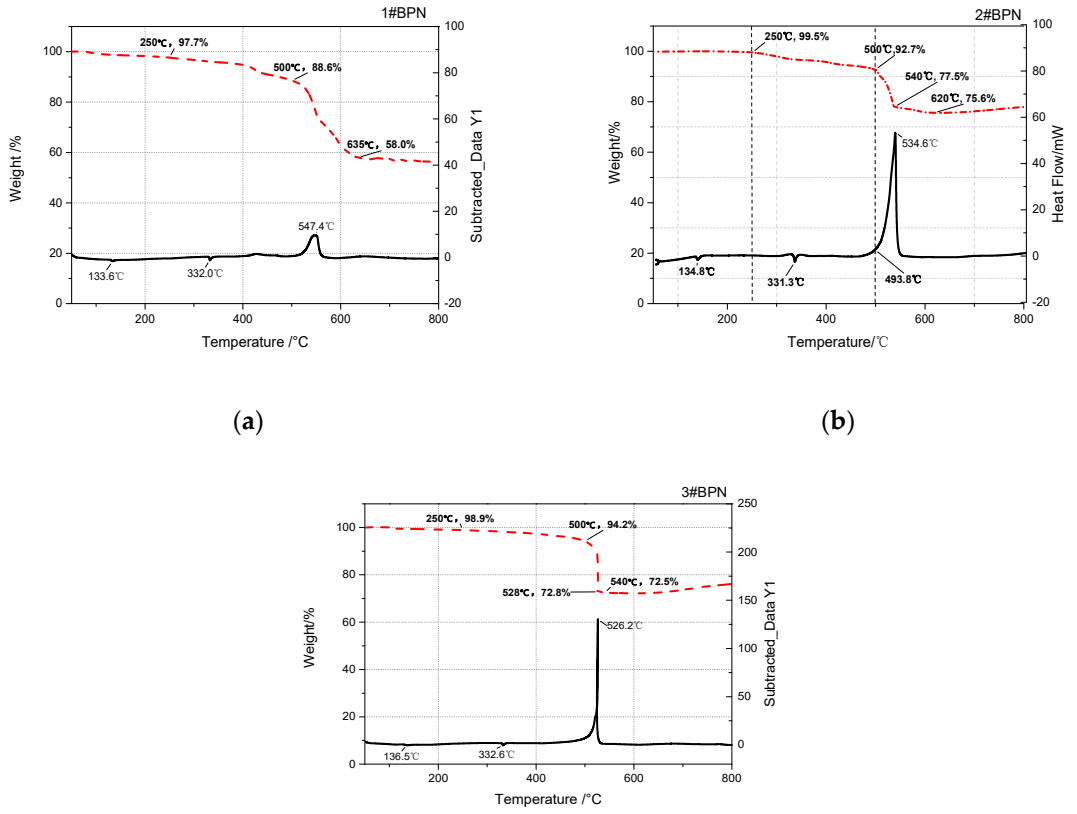



**Figure 3.** (**a**) TG–DSC curve of 1#BPN (15:85); (**b**) TG–DSC curve of 2#BPN (25:75); (**c**) TG–DSC curve of 3#BPN (33:67) (heating rate 5 °C/min).

As shown in Figure 3, the first endothermic peak (approx. 134 °C) corresponds to the conversion temperature of $KNO_3$, and the second endothermic peak (approx. 332 °C) corresponds to the melting point of $KNO_3$. Before 500 °C, the mass change of sample 1# and 2# is about 9%, while that of sample 3# is less than 5%. Between 500 °C and 650 °C, there is a drastic decomposition reaction, and the

sample weight drops sharply. The temperature of the decomposition reaction is about 200 °C higher than the melting point. The main reaction at this stage is

$$B + KNO_3 \rightarrow KBO_2 + NO. \quad (4)$$

The weight ratio results of BPN samples with different proportions at typical temperatures are shown in Table 3. At 200 °C, the mass variation of BPN samples with three ratios are in the range 0.9%–1.7%, and at 500 °C, 5.8%–11.4%. At 650 °C, the 2# (25:75) BPN sample (zero oxygen balance ratio) has the least weight loss. Based on TG analysis of $KNO_3$, the initial reaction temperature of BPN (500 °C) is about 50 °C lower than that of $KNO_3$ (545 °C). However, when comparing the endothermic peak temperature of DSC curves of samples, the exothermic peak temperature showed a trend of rising with the increase of boron content, as shown in Table 4.

