

Review

Synthetic Methods towards Energetic Heterocyclic N-Oxides via Several Cyclization Reactions

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Abstract: Due to the introduction of oxygen atoms, N-oxide energetic compounds have a unique oxygen balance, excellent detonation properties, and a high energy density, attracting the extensive attention of researchers all over the world. N-oxides are classified into two categories based on the structural characteristics of their skeletons: azine N-oxides and azole N-oxides, whose N→O coordination bonds are formed during cyclization. There are six kinds of azine N-oxides, namely 1,2,3,4-tetrazine-1,3-dioxide, 1,2,3,5-tetrazine-2-oxide, 1,2,3-triazine-3-oxide, 1,2,3-triazine-2-oxide, pyridazine-1,2-dioxide, and pyrazine-1-oxide. Azole N-oxides include 1,2,5-oxadiazole-2-oxide, pyrazole-1-oxide, and triazole-1-oxide. Synthetic strategies towards these two categories of N-oxides are fully reviewed. Corresponding reaction mechanisms towards the aromatic N-oxide frameworks and examples that use the frameworks to create high-energy substances are discussed. Moreover, the energetic properties of N-oxide energetic compounds are compared and summarized.

Keywords: N-oxides; cyclization reaction; synthesis; reaction mechanism; detonation performance



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1. Introduction

Research on energetic materials continuously develops energetic materials with higher detonation performance and energy density, taking it as an eternal quest. Since the advent of conventional energetic materials such as trinitrotoluene (TNT), RDX, and HMX, researchers worldwide have been extensively exploring energetic materials with chain, ring, and cage parent nucleus structures composed of C, H, and N as the main elements as well as new energetic parent frameworks such as tetrazine, triazole, and furazan [1–11]. Meanwhile, they strive to improve the performance of the compounds by introducing energetic groups, including nitroamino groups, trinitroethyl groups, fluoroacyl dinitroethyl groups, and azide groups [12–17]. As a typical energetic group for improving the detonation performance of compounds, the nitro group (-NO₂) could not only increase the energy density of CHON-based compounds but also enhance the oxygen balance of the energetic compounds, which is conducive to energy release. However, excessive introduction of nitro groups could also lead to problems such as increased sensitivity, complex synthetic process and low yield [18]. In addition, there is an upper limit on the energy density theory of CHON-based energetic compounds represented by nitro groups. For example, hexanitrohexaazaisowurtzitane (CL-20) exhibits high detonation performance and energy density. However, to further improve its performance, its synthetic strategy needs to be changed to break through the energy limit of CHON-based energetic materials [19,20].

The energy density of energetic materials can be effectively increased by forming NO coordination bonds through the oxidation of N atom in the heterocyclic aromatic framework. The formation of N→O bonds at a suitable position in the heterocyclic aromatic ring could not only enhance the energy density but could also improve the oxygen balance of energetic

compounds. More importantly, the N→O bond with the characteristics of a coordination double bond could eliminate the electron repulsion of nitrogen in a N-heterocyclic system and promote σ - π orbital separation to stabilize molecules [21,22]. To study the effect of an N→O bond on the structures and properties of the energetic compounds, Lai Weipeng et al. employed the density functional theory to conduct theoretical calculations of pyrazines, 1,2,3,4-tetrazines, tetrazinofuranzans, and their N-oxides [23]. The results showed that the N→O bond shortens the length of the C–C bond in the ring, lengthens the C–N bond close to the N→O bond and improves the detonation performance of most energetic compounds. It was also found that the improvement is positively correlated with the number of N→O bonds in the energetic compounds (Figure 1).

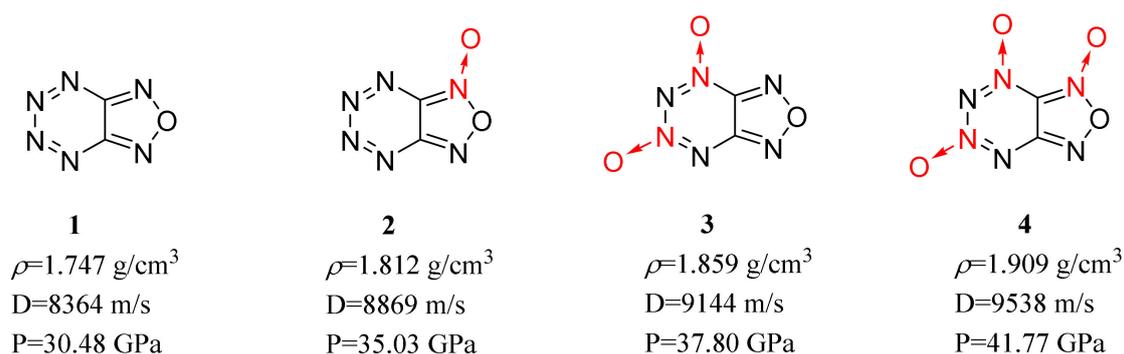


Figure 1. Calculated performance of compounds 1–4.

Using the N-heterocyclic skeleton as the precursor, an N→O coordination bond could be directly formed by the oxidation of hypochlorous acid (HOF), H₂O₂/H₂SO₄ and other oxidation systems. Most of the N-heterocyclic aromatic frameworks could be converted to N-oxides through direct oxidation, yet N-heterocyclic skeletons require certain energy and the corresponding oxidation systems need to be adopted [24]. In the process of constructing heterocyclic skeletons, an N→O coordination bond could be directly generated via the cyclization reaction, thereby bypassing the step of oxidation, shortening the reaction process, and improving production efficiency.

The synthetic methods towards energetic heterocyclic N-oxides, which are simultaneously synthesized during cyclization, are elaborated in this study. The N-oxides could be classified into nine categories based on the structural characteristics of the N-heterocyclic aromatic skeleton. The categories are: 1,2,3,4-tetrazine-1,3-dioxide, 1,2,3,5-tetrazine-2-oxide, 1,2,3-triazine-3-oxide, 1,2,3-triazine-2-oxide, pyridazine-1,2-dioxide, pyrazine-1-oxide, 1,2,5-oxadiazole-2-oxide (furoxan), pyrazole N-oxide, and triazole N-oxide. Some typical cyclization reaction mechanisms are also discussed. The physicochemical properties and detonation performance of the N-oxides are introduced. Direct synthetic strategies towards N-oxides through cyclization reaction would provide a theoretical guidance for the design and development of new energetic compounds.

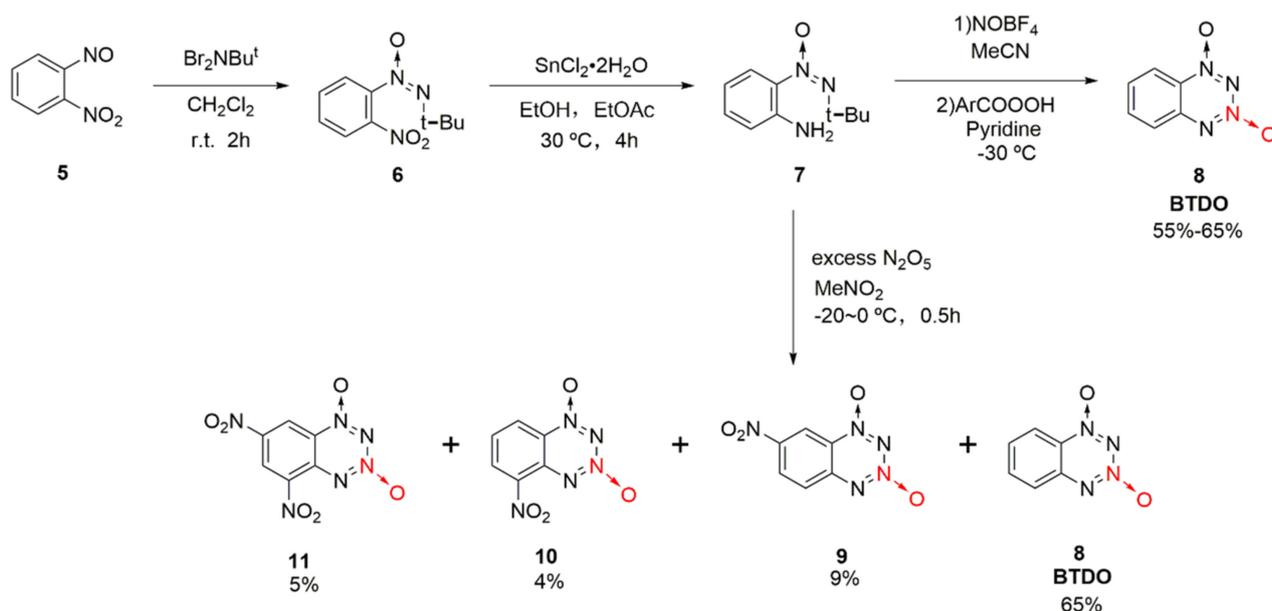
2. Energetic Heterocyclic N-Oxides via Different Cyclization Reaction

2.1. Azine N-Oxides

2.1.1. 1,2,3,4-Tetrazine-1,3-Dioxide

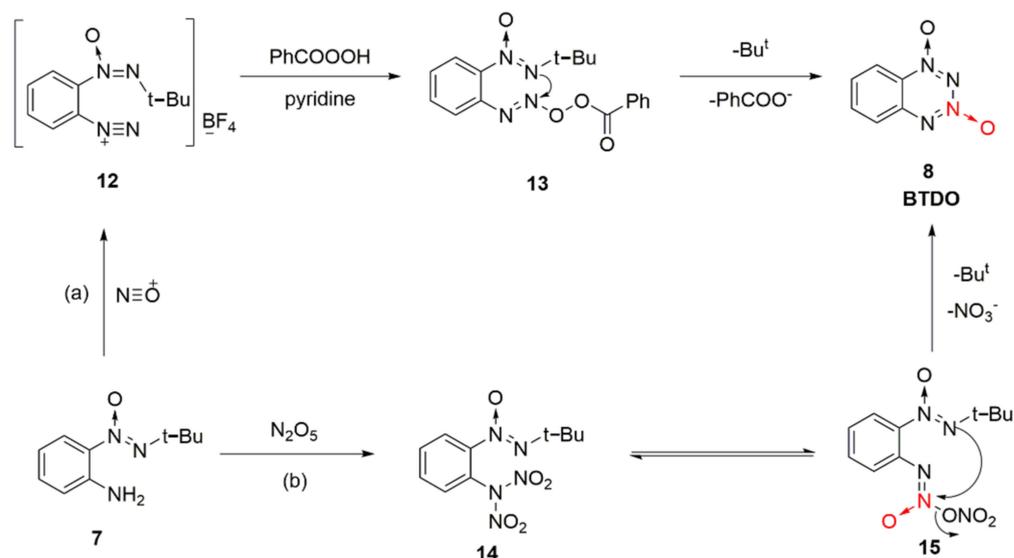
1,2,3,4-Tetrazine-1,3-dioxide was originally derived from 1,2,3,4-tetrazine compounds. According to Churakov et al. [25,26], converting tetrazine into its N-oxide might improve its energetic properties, while the benzene ring was introduced to increase the stability of the tetrazine N-oxide. Benzo-1,2,3,4-tetrazine dioxide (**8**, BTDO) was synthesized by diazotization or nitration from an intermediate O-tert-butyl-NNO-azoxyaniline (**7**) [27]. This method is also applicable for the synthesis of 1,2,3,4-tetrazine dioxide. Using o-nitrosonitrobenzene (**5**) as the raw material, and the intermediate **7** was obtained by a two-step reaction. First, nitroso was transformed into tert-butyl-NNO-azoxy group under

the action of *N,N*-dibromo-*t*-butylamine. Then, the nitro group was reduced to amino group by SnCl_2 to produce the intermediate **7** with a yield of 77%. **BTDO** was obtained by the diazotization oxidation reaction of intermediate **7** with NOBF_4 and benzoic acid peroxide or direct nitration reaction with excess N_2O_5 . By direct nitration, several nitro-substituted benzo-1,2,3,4-tetrazine dioxides have been obtained via the nitration of benzene in excessive N_2O_5 (Scheme 1 9–11).