**Table 3.** Weight statistics of potassium boron nitrate samples at different temperatures.

| Samples | Weight Ratio @ 100 °C (%) | Weight Ratio @ 200 °C (%) | Weight Ratio @ 400 °C (%) | Weight Ratio @ 500 °C (%) | Weight Ratio @ 650 °C (%) |
|---|---|---|---|---|---|
| 1#BPN (15:85) | 99.3 | 98.3 | 94.8 | 88.6 | 57.5 |
| 2#BPN (25:75) | 99.9 | 98.5 | 93.2 | 92.7 | 75.7 |
| 3#BPN (33:67) | 100.0 | 99.1 | 97.4 | 94.2 | 72.5 |

**Table 4.** Peak temperature of DSC with different ratios of BPN.

| Samples | First Endothermic Peak (°C) | Second Endothermic Peak (°C) | Exothermic Peak (°C) |
|---|---|---|---|
| 1#BPN (15:85) | 133.6 | 332.0 | 547.4 |
| 2#BPN (25:75) | 134.8 | 331.3 | 534.6 |
| 3#BPN (33:67) | 136.5 | 332.6 | 526.2 |

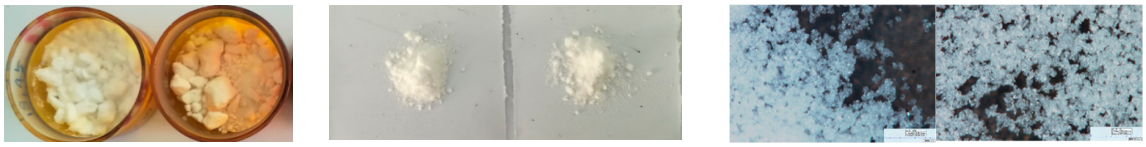
The results show that with an increase of boron content, the exothermic peak is advanced, but the thermal stability of BPN samples are improved, with the 2#BPN sample (25:75) showing the best performance. Analysis at 180 °C shows that the DSC decomposition temperature of BPN is above 500 °C, and TG weight loss ranges from 5.8% to 11.4% at 500 °C. It can be qualitatively judged that BPN is stable at 180 °C.

### *3.3. Thermal Exposure Test at 180 °C and Analysis*

After drying at 60 °C for 4 h, the samples of BPN, boron powder and $KNO_3$ were placed in a temperature environment testing instrument for a thermal exposure test. The temperature settings were 180 °C for two and five days. The apparent morphology, DSC parameters, weight loss ratios and output performance of samples before and after the test were compared and analyzed.

Apparent Morphology

The apparent morphologies of $KNO_3$, boron and 4#BPN samples before and after different temperature storage are shown in Figures 4–6.



60 °C, 4 h 180 °C, 2 days 60 °C, 4 h 180 °C, 2 days 60 °C, 4 h 180 °C, 2 days

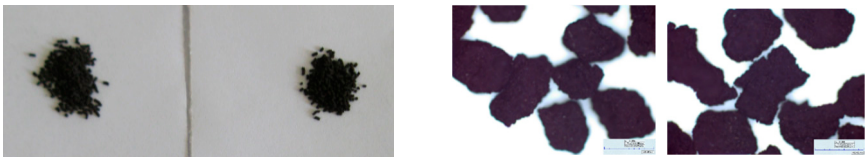
(**a**) (Original sample) (**b**) ((Original sample against white background) (**c**) (enlarged 100 times)