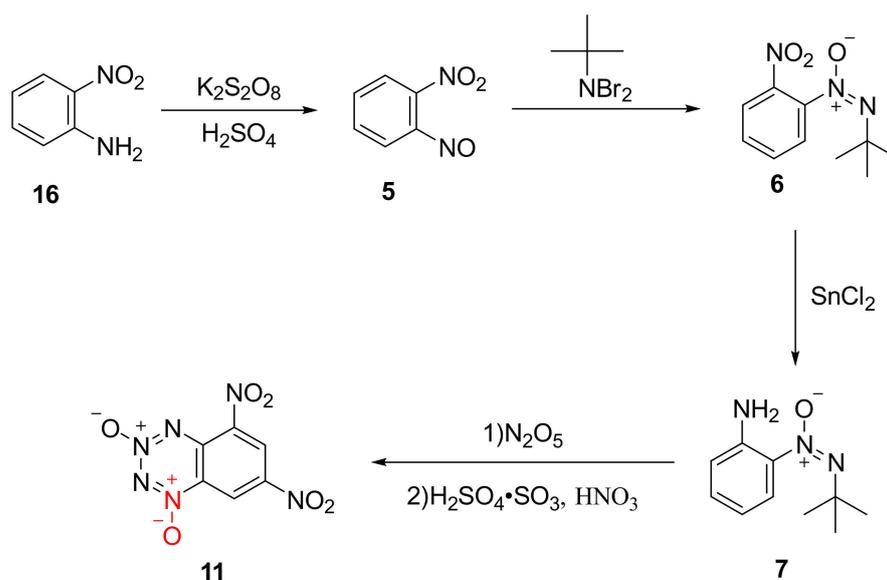
Scheme 1. Synthetic route for **BTDO**.

For the synthesis reaction of **BTDO** by diazotization oxidation and nitration, the reaction mechanism was also examined [25]. Based on the diazotization reaction of nitroso positive ions from NOBF_4 and amino group on the benzene ring of intermediate **7**, diazonium salt intermediate **12** was generated, and an unstable intermediate **13** formed from **12** and benzoic acid peroxide. The intermediate attacked the N atom connected with tert-butyl to the N atom connected with oxygen atom, and the product **BTDO** was finally obtained from intramolecular electron transfer after eliminating the benzoic acid anion and tert-butyl cation (Scheme 2a). An intermediate **14** of *N,N*-dinitroamine was formed by direct nitration of compound **7** using excess N_2O_5 as the nitrating agent. *ONN*-azoxy nitrate compound **15** was produced by intramolecular rearrangement. Similarly, the O atom connected with the tert-butyl group attacked the N atom connected with nitrate for addition elimination, and the product **BDTO** was obtained after removing the tert-butyl cation and nitrate ion (Scheme 2b).



Scheme 2. Different reaction mechanism (a) and (b) of BTDO.

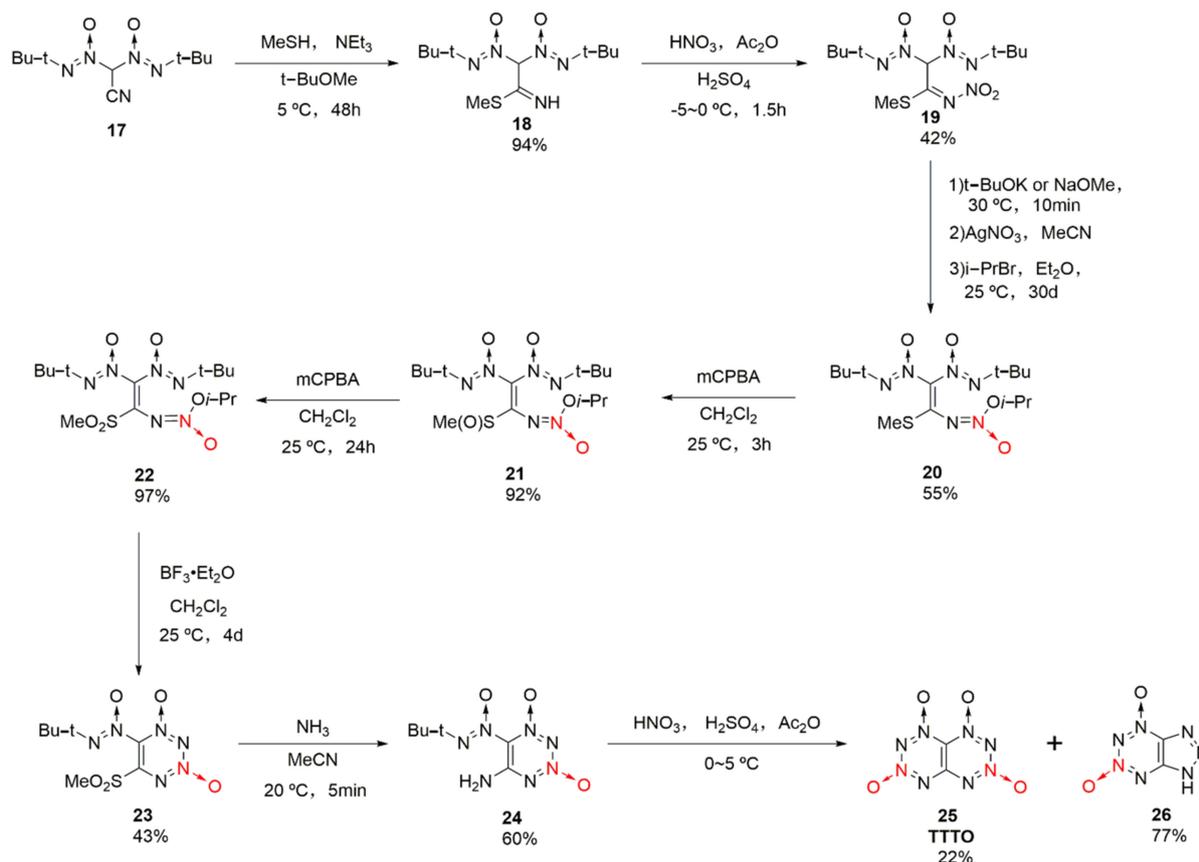
The by-product **11** was produced by nitrating compound **7** with N₂O₅ for further improving the detonation performance of the compound through introducing two nitro groups into the benzene ring. Using o-nitroaniline (**16**) as the raw material, compound **7** was synthesized by Klapotke et al. [28] as follows: The compound **5** was first obtained by the nitration of the amino group with potassium persulfate and sulfuric acid, and then compound **7** was formed by the condensation of dibromo-*t*-butylamine with nitroso group and a further reduction reaction using SnCl₂. Using N₂O₅/dichloromethane as the nitration system, compound **11** as yellow crystal was finally synthesized (Scheme 3). The density of compound **11** was 1.896 g/cm³, and its sensitivity (*IS* = 5 J) was higher than that of RDX (*IS* = 7.5 J). Based on theoretical calculation, its detonation performance (*D* = 8411 m/s, *P* = 33.0 GPa) was equal to that of RDX (*D* = 8748 m/s, *P* = 34.9 GPa).



Scheme 3. Synthetic route for compound **11**.

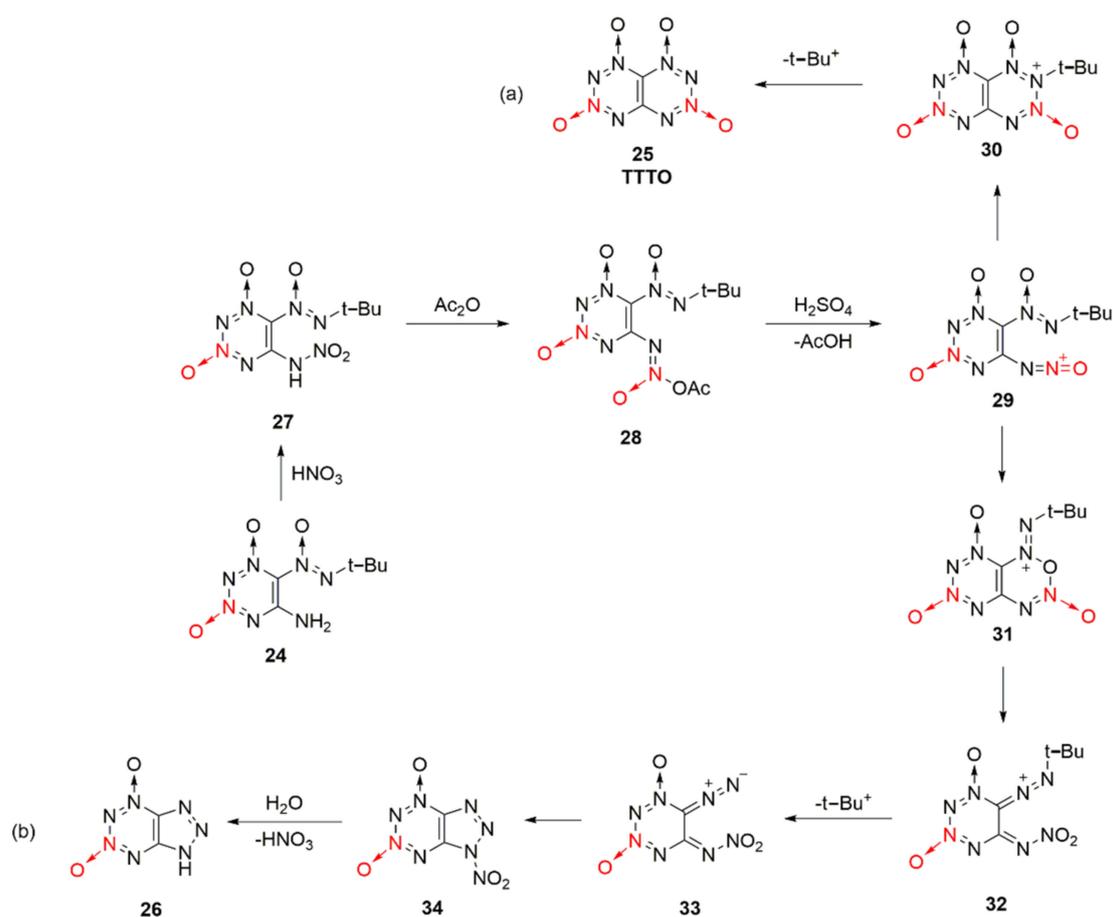
A large number of theoretical calculations [29–32] showed that [1–4]tetrazino [5,6-*e*][1–4]tetrazino-1,2,3,4-tetraoxide (**25**, **TTTO**) is an energetic material with a high energy density ($\rho = 1.899$ g/cm³) and high detonation performances (*D* = 9710 m/s, *P* = 43.2 GPa),

superior to CL-20 ($D = 9420 \text{ m/s}$, $P = 42.0 \text{ GPa}$). Its symmetrical “butterfly” structure has also attracted extensive attention from researchers. Using 2,2-bis(tert-butyl-*NNO*-azoxy)acetonitrile (**17**) as the raw material, **TTTO** was synthesized by Klenov et al. [33] based on a 10-step synthetic strategy with a total yield of 1.1% (Scheme 4). The synthesis process was too complex and the yield was too low, and chromatographic separation was required for purifying key intermediates. Therefore, yet the synthesis of **TTTO** has great theoretical value, there is currently no prospect for industrial applications.



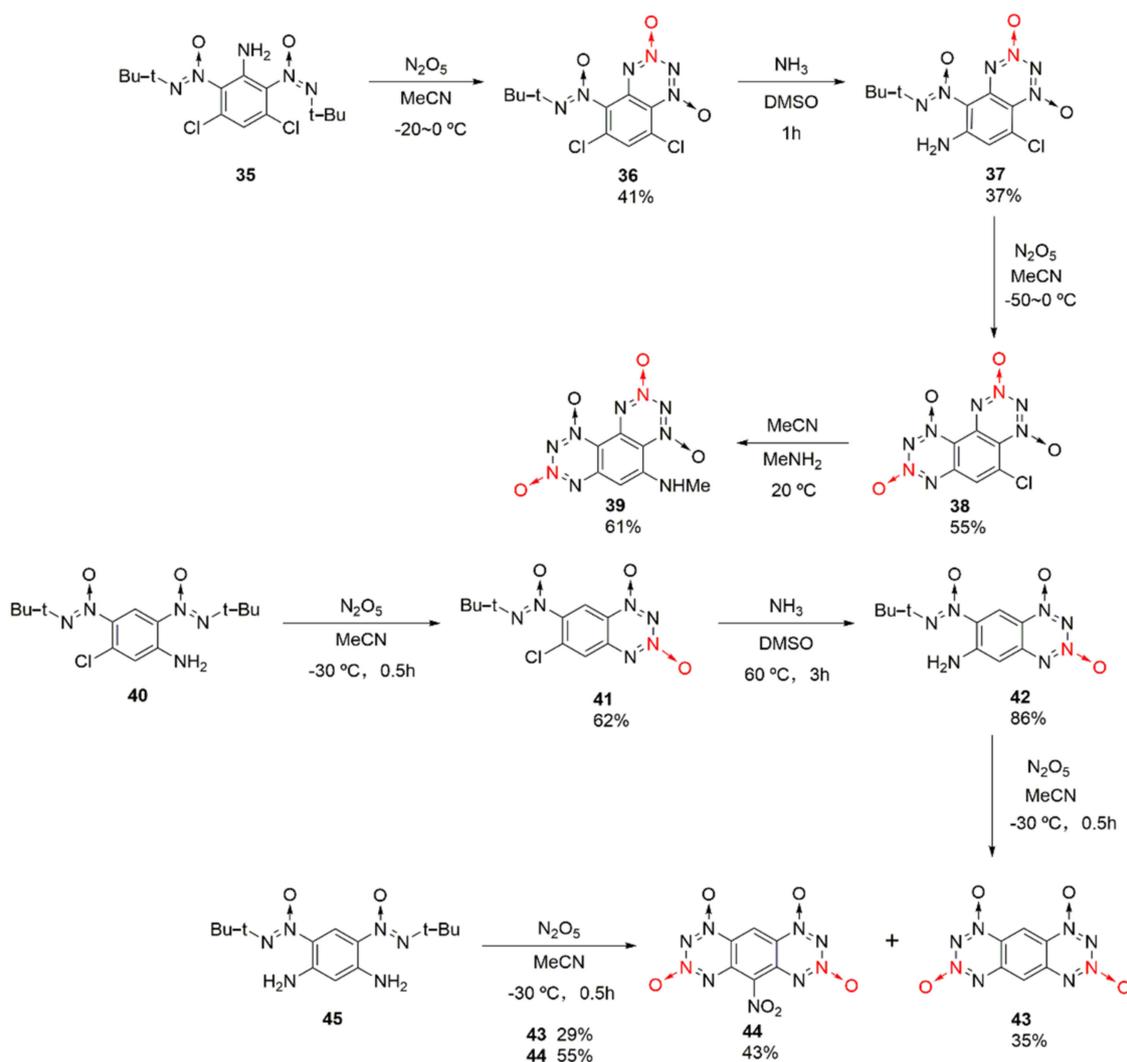
Scheme 4. Synthetic route for **TTTO**.