**Figure 4.** The apparent morphology of $KNO_3$ compared before and after different temperature tests.

60 °C, 4 h 180 °C, 2 days 60 °C, 4 h 180 °C, 2 days

(**a**) (Original sample) (**b**) (enlarged 100 times)

**Figure 5.** The apparent morphology of boron compared before and after different temperature tests.



60 °C, 4 h 180 °C, 2 days 60 °C, 4 h 180 °C, 2 days

(**a**) (Original sample against white background) (**b**) (enlarged 100 times)

**Figure 6.** The apparent morphology of 4#BPN compared before and after different temperature tests.

After observing the boron powder, $KNO_3$ and 4#BPN samples before and after high temperature, it is found that the color of the $KNO_3$ sample changes slightly from white to yellow, and the particle size and shape do not change. The particle size, shape and color of boron powder and 4#BPN are not observed to change. In addition, there is no change in appearance quality, such as expansion of fractures, loose pits, shrinkage or melting residue.

DSC test

The DSC curves and DSC parameter comparison of 4#BPN sample are given in Figure 7 and Table 5 respectively.

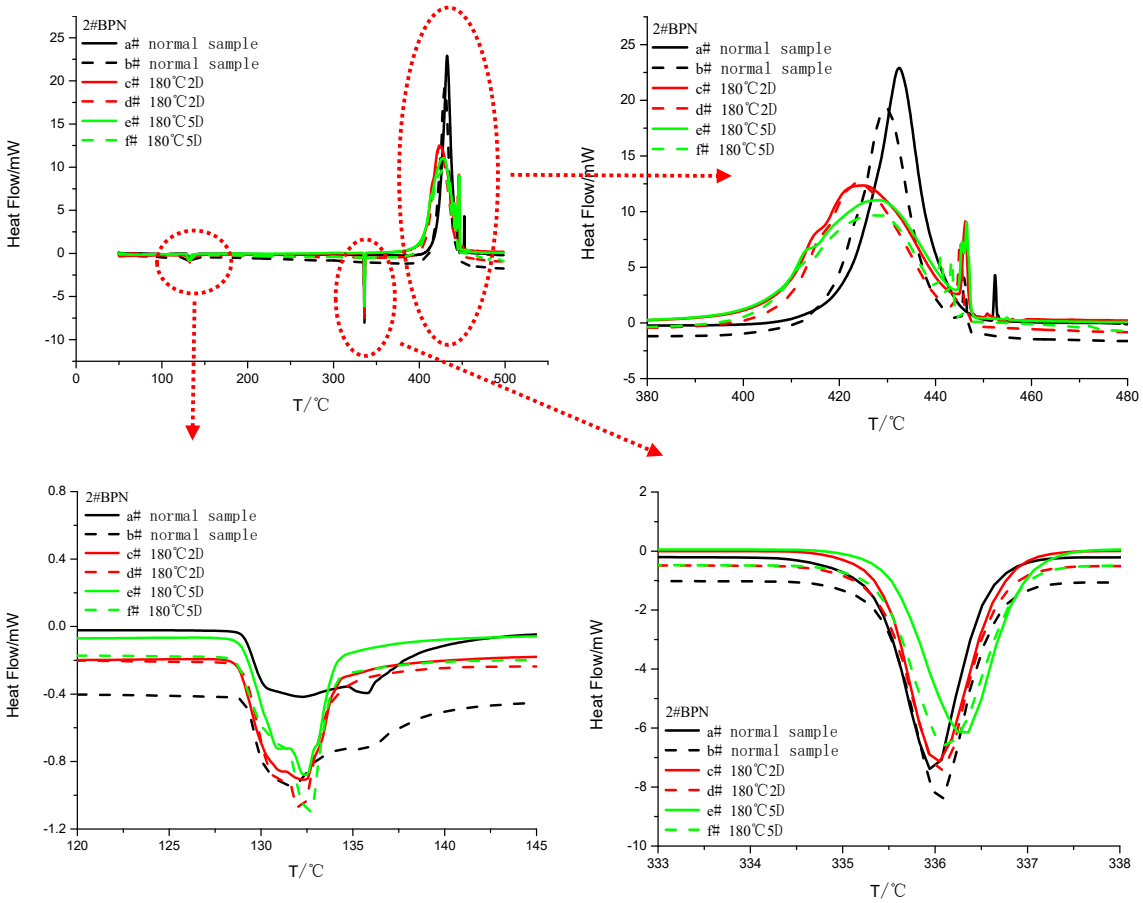



**Figure 7.** DSC curves of 4#BPN 60 °C,4 h samples and 180 °C samples (heating rate 5 °C/min).

**Table 5.** DSC parameter comparison of 4#BPN sample (°C) (heating rate 5 °C/min).

| Parametric | 60 °C, 4 h | 180 °C, 2 days | 180 °C, 5 days |
|---|---|---|---|
| Initial temperature of first endothermic peak (°C) | 129.04 | 129.45 | 128.84 |
| First endothermic peak (°C) | 131.15 | 131.35 | 131.55 |
| Initial temperature of second endothermic peak (°C) | 334.95 | 335.12 | 335.35 |
| Second endothermic peak (°C) | 336.02 | 336.06 | 336.23 |
| Initial temperature of exothermic peak (°C) | 405.34 | 406.37 | 404.33 |
| Exothermic peak (°C) | 431.28 | 424.77 | 428.51 |
| Decomposition heat E ($J \cdot g^{-1}$) | 3447 | 3454 | 3367 |
| Energy loss rate [1] (%) | 0 | 1.01 | 3.26 |

[1] Energy loss rate: $(E_{60°C4h}–E_{180°C,xd})/E_{60°C4h}$.

According to the DSC analysis of the variation of the peak temperature, the temperature difference between the first endothermic peak and the second endothermic peak is very small, comparing the samples at 180 °C for two days, 180 °C for five days, and 60 °C for 4 h; $\Delta T < 1$ °C. The exothermic peak temperature variations of the samples at two days and five days are −6.51 °C and −2.77 °C, respectively, but the failure rates of the agents are 1.01% and 3.26%, respectively. This indicates that the exothermic peak temperature of the sample is advanced, but the energy is not consumed. It can be preliminarily concluded that BPN containing $KNO_3$ and boron powder has good thermal stability at 180 °C for two days and five days.

- Weight loss ratio

The weight loss ratios of BPN samples in 180 °C test are given in Table 6. Furthermore, the component variation of BPN samples within 180 °C test are given in Table 7.

**Table 6.** Weight loss ratios of BPN samples in 180 °C test.

| Sample [1] | Weight Loss Ratio after 60 °C, 4 h (%) | Weight Loss Ratio after 180 °C, 2days (%) | Weight Loss Ratio after 180 °C, 5days (%) |
|---|---|---|---|
| 1#BPN (15:85) | 0.097 | 0.12 | 0.11 |
| 4#BPN (25:75) | 0.372 | 1.04 | 0.98 |
| 5#BPN (25:75) | 0.095 | 1.19 | 1.59 |
| $KNO_3$ | 0.0083 | 0.044 | – |
| Boron | 1.549 | 5.26 | – |

[1] Binders of 4#BPN, 5#BPN are fluorine rubber, and unsaturated polyester, respectively.