The reaction process of compound **24** forming **TTTO** and by-product **26** was also reasonably speculated [33]. Under the action of nitric acid, the mononitroamine compound **27** was generated from compound **24**, and compound **28** created by further acetylation of the acetic anhydride. Compound **28** was protonated in sulfuric acid after removing an acetic acid molecule to form oxidized diazonium ion intermediate **29**, which could be cyclized in two different ways. One was to conduct electron transfer between the oxidized diazo positive ion and the N atom connected with tert-butyl group, and then **TTTO** was formed by cyclization after removing the tert-butyl positive ion (Scheme 5a). For the other method, compound **31** was obtained by cyclization based on the nucleophilic attack of the O atom in the oxidizing diazo positive ions. However, compound **31** was unstable, so diazo ketone compound **33** was obtained after the ring-opening reaction of **31** and by removing the tert-butyl positive ions. Eventually, by-product **26** was produced by further cyclization and hydrolysis (Scheme 5b)).



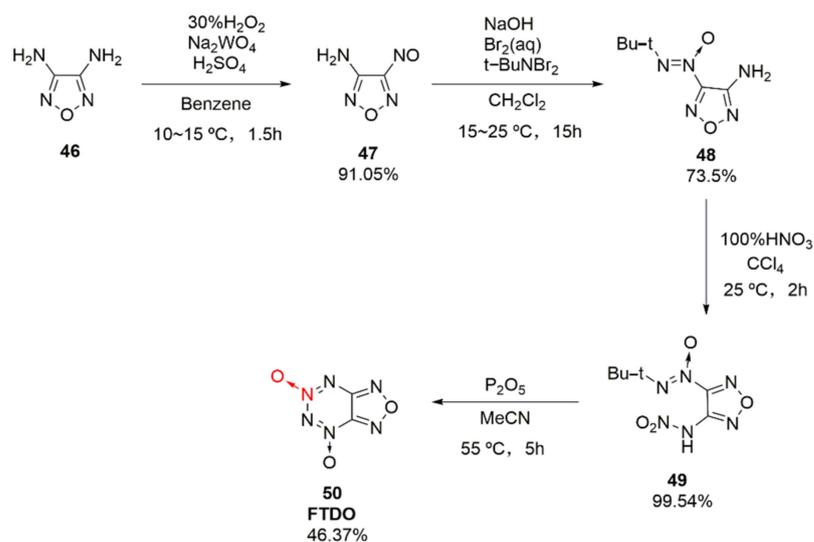
Scheme 5. Possible synthetic routes (a) and (b) for compound 26 and TTTO.

Based on the structuring idea of using anthracene ring and phenanthrene ring, two fused tetrazine dioxides, 1,2,3,4-tetrazino [5,6-f]benzo-1,2,3,4-tetrazino-1,3,7,9-tetraoxide (38) and 1,2,3,4-tetrazino [5,6-g]benzo-1,2,3,4-tetrazino-1,3,7,9-tetraoxide (42), were synthesized by Frumkin et al. [34,35] from different raw materials. Using compound 35 as the starting material, compound 36 was obtained in the first cyclization reaction using nitration with nitric anhydride. Then, compound 38 was obtained by amino substitution and the second cyclization reaction via nitric anhydride. The chlorine atom on compound 38 was easily replaced by some nucleophiles to form other derivatives, such as compound 39, and the properties of the substituted compounds were improved, such as a higher thermal decomposition temperature ($T_d = 210\text{ }^\circ\text{C}$) than that of compound 38 ($T_d = 140\text{ }^\circ\text{C}$). Using compound 40 as the starting material, compound 43 was synthesized through nitration using nitric anhydride, amino substitution, and secondary nitration-cyclization. By-product 44 with a nitro group on the benzene ring would also be produced. Meanwhile, compound 43 could be synthesized by one-step nitration from compound 45 (Scheme 6).



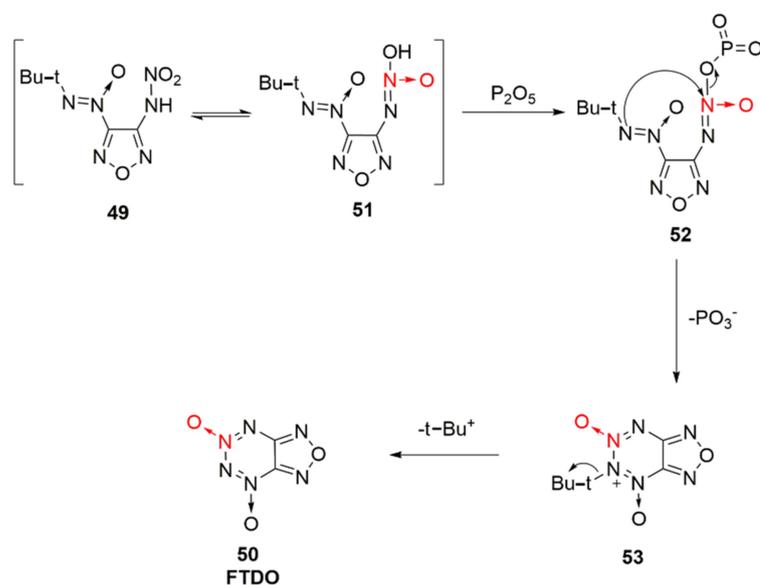
Scheme 6. Synthetic routes for compounds 38 and 43.

Based on the fusing furazan with tetrazine dioxide, an energetic compound furazano [3,4-e]-1,2,3,4-tetrazine-4,6-dioxide (**50**, **FTDO**) was synthesized by Churakov et al. [36] for the first time. **FTDO** displays a broad prospect with a measured density of 1.85 g/cm³, formation enthalpy of 4.23 MJ·kg, theoretical detonation velocity of 9802 m/s, and explosion pressure of 44.78 GPa, arousing widespread research interests [37,38]. It was synthesized through the nitration-cyclization of compound **48** by using tetrafluoroborate nitrate as the nitration reagent. Yet, the price of tetrafluoroborate nitrate was too expensive, and the nitrated product was difficult to purify. Using 3,4-diaminofurazan (**46**) as the raw material, compound **48** was obtained by Li Xiangzhi et al. [39] via oxidation and condensation, followed by the nitration of 100% HNO₃ and cyclization of P₂O₅, leading to the high-purity product **FTDO** (Scheme 7). The effects of N₂O₅, NO₂BF₄, 100% HNO₃, etc. nitration systems on the product and purity were also compared. It was concluded that using 100% HNO₃ as the nitrating agent, a maximum yield of 99.54% and purity of 99.18% could be achieved.



Scheme 7. Synthetic route for FTDO.

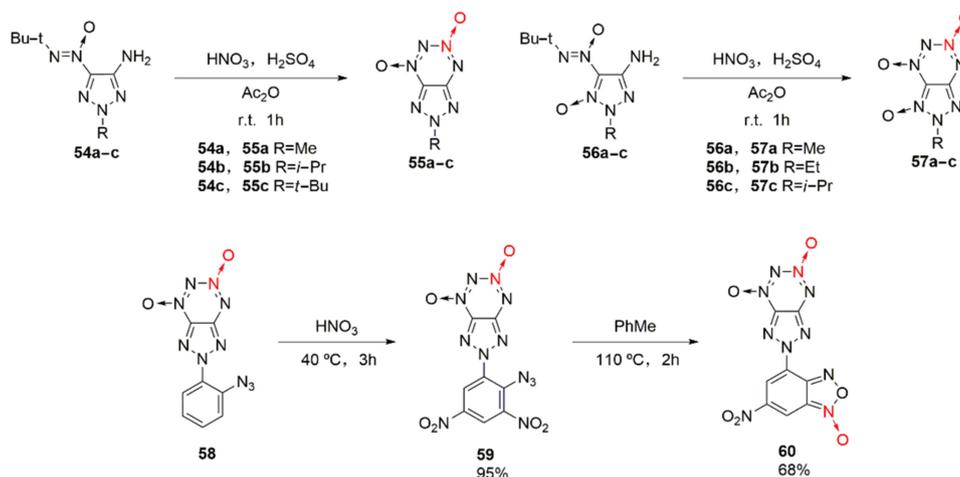
In this reference [39], the cyclization mechanism under the action of P_2O_5 was discussed (Scheme 8). The nitroamino group in compound **49** was isomerized to produce compound **51** containing a *N*-hydroxyl group. P_2O_5 was esterified with the hydroxyl group on compound **51** to produce 3-(tert-butyl-*NNO*-azoxy)-furazan-4-azoxy alcohol phosphite (**52**). The N atom connected with tert-butyl group in compound **52** attacked the nucleophilic N atom connected to phosphite. Moreover, the metaphosphate group was removed while electron transfer was performed. The tert-butyl positive ion was then removed to finally obtain **FTDO**.



Scheme 8. Cyclization mechanism of compound **49** under the action of P_2O_5 .

Although the fusion of a five-membered furazan ring with tetrazine dioxide has achieved great success, its low decomposition temperature of 112 °C for **FTDO** still limits its application as an energetic material [40]. Based on the fusing the five-membered triazole ring with tetrazine dioxide, after introducing alkyl into the triazole ring, a series of triazole tetrazine dioxides (Scheme 9 **55a-c**, **57a-c**) with stable thermal properties were obtained by Voronin et al. [41]. Energetic compounds with excellent detonation properties were also obtained by introducing energetic groups ($-N_3$, $-NO_2$, others) into the triazole ring [42].

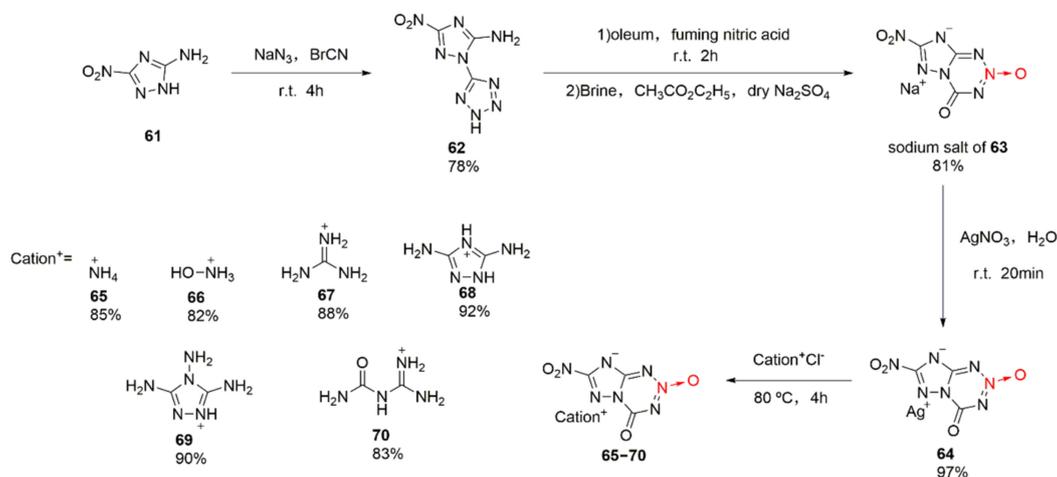
Among them, the thermal decomposition temperature of compound **55a** is 199 °C, while that of compound **57a-c** is within 208 ~ 230 °C. Due to the introduction of a benzofurazan ring into the triazole ring, compound **60** as a potential energetic compound was further obtained by Shvets et al. [43]. It exhibits an energy density of 1.84 g/cm³, a thermal decomposition temperature of 190 °C, and a calculated enthalpy of formation of 1005 kJ/mol.



Scheme 9. Synthetic routes for compounds **55a-c**, **57a-c** and **60**.

2.1.2. 1,2,3,5-Tetrazine-2-Oxides

Bian Chengming et al. were the first to study the synthetic methods for 1,2,3,5-tetrazine-2-dioxide [44]. After fusing 1,2,3,5-tetrazine-2-dioxide with triazole, 7-nitro-4-one-4,8-dihydro-1,2,4-triazolo [5,1-d]-1,2,3,5-tetrazine-2-oxide (**63**), a series of energetic ionic salts were designed and synthesized (Scheme 10 **65–70**). Using 5-amino-3-nitro-1,2,4-triazole (**61**) as the raw material [45], a tetrazole ring was introduced under the action of cyanogen bromide and sodium azide to obtain compound **62**. Nitric acid and fuming sulfuric acid were subjected to nitration and cyclization, and the sodium salt of compound **63** was obtained after extraction and washing with brine. At last, the energetic ionic salts **65–70** were obtained by an ion exchange reaction for the sodium salt of compound **63** and silver nitrate. Compounds **65–70** display good thermal stability, high density, high detonation performance, and low sensitivity (Table 1). Among them, compound **66** with a hydroxylaminium cation shows the highest potential to be used as an energetic material.

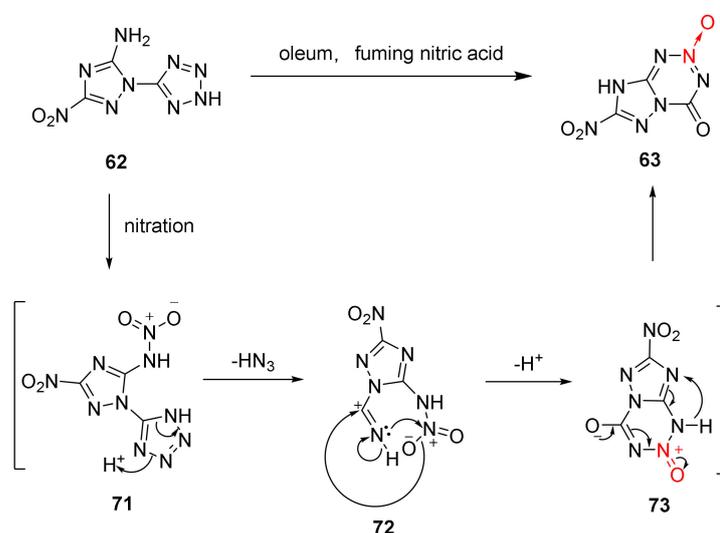


Scheme 10. Synthetic routes for compounds **65–70**.

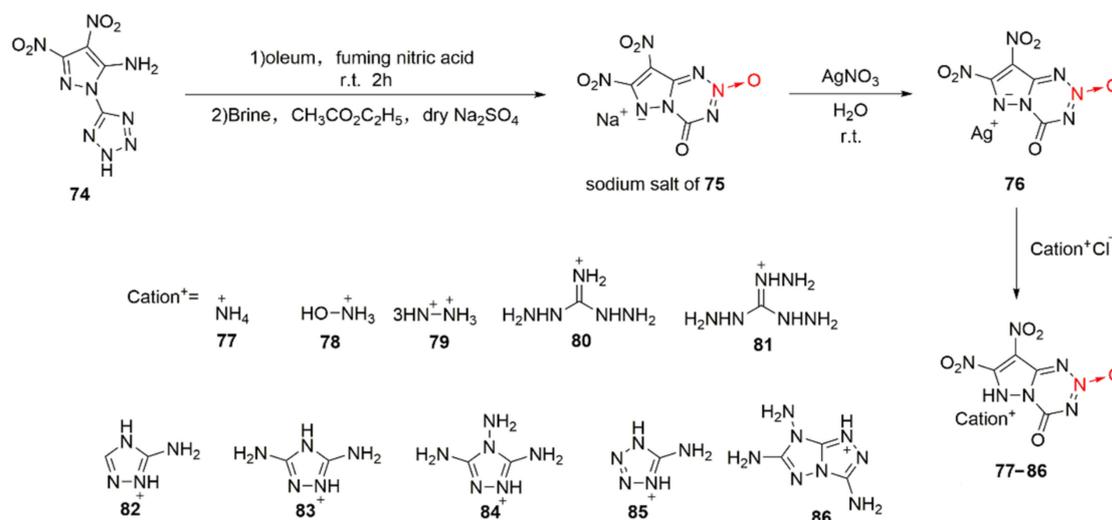
Table 1. Physiochemical properties and detonation parameters of energetic salts 65–70.

| Compound | $\rho/\text{g}\cdot\text{cm}^{-3}$ | $D/\text{m}\cdot\text{s}^{-1}$ | P/GPa | IS/J | FS/N | $T_d/^\circ\text{C}$ |
|-----------|------------------------------------|--------------------------------|----------------|--------|--------|----------------------|
| 65 | 1.77 | 8252 | 29.0 | >40 | 324 | 249 |
| 66 | 1.97 | 9069 | 39.5 | >40 | 324 | 197 |
| 67 | 1.78 | 8113 | 27.1 | >40 | 324 | 269 |
| 68 | 1.89 | 8463 | 30.7 | >40 | 360 | 252 |
| 69 | 1.81 | 8373 | 29.2 | >40 | 324 | 237 |
| 70 | 1.80 | 7856 | 25.2 | >40 | >360 | 241 |
| TATB [43] | 1.93 | 8114 | 31.2 | 50 | >360 | ~360 |
| RDX [43] | 1.82 | 8748 | 34.9 | 7 | 120 | 230 |

During the nitration reaction of **62**, a white precipitate AgN_3 was generated from the reaction of AgNO_3 and the released gas, which was later verified to be azide acid. According to the infrared spectrum of compound **63**, a strong peak appears at 1787 cm^{-1} and no obvious absorption peak is found at $3600\sim 2500\text{ cm}^{-1}$. It was verified that the 4-position in compound **63** was acyl group rather than hydroxyl group. Based on the experimental facts, the cyclization mechanism of compound **62** was reasonably speculated [44]: Compound **62** was nitrated in the $\text{HNO}_3/\text{H}_2\text{SO}_4$ mixed acid system to produce nitramine intermediate **71**. The tetrazole in intermediate **71** carried out electron transfer. Then, a molecule of HN_3 was removed and a $\text{C}=\text{N}$ bond was created to form intermediate **72**. The O atom on the nitro group initiated a nucleophilic attack on the C atom on the $\text{C}=\text{N}$ bond, reducing the density of the electron cloud on the N atom of the nitro group to make it appear deficiently electronic. The N atom on the $\text{C}=\text{N}$ bond attacked the N atom of the nitro group. With the electron transfer and proton removal, a tetrazine ring was basically formed for producing intermediate **73**. The intermediate **73** was aromatized to perform electron and proton transfer, and the energetic compound **63** was finally obtained (Scheme 11).

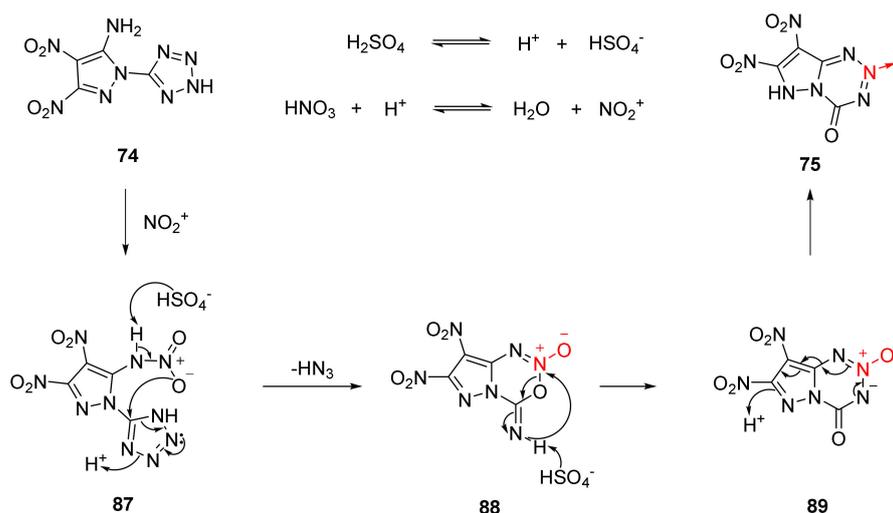
**Scheme 11.** Proposed synthetic route for compound **63**.

By replacing the triazole ring in compound **63** with a pyrazole ring and introducing another nitro group into the pyrazole ring, Zhao et al. [46] synthesized 7, 8-dinitro-4-keto-4,6-dihydropyrazolo [5,1-d]-1,2,3,5-tetraazine-2-oxide (**75**). Due to the acidity of **75**, a series of energetic ionic salts (Scheme 12 **77–86**) was synthesized by the same ion exchange method. After analyzing and comparing the measured density with the theoretically calculated detonation performance, it was found that the hydroxylaminium salt of compound **78** also display excellent properties in all aspects. Its density and detonation performance ($\rho = 1.95\text{ g/cm}^3$, $D = 9228\text{ m/s}$, $P = 39.4\text{ GPa}$) are similar to those of HMX ($\rho = 1.91\text{ g/cm}^3$, $D = 9186\text{ m/s}$, $P = 39.7\text{ GPa}$) and low sensitivity is also presented ($IS = 19\text{ J}$, $FS = 360\text{ N}$).



Scheme 12. Synthetic routes for compounds 77–86.

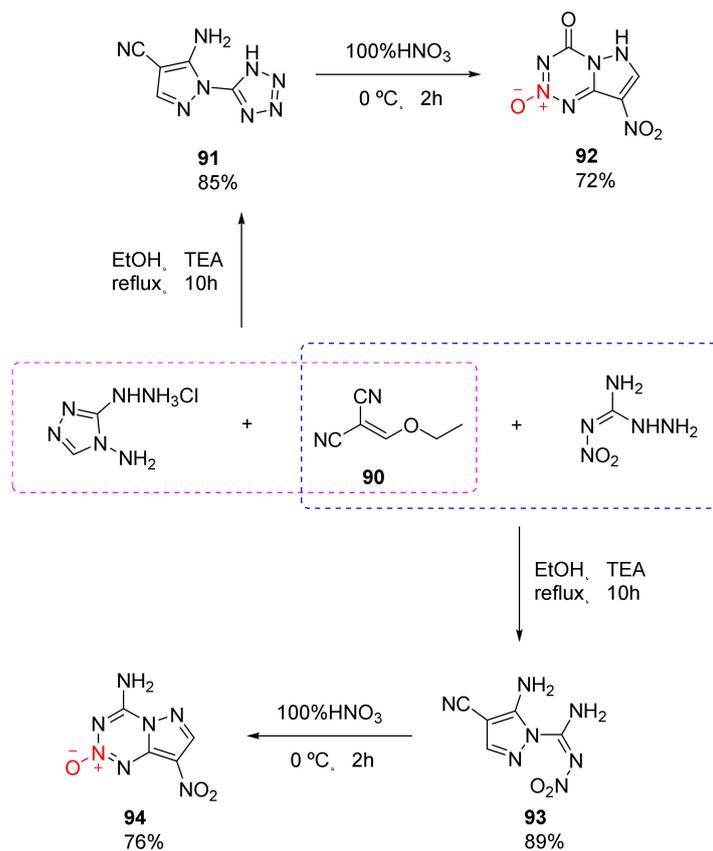
According to the experimental fact that gas was produced when nitration reacted with AgNO₃ solution to obtain the white precipitate AgN₃ [46], the nitration-cyclization mechanism of compound 74 was reasonably described as follows (Scheme 13). The amino group (-NH₂) on compound 74 first reacted with the NO₂⁺ to obtain the nitroamine intermediate 87, and the nitroamine intermediate was unstable. After the H atom on the nitroamine group was captured by HSO₄⁻ in the system, the O atom on the nitro group attacked the C atom of the tetrazole ring, and the tetrazole ring carried out electron transfer, the intermediate 88 was obtained by removing a molecule of HN₃ and cyclization reaction between the remaining C = N unit of the tetrazole ring and the nitro oxygen atom. The intermediate 88 was rearranged under the action of HSO₄⁻ to produce a fused ring intermediate 89 containing 1,2,3,5-tetrazine-2-oxide. Further aromatization was carried out to obtain the product compound 75 via intramolecular protons and electron transfer.



Scheme 13. Proposed synthetic route for compound 75.