**Table 7.** Component variation of BPN samples in 180 °C test [18].

| Sample | Component | 60 °C, 4 h (%) | 180 °C, 2 days (%) | 180 °C, 5 days (%) |
|---|---|---|---|---|
| 1#BPN (15:85) | $KNO_3$ (%) | 85.80 | 85.66 | 85.90 |
| | Boron (%) | 14.87 | 14.88 | 14.85 |
| 4#BPN (25:75) | $KNO_3$ (%) | 73.32 | 73.79 | 74.36 |
| | Boron (%) | 23.04 | 27.38 | 26.24 |

As shown in Table 6, from the comparison of the weight loss ratios of BPN samples in the 180 °C test for different times, after five days, the weight loss ratio of 1# BPN without binder is approximately 0.1%, that of 4#BPN containing fluororubber binder is approximately 1%, and that of 5# BPN containing unsaturated polyester is approximately 2%. Combined with the analysis of component content, the change of $KNO_3$ and boron in 1#BPN without binder in the 5-day 180 °C test is 0.5%, i.e., almost no change. Thus, it can be judged to some extent that the stability of BPN in which the main components are $KNO_3$ and boron is well under 180 °C for two days and five days. The reason for the component variation of 4#BPN and 5#BPN is the binder (i.e., 4#BPN contains 3% fluororubber and 5#BPN contains 5.6% unsaturated polyester).

- P-t curve

P-t curve data of BPN samples in 180 °C test is given in Table 8.

**Table 8.** P-t curve of BPN samples in 180 °C test [19,20].

| Sample | Component | Peak Pressure (MPa) | Rise Time (ms) | Rate of Peak Pressure Change (%) |
|---|---|---|---|---|
| 1#BPN (15:85) | 60 °C, 4 h | 2.11 | 3.09 | −0.95 |
| | 180 °C, 5 days | 2.09 | 2.94 | |
| 4#BPN (25:85) | 60 °C, 4 h | 2.57 | 1.82 | −10.89 |
| | 180 °C, 5 days | 2.29 | 1.33 | |
| 5#BPN (25:75) | 60 °C, 4 h | 3.34 | 4.09 | −25.75 |
| | 180 °C, 5 days | 2.48 | 4.59 | |

It can be seen from the data in Table 8 that the peak pressure of the three kinds of BPN decreases with increasing time of the 180 °C temperature test. The thermal analysis of the single component shows that boron and $KNO_3$ are relatively stable at 180 °C, and the peak pressure attenuation of the 1#BPN sample without binder is 0.95% (i.e., <1%), which also supports this argument. It is also known that the binder has a great impact on the high temperature stability of BPN. The high temperature stability of the fluororubber binder is better than that of unsaturated polyester.

## 4. Conclusions

In conclusion, we studied the thermal decomposition process of $KNO_3$, boron and BPN based on TG and DSC test data. The weight change of boron powder caused by chemical reaction occurred above 500 °C. When the temperature was lower than the peak exothermic temperature of decomposition, no

obvious chemical reaction occurred with $KNO_3$, and only physical changes (crystal transformation and melting) occurred. Combined with a verification test at 180 °C for two days, it is concluded that boron and $KNO_3$ components are stable at 180 °C. With the increase of boron content, the thermal stability of BPN sample improved, and the best performance was achieved when the ratio was 25:75 (B:$KNO_3$).

BPN samples without binder have the best thermal stability. In the 5 day 180 °C test, the binder affected the weight loss and p-t curve of BPN. Finally, BPN with fluororubber binder is better than BPN with unsaturated polyester binder.

**Author Contributions:** Conceptualization, C.L. and N.Y.; methodology, C.L. and Z.L.; formal analysis, N.Y.; data curation, J.H. and N.Z.; writing—original draft preparation, C.L.; writing—review and editing, N.Y. and Y.Y.; visualization, X.H.