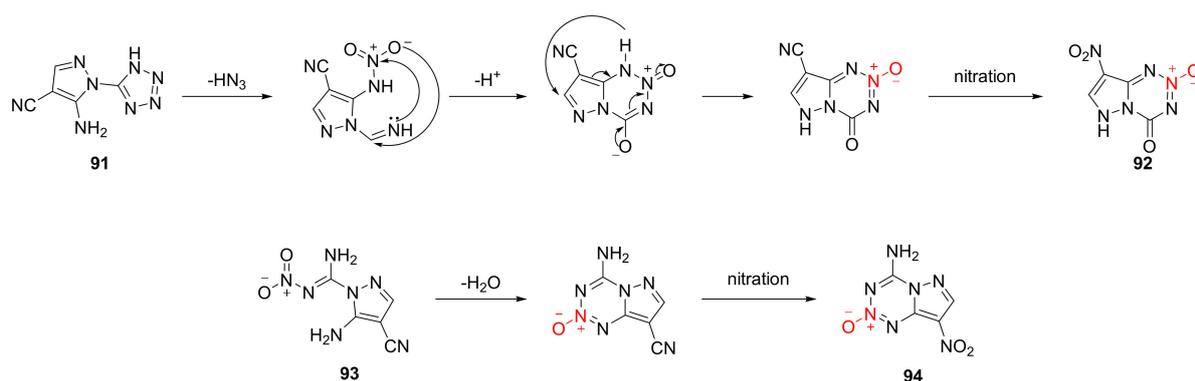
Compound 63 and compound 75 both exhibit excellent detonation properties, but the separation is difficult due to their strong moisture absorption. Moreover, the reagent required for the synthetic process is toxic and the gas produced during reaction is dangerous, limiting their applications to a great extent. An efficient and safe synthesis route for 1,2,3,5-tetrazine-2-oxide was independently developed by Lei et al. [47]. Based on the reactivity of

the hydrazino group, two pyrazolo 1,2,3,5-tetrazine-2-oxides with no hygroscopicity, high density, excellent detonation performance, and low sensitivity were obtained (Scheme 14 92, 94). Using ethoxymethylene malononitrile (90) as the raw material, the two compounds 92 and 94 were synthesized via different cyclization and nitration. Based on theoretical calculation and practical analysis, compound 94 display high density ($\rho = 1.874 \text{ g/cm}^3$), high detonation velocity ($D = 8983 \text{ m/s}$), high detonation pressure ($P = 34.5 \text{ GPa}$), and low sensitivity ($IS = 20 \text{ J}$, $FS > 360 \text{ N}$). At the same time, its high thermal decomposition temperature ($T_d = 302 \text{ }^\circ\text{C}$) endows it with the potential to become a heat-resistant explosive.



Scheme 14. Synthetic routes for compounds 92 and 94.

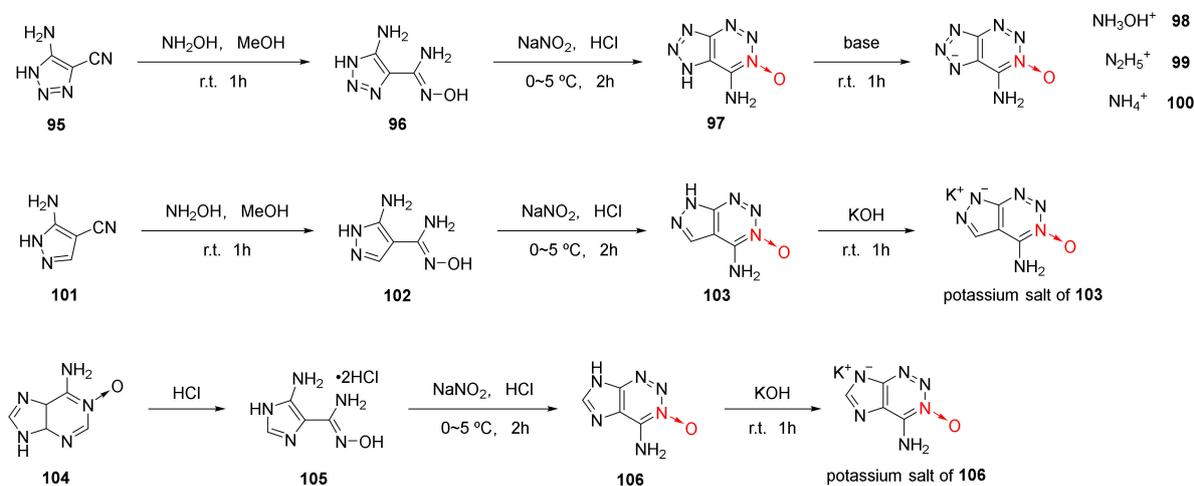
The possible cyclization mechanism for compound 91 and compound 93 was described as follows [47] (Scheme 15). The amino group of compound 91 was nitrated to a nitroamine group, and the *o*-tetrazole group exposed C = N moiety after removing a molecule of HN₃ by electron transfer. A cyclization was carried out after the C = N moiety and nitro group had a nucleophilic reaction. With the electron induction of ring, the cyano group was replaced by a nitro group in the nitration reaction to produce compound 92. Compound 93 was cyclized by the dehydration condensation of nitro and amino groups in the imine structure, also under the induction effect of 1,2,3,5-tetrazine-2-oxycycle. Then, the cyano group was substituted with nitro to obtain compound 94.



Scheme 15. Possible synthetic routes for compounds 92 and 94.

2.1.3. 1,2,3-Triazine-3-Oxides

Using o-cyano N-heterocyclic aromatic amine as the starting material, 1,2,3-triazine-3-oxide skeleton was formed by the addition, diazotization and cyclization reaction via the reactivity of an amino group with the o-cyano group. Based on the above design ideas of 1,2,3-triazine-3-oxide skeleton, three energetic compounds (Scheme 16 97, 103, 106) in which 1,2,3-triazine-3-oxide was fused with triazole, imidazole, and pyrazole, were synthesized by Tang et al. [48] for the first time. Since triazole and pyrazole are acidic under the action of strong electron absorbing groups, five energetic ionic salts (98–100, 103 and 106) were obtained by the neutralization reaction from three fused energetic compounds, namely 97, 103, and 106. Based on theoretical calculation and experimental study, it was found that compound 99 displayed the best detonation performance ($D = 9358$ m/s, $P = 33.6$ GPa), even exceeding RDX ($D = 8795$ m/s) in detonation velocity (Table 2).

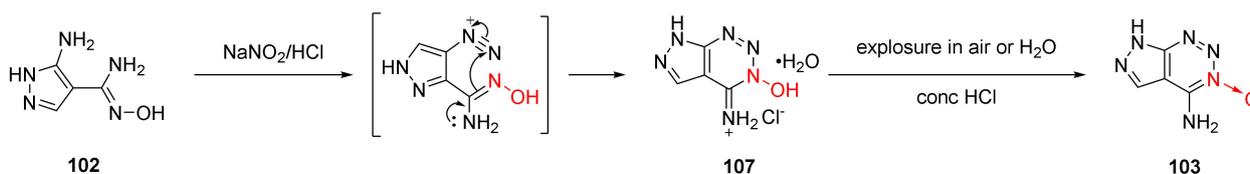


Scheme 16. Synthetic routes for ionic salts 98–100 and compounds 97, 103, 107.

Table 2. Energetic properties and detonation parameters of ionic salts 98–100 and compounds 97, 103, 107.

| Compound | $\rho/\text{g}\cdot\text{cm}^{-3}$ | $D/\text{m}\cdot\text{s}^{-1}$ | P/GPa | IS/J | FS/N | $T_d/^\circ\text{C}$ |
|----------|------------------------------------|--------------------------------|----------------|------|------|----------------------|
| 97 | 1.815 | 8792 | 30.3 | 30 | 360 | 194 |
| 98 | 1.772 | 8670 | 28.0 | 20 | >360 | 137 |
| 99 | 1.800 | 9358 | 33.6 | 25 | >360 | 160 |
| 100 | 1.740 | 8744 | 28.2 | 30 | >360 | 180 |
| 103 | 1.772 | 8271 | 25.6 | >40 | >360 | 221 |
| 106 | 1.743 | 8008 | 23.3 | >40 | >360 | 227 |
| RDX [47] | 1.800 | 8795 | 34.9 | 7.5 | 120 | 204 |

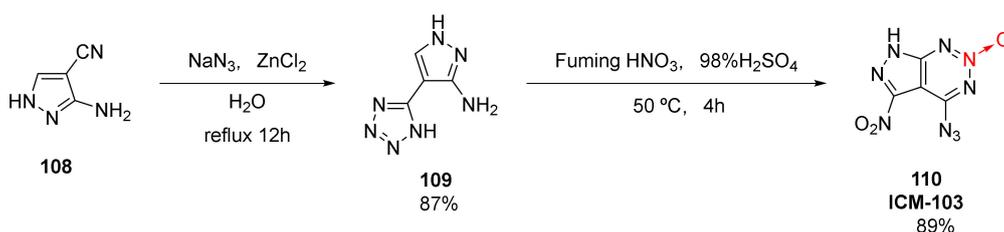
In the nitrosation reaction of compound **102** with dilute hydrochloric acid, a white precipitate was firstly produced, which turned yellow after being exposed to air for several days or being washed with water. Its crystal structure was confirmed by X-ray single-crystal diffraction. It was a hydrochloride intermediate (**107**) formed after amino diazotization and cyclization with a hydroxime group. According to the experimental results of the synthetic compound **103**, the cyclization mechanism of 1,2,3-triazine-3-oxide was proposed as follows [48] (Scheme 17): The diazonium positive ions was generated by the nitrosation reaction of the amino group. The hydrochloride intermediate **107** was obtained by further cyclization with a hydroxime group. Finally, compound **103** was obtained after removing HCl and H₂O.



Scheme 17. Proposed synthetic route for compound **103**.

2.1.4. 1,2,3-Triazine-2-Oxides

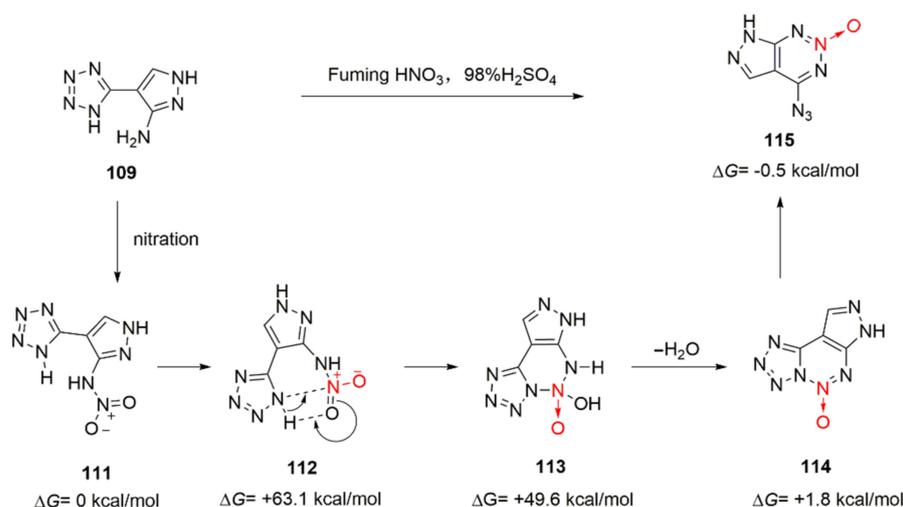
High detonation performance, appropriate mechanical sensitivity, and high chemical and thermal stability are the basic characteristics of green detonators. A fused ring energetic compound 6-nitro-7-azido-pyrazolo [3,4-d]-1,2,3-triazine-2-oxide (**110**, **ICM-103**) was synthesized by Deng Mucong et al. [49,50] from industrial 3-amino-4-cyanopyrazole (**108**). First, under the action of the catalyst ZnCl₂, the cyano group on the pyrazole ring reacted with azide anion to form a tetrazole ring. Then, the nitration reaction was cyclized to form 1,2,3-triazine-2-oxide (Scheme 18). The total yield of the two-step reaction was 77.4%. Especially, by only one nitration, azido and nitro groups were formed and cyclized, laying a foundation for the industrial mass production of **ICM-103**. Additionally, a high measured density and excellent calculated detonation performance ($\rho = 1.86 \text{ g/cm}^3$, $D = 9111 \text{ m/s}$, $P = 35.14 \text{ GPa}$), **ICM-103** shows an appropriate mechanical sensitivity ($IS = 4 \text{ J}$, $FS = 60 \text{ N}$), and its flame sensitivity (Flame S > 60 cm) even exceeds that of the widely used azide dinitrophenol (DDNP) (Flame S = 17 cm). More importantly, **ICM-103** does not contain metal components and is environmentally friendly. Thus, its synthesis is of great significance for the research of green primary explosives.



Scheme 18. Synthetic route for **ICM-103**.

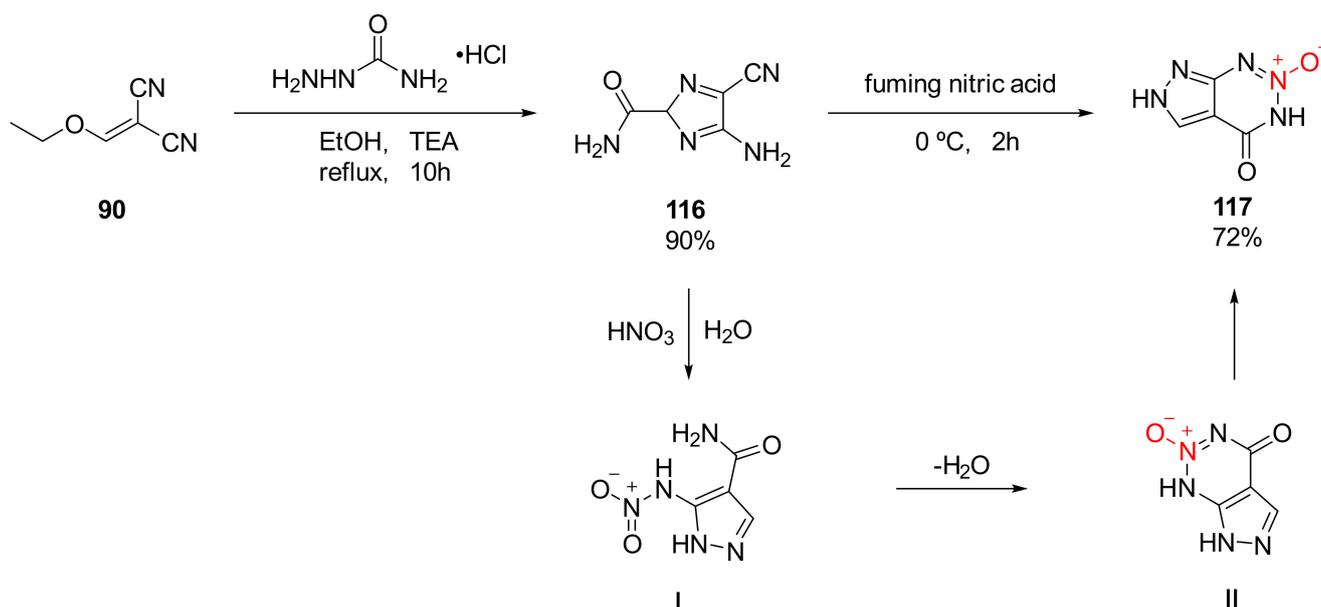
Deng Mucong proposed a reasonable cyclization mechanism for compound **109** based on the theoretical calculation of the Gibbs free energy of various intermediates encountered in the reaction process [49] (Scheme 19). Compound **109** was first nitrated with mixed acid to produce an unstable nitroamine intermediate **111**, and its Gibbs free energy was defined as 0 ($\Delta G = 0 \text{ kcal.mol}^{-1}$). With the induction of the intramolecular hydrogen bond, the N-H in the tetrazole ring reacted with the N = O in the nitro group and intermediate **113** was generated via the transition state **112**. After an intramolecular elimination reaction was conducted, a fused ring intermediate **114** was obtained by removing a molecule of water. The tetrazole ring on the intermediate **114** was isomerized to form a azido group

and obtain 7-azido-pyrazolo-[3,4-d]-1,2,3-triazine-2-oxide(**115**). **IMC-103** was obtained by further nitration and introduction of a nitro group at the position 6 of **115**.



Scheme 19. Possible synthetic route for **ICM-103**.

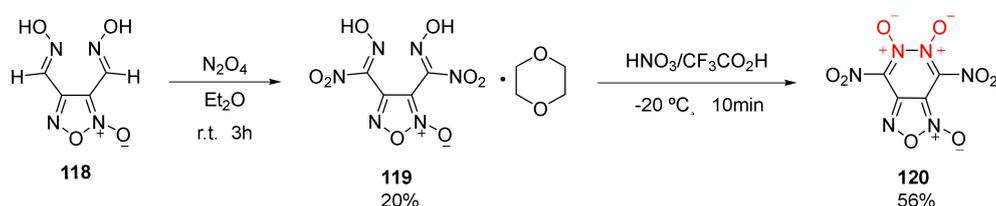
Using ethoxymethylene malononitrile (**90**) and carbamoyl hydrazide as raw materials, compound **116** was obtained by the condensation cyclization reaction in the solution of triethylamine and ethanol, and pyrazolo-1,2,3-triazine-2-oxide(**117**)($\rho = 1.825 \text{ g/cm}^3$, $D = 8323 \text{ m/s}$, $P = 27.7 \text{ GPa}$, $IS > 20 \text{ J}$, $FS > 360 \text{ N}$) was synthesized by Lei et al. [47] via further nitration and cyclization using fuming nitric acid. Due to the high thermal decomposition temperature ($T_d = 275 \text{ }^\circ\text{C}$), compound **117** could be used as a heat-resistant explosive. The cyclization mechanism of compound **116** was basically the same as that of compound **109**: By removing the amide group on the pyrazole ring using compound **116** under the action of nitric acid, while hydrolyzing the cyano group on the ring to an amide group, the amino group was nitrated to a nitroamino group. Similarly, with the induction of a hydrogen bond, the nitro group and the amino group underwent electrophilic addition and elimination reaction to remove a molecule of water. Then, further intramolecular electron transfer was performed to obtain compound **117**(Scheme 20).



Scheme 20. Possible synthetic route for compound **117**.

2.1.5. Pyridazine-1,2-Dioxide

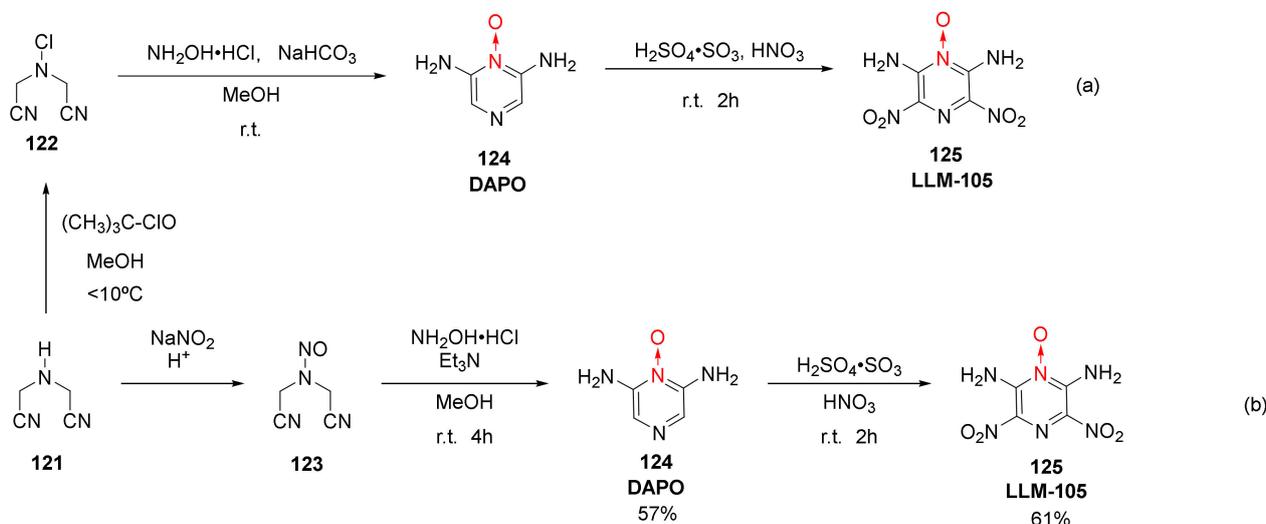
According to the characteristics of NO donor drugs, 4,6-dinitro-furazan [3,4-d]-1,5,6-trioxide (**120**) was obtained by Ogurstov et al. [51] by fusing furoxan with pyridazine-1,2-dioxide. Using 3,4-dihydroxyfuroxan (**118**) as the raw material, a 1:1 stable complex of furazan dinitroxime acid (**119**) with 1,4-dioxane was obtained by the nitration of N_2O_4 in Et_2O solution. Then, compound **120** (m.p. = 50–52 °C) was synthesized in the nitration system of HNO_3 and CF_3COOH (Scheme 21). As compound **120** could not exist stably in organic solvents such as CH_2Cl_2 and MeCN, it could not be detected by elemental analysis and mass spectrometry. Its structure, however, could still be observed by infrared spectrum in KBr and carbon spectrum in deuterated acetone. Compound **120** has a density as high as 1.98 g/cm^3 and a calculated detonation velocity of 9.52 km/s , making it comparable to CL-20. Yet, its applications as an energetic material are largely limited by its poor thermal stability.



Scheme 21. Synthetic route for compound **120**.

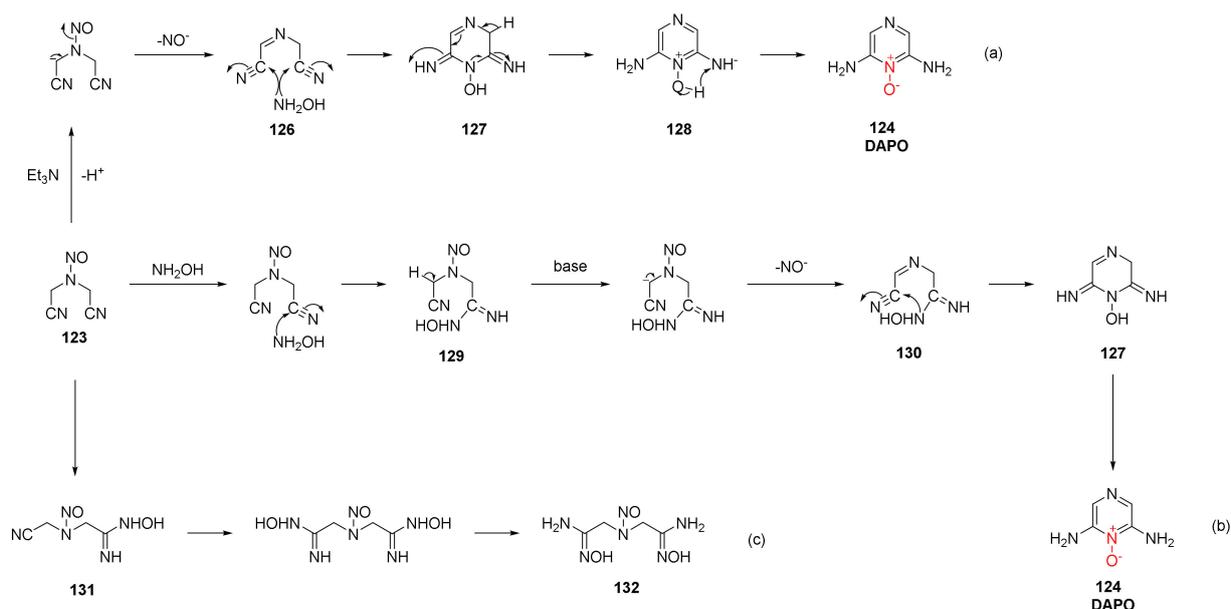
2.1.6. Pyrazine-1-Oxide

The 2,6-diamino-3,5-dinitro-1-oxide (**125**, LLM-105) has a crystal density of 1.918 g/cm^3 , experimental detonation velocity [52] of 8560 m/s , and DSC exothermic peak of 342 °C . It exhibits good thermal stability, an impact sensitivity of 117 cm , high sensitivity, and excellent comprehensive properties, thus being widely used in the field of energetic materials. It could not only be used as the main charge and insensitive initiator of weapons but it also has potential in civil engineering, such as oil exploration. Jing Suming et al. used iminodiacetonitrile (**121**) as the raw material to synthesize LLM-105 by a three-step process of substitution, condensation, and nitration (Scheme 22a) [52]. LLM-105 was also synthesized by Zhao Xiaofeng et al. [53] using a novel synthesis method of nitrosation, condensation, and nitration (Scheme 22b), which shows potential for industrial applications.



Scheme 22. Synthetic routes (a) and (b) for LLM-105.

Zhao Xiaofeng et al. discussed the reaction mechanism for synthesizing DAPO [54]. Compound **123** was stripped of a proton under the alkaline action of Et_3N , and the nitrogen oxide anion (NO^-) was removed after electron transfer to form intermediate **126**. Intermediate **126** was then condensed and cyclized with free hydroxylamine to obtain compound **127**, which was further aromatized to obtain compound **128**. Finally, the product DAPO was obtained by intramolecular proton transfer (Scheme 23a). On such basis, a new possible reaction mechanism was proposed by Wang Jinmin et al. [55], who used sodium hydroxide as alkaline medium for the preparation of DAPO. A cyano group in compound **123** first reacted with hydroxylamine to obtain compound **129**. Under the alkaline condition of NaOH , HNO (H^+ and NO^-) was removed to obtain intermediate **130**, and the hydroxylamino group of the intermediate condensed with another cyano group to obtain compound **127**. After further intramolecular electron and proton transfer, the product DAPO was obtained (Scheme 23b). Li et al. [56] found that compound **131** and compound **134** (Scheme 23c) could be separated from the product by changing the ratio of compound **123**, hydroxylamine hydrochloride, and alkaline medium. Then, the cyclization mechanism of DAPO was divided into two stages. In the first stage, the basic reagent reacted with hydroxylamine hydrochloride to obtain free hydroxylamine and condensed with compound **123** to form compound **129**. In the second stage, Et_3N grabbed protons to separate nitrogen oxide anions and then condensed and cyclized to obtain the product DAPO.

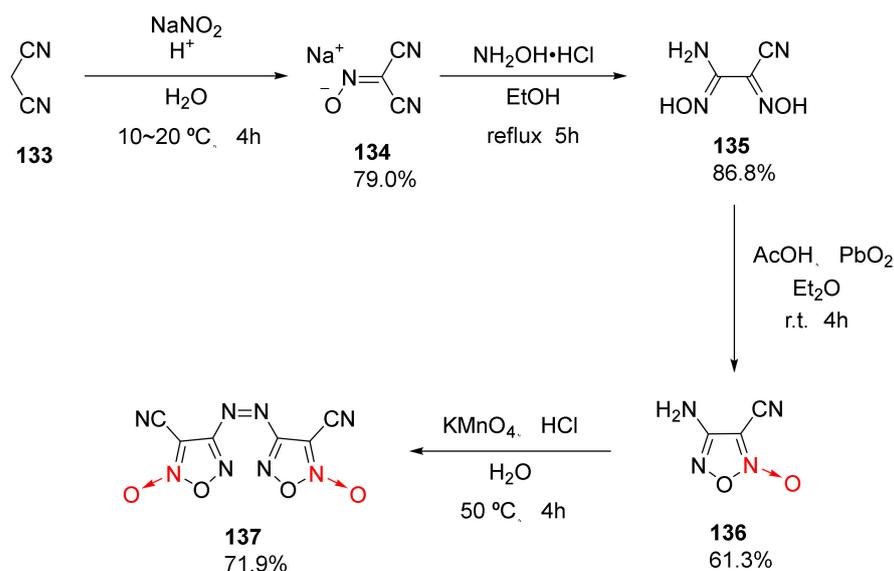


Scheme 23. Synthetic routes (a), (b) and (c) for DAPO.

2.2. Oxazole N-Oxide Energetic Compounds

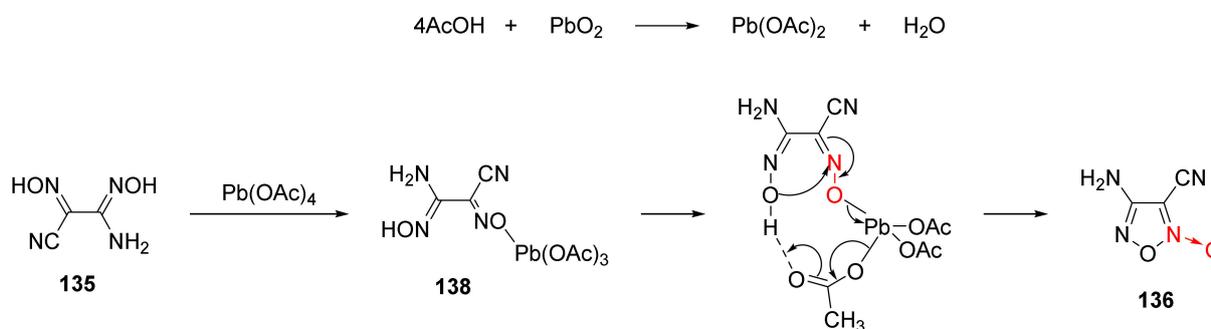
2.2.1. 1,2,5-Oxadiazole-2-Oxides

1,2,5-Oxadiazole-2-oxide is also called furoxan. Due to the coordinated oxygen atom on its ring, it has a unique “potential nitro” structure, and it can be used as an energetic group to effectively improve the detonation performance and energy density of compounds, thus attracting wide research interests. Using malondinitrile (**133**) as the starting material, 3,3'-dicyano-4,4'-azofuroxan was synthesized by Luo Yifen et al. [57] via nitrosation, NH_2OH addition, and PbO_2 and KMnO_4 secondary oxidation. The four-step reaction had a yield of 30.2% (Scheme 24).



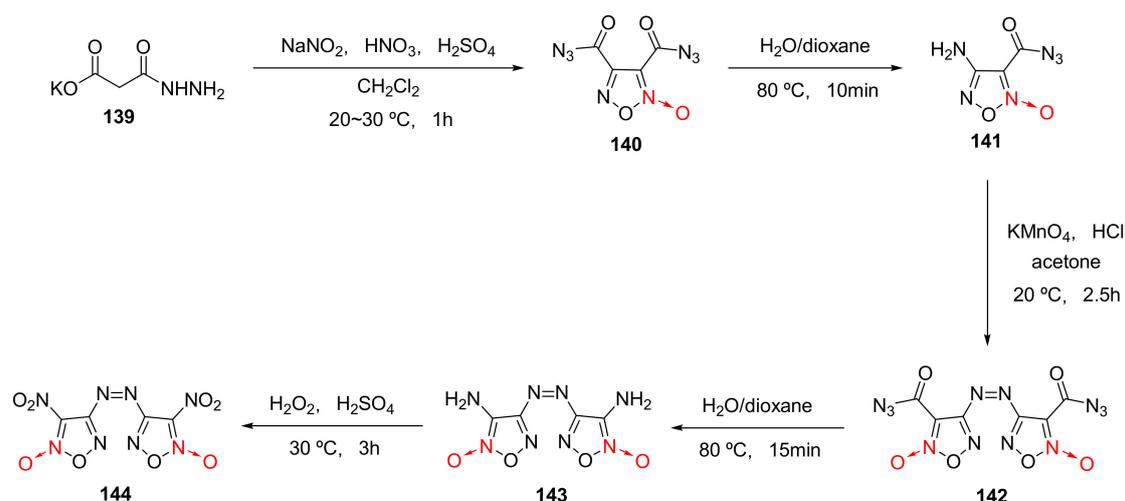
Scheme 24. Synthetic route for compound **137**.

The oxidation-cyclization mechanism under the action of lead peroxide was analyzed [57] as follows (Scheme 25). First, lead peroxide reacted with acetic acid to obtain lead tetraacetate. Then, the hydroxyl in compound **135** reacted with lead tetraacetate to obtain intermediate **138**. Under the action of the intramolecular hydrogen bond, intermediate **138** experienced intramolecular coupling and intramolecular electron transfer via a macrocyclic transition state. Compound **136** was obtained by the cyclization reaction after removing a molecule of lead acetate and a molecule of acetic acid.



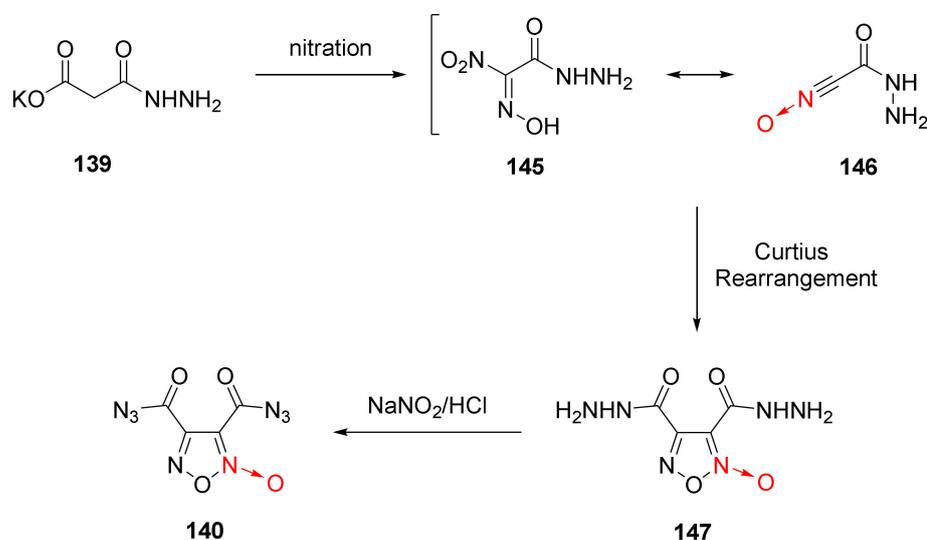
Scheme 25. Possible synthetic route for compound **136**.

Using malonyl monohydrazide monopotassium salt (**139**) as the raw material, dinitroazofurazan (**144**) was synthesized by nitrosation-nitration, first hydrolysis, oxidative coupling, second hydrolysis and oxidation [58] (Scheme 26). Dinitroazofurazan has a density as high as 2.002 g/cm³ and a measured detonation velocity of 10 km/s. Such characteristics as high density and high detonation velocity make it an important component for energetic composite solid propellants.



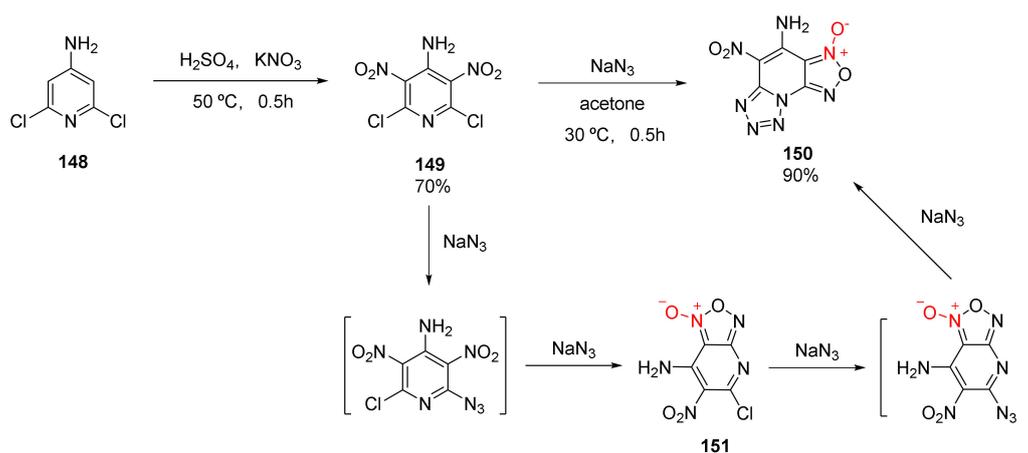
Scheme 26. Synthetic route for compound **144**.

The reaction mechanism of compound **140** was discussed as follows [58] (Scheme 27). Compound **139** was first nitrated to produce intermediate **145** with a resonance structure **146**. The intermolecular hydrogen bond of compound **146** increased the stability of the compound. After Curtius rearrangement, compound **147** was generated. The hydrazido group in compound **147** was transformed into an azido group after nitrosation to obtain compound **140**.



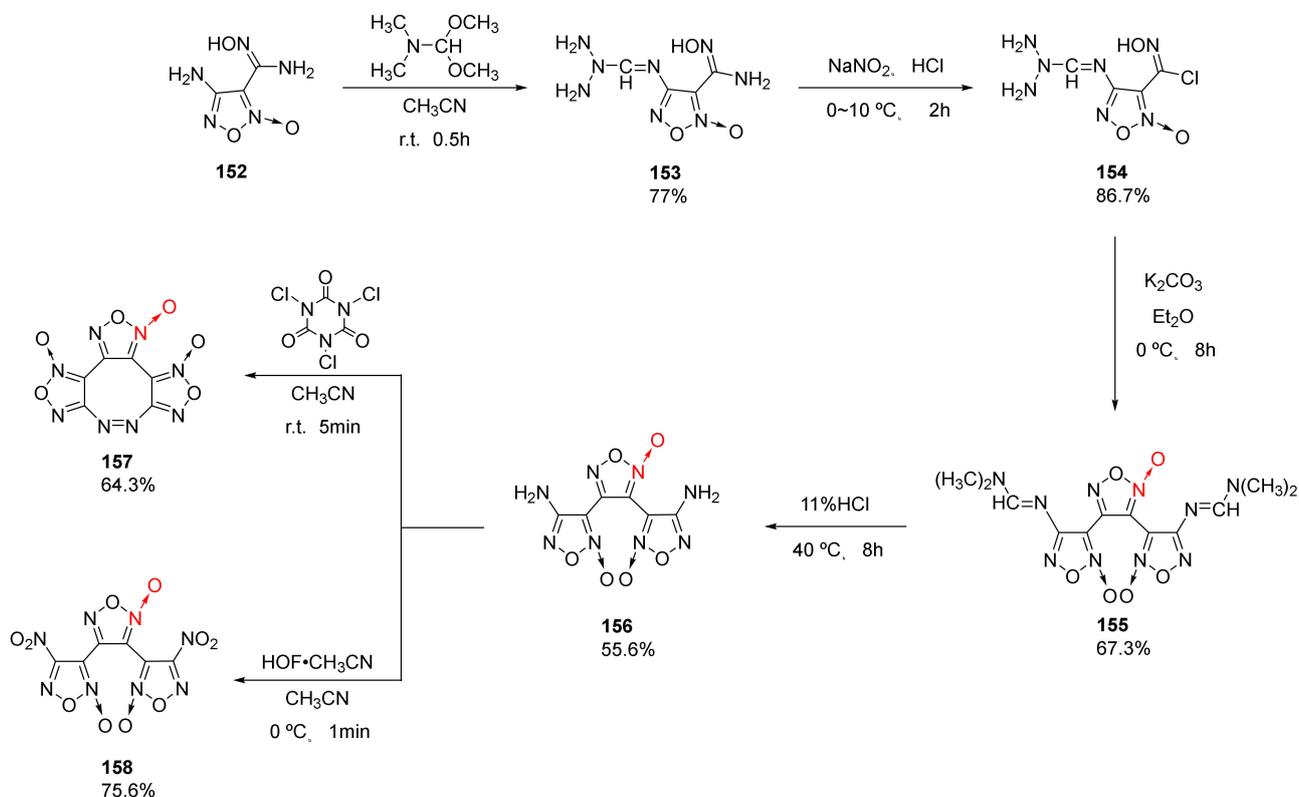
Scheme 27. Synthetic route for compound **140**.

Ma et al. synthesized a fused ring energetic compound 4-amino-5-nitro-1,2,5-oxadiazolo [3,4-e]tetrazolo [1,5-a]pyridine-3-oxide (**150**) from industrial 4-amino-2,6-dichloropyridine (**148**) via two steps, nitration and substitution-cyclization [59] (Scheme 28). The existence of compound **151** could be detected during the second step of the reaction, indicating that the azide group was not introduced into the pyridine ring at one time but was divided into two steps. The first introduced azide group was cyclized with a nitro group and a molecule of N_2 was removed to generate compound **151**. After the second azide group was introduced, the tautomerization of azide-tetrazole occurred due to the electron deficiency of the pyridine ring, resulting in compound **150**. With a density of 1.921 g/cm^3 , a calculated detonation velocity of 8838 m/s , and a detonation pressure of 36.01 GPa , compound **150** could be an energetic material with an excellent detonation performance.



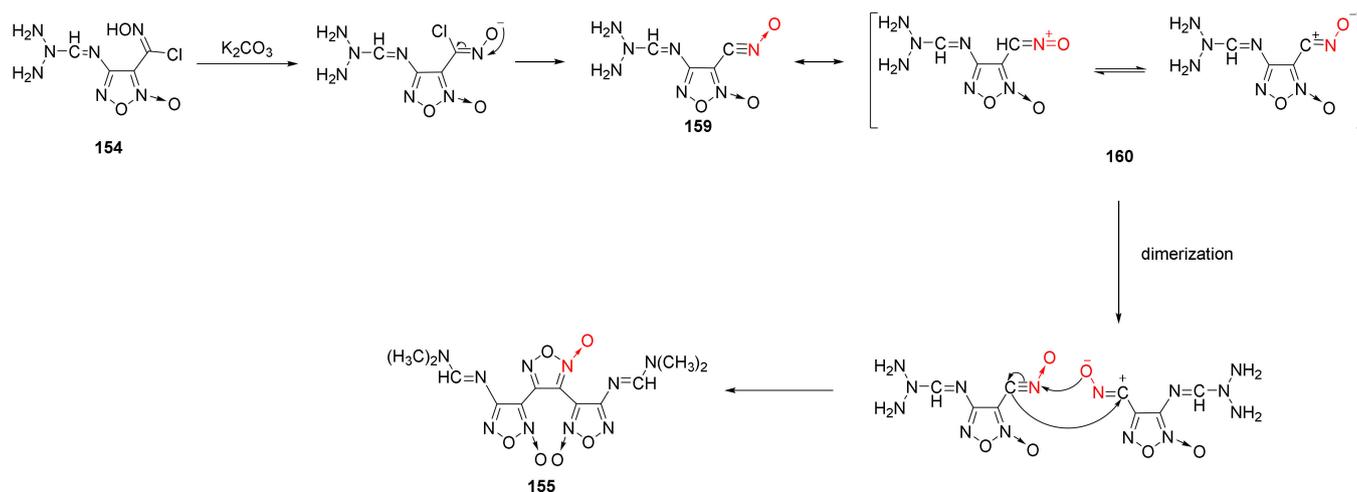
Scheme 28. Synthetic route for compound 150.

Using 4-amino-3-amidoximo furoxan(**152**) as a starting material, 3,4-bis(4'-aminofuroxan-3'-yl)furoxan(**156**) ($\rho = 1.787\text{ g/cm}^3$, $D = 8480\text{ m/s}$, $P = 31.0\text{ GPa}$) was synthesized by He et al. [60] via amino protection, diazotization-chlorination, intermolecular condensation cyclization, and hydrolysis. Then, compounds **157** ($\rho = 1.895\text{ g/cm}^3$, $D = 9417\text{ m/s}$, $P = 39.6\text{ GPa}$), and **158** ($\rho = 1.914\text{ g/cm}^3$, $D = 9503\text{ m/s}$, $P = 40.8\text{ GPa}$) were obtained through oxidative coupling or oxidation (Scheme 29). The three compounds show good detonation performance and energy density. Compound **158** exhibit a positive oxygen balance (OB = +18.6%) with good detonation performance, and its sensitivity ($IS = 3\text{ J}$, $FS = 40\text{ N}$) is close to that of CL-20. Due to its outstanding properties, it could be used as an energetic component in solid rocket propellants.



Scheme 29. Synthetic routes for compounds 156–158.

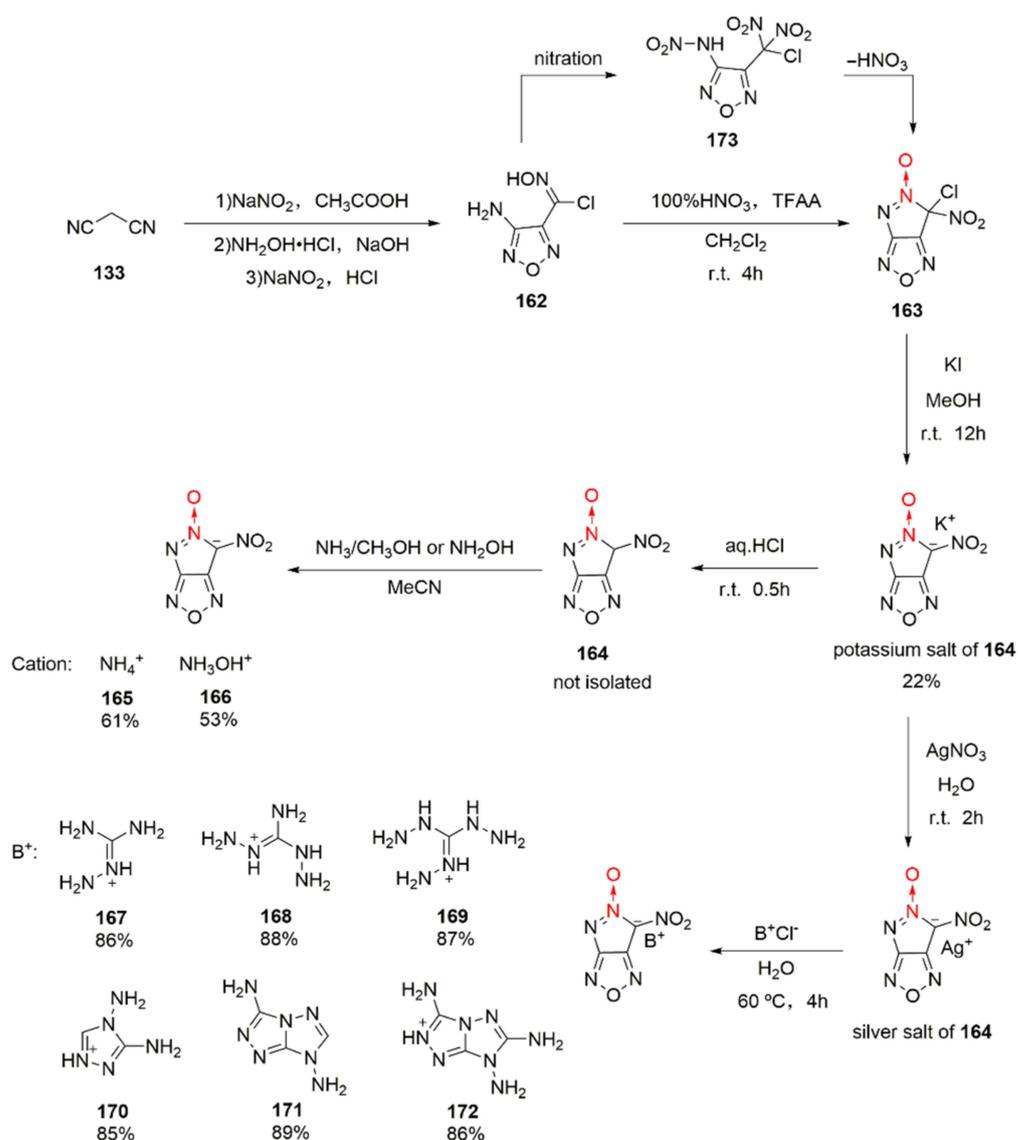
Using on-line infrared technology to monitor the synthesis of 3,4-bis(4'-aminofuroxan-3'-yl)furoxan, Sun Kunlun et al. observed the infrared spectrum of the pure substance of the intermediate component produced in the reaction to deduce the reasonable reaction mechanism of furoxan construction from chloro-oxime via dimerization and cyclization [61] (Scheme 30). Under alkaline conditions, the O–H bond and C–Cl bond of the chloro-oxime group broke and removed a molecule of HCl. Then, intramolecular electron transfer was carried out to obtain intermediate **159**. As the reaction progressed, intermediate **159** generated the resonance structure of intermediate **160**, which was dimerized with intermediate **159** to obtain product **156**.



Scheme 30. Synthetic route for compound **155**.

2.2.2. Pyrazole-1-Oxide

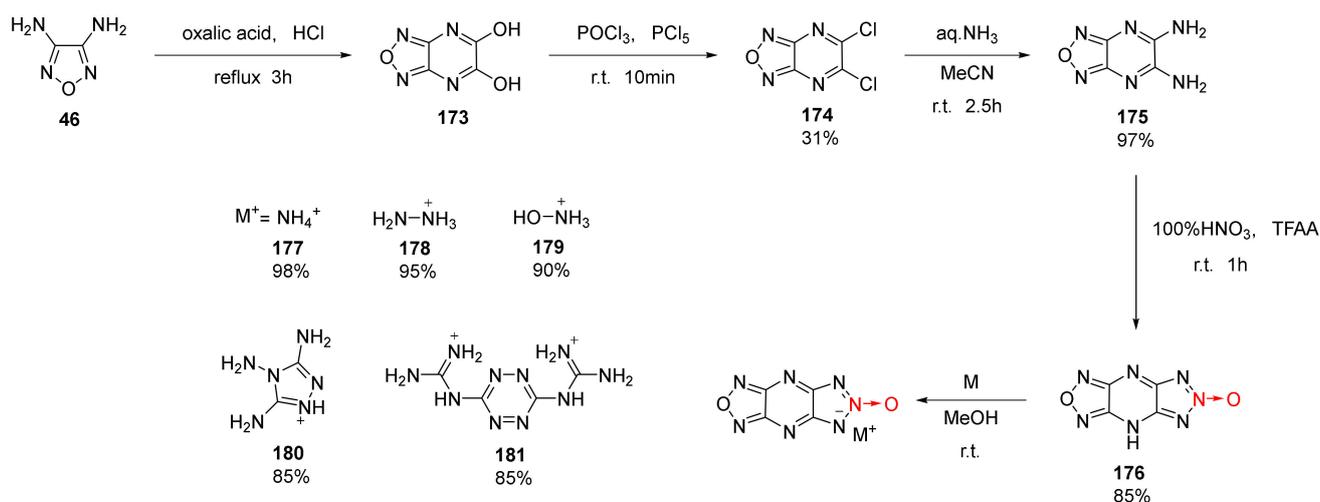
4-Amino-3-chlorooximofurazan (**162**) can be oxidized to be the dipotassium salt of 3-dinitromethyl-4-nitroaminofurazan. Yet, when Li et al. used this synthetic approach, the potassium salt of 6-nitro-pyrazolo [3,4-c]furoxan-5-oxide (**164**) was accidentally isolated [62]. This unique reaction process was thoroughly studied by Tang et al., [63]. Using malonic nitrile as the starting material, 4-amino-razan-3-chlorooxime (**162**) was obtained by three steps, namely nitration, addition, and cyclization. Then, the 100% HNO₃/TFAA system was used for nitration. Compound **162** was first nitrated to be intermediate **173** during nitration, and intermediate **173** experienced an intramolecular electron transfer to remove HNO₃ for generating compound **163**. Compound **163** was dissolved in methanol and was ion-exchanged with KI to obtain the potassium salt of compound **164**. Based on the reaction characteristics of **164**, a series of energetic ionic salts