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**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Shi, C.H. In–line ignition system and its acceptable charge. *Initiat. Pyrotech* **1997**, *01*, 48–52.
2. MIL–STD–1901A. Munition Rocket and Missile Motor Ignition System Design, Safety Criteria. 2002.
3. Zou, Y.L.; Ouyang, Z.Y.; Xu, L.; Liu, J.J.; Xu, T. Lunar surface environment characteristics. *Quat. Sci.* **2002**, *22*, 533–539.
4. Carl, S.; Gorzynski, J.R.; Maycock, J.N. Explosives and pyrotechnic propellants for use in long–term deep space mis–sions. *J. Spacecr. Rocket.* **1974**, *11*, 211–212.
5. Macdonald, M.; Badescu, V. *The International Handbook of Space Technology*; Springer: Berlin, Germany, 2014; pp. 230–232.
6. Rani Krishan, K.R.; Anandavally Ammal, R.; Hariharanath, B.; Rajendran, A.G.; Kartha, C.B. Addition of RDX/HMX on the Ignition Behaviour of Boron–Potassium Nitrate Pyrotechnic Charge. *Def. Sci. J.* **2006**, *56*, 329–338.
7. Turcotte, R.; Fouchard, R.C.; Turcotte, A.M.; Jones, D.E.G. Thermal analysis of black powder. *J. Therm. Anal. Calorim.* **2003**, *73*, 105–118. [CrossRef]
8. Pouretedal, H.R.; Ebadpour, R. Application of non–isothermal thermogravimetric method to interpret the decomposition kinetics of $NaNO_3$, $KNO_3$, and $KClO_4$. *Int. J. Thermophys.* **2014**, *35*, 942–951. [CrossRef]
9. Freeman, E.S. The kinetics of the thermal decomposition of potassium nitrate and of the reaction between potassium nitrite and oxygen. *J. Am. Chem. Soc.* **1957**, *79*, 838–842. [CrossRef]
10. Hosseini, S.G.; Eslami, A. Thermoanalytical investigation of relative reactivity of some nitrate oxidants in tin–fueled pyrotechnic systems. *J. Therm. Anal. Calorim.* **2010**, *101*, 1111–1119. [CrossRef]
11. Eslami, A.; Hosseini, S.G.; Pourmortazavi, S.M. Thermoanalytical investigation on some boron–fuelled binary pyrotechnic systems. *Fuel* **2008**, *87*, 3339–3343. [CrossRef]
12. Zeng, X. Experimental and Theoretical Studies on the Thermal Stability of Nitrates. Ph.D. Dissertation, Nanjing University of Science and Technology, Nanjing, China, June 2007; p. 02.
13. Qi, H.T.; Zhang, J.L. Processing technology and formulation design of ignition composition of boron/ultra–fine potassium nitrate. *Chin. J. Ener. Mater.* **2011**, *19*, 180–183.
14. Wang, L.; Xu, W.Z.; Wang, J.Y. Study on preparation and peoperities of boron–potassium nitrate igniter. *Chem. Intermed.* **2010**, *11*, 38–41.
15. Lv, Q.l. Preparation of boron/potassium nitrate (BPN) ignition charge and analysis of the effect of particle size on its properties. In Proceedings of the 11th Annual Conference of the Chinese Ordnance Institute of Pyrotechnics, Guangxi, China, 18–22 May 2001; pp. 217–220.
16. Shen, R.Q.; Ye, Y.H.; Hu, Y.; Wang, Z.G. Laser Ignition Performance of Boron-Potassium Nitrate Composite at Different Oxygen/Fuel Ratio. *Chin. J. Lasers* **2009**, *36*, 338–341.
17. Rugunanan, R.A.; Brown, M.E. Reactions of powdered silicon with some pyrotechnic oxidants. *J. Therm. Anal. Cal–orim* **1991**, *37*, 1193–1211. [CrossRef]

18. GJB 5381.10–2005. Methods of Chemical Analysis for Pyrotechnic, Part 10: Determination of Potassium Nitrate Content–Sodium Tetraphenylboron Method. Chinese Military Standard. 2005.
19. GJB 5309.23–2004. Test Methods of Initiating Explosive Devices. Part 23: Measurement of Function Alsynchronization Electron–Optical Method, Chinese Military Standard. 2004.
20. GJB 5309.9–2004. Test Methods of Initiating Explosive Devices. Part 9: Electric–Fire Sensitivity Test, Chinese Military Standard. 2004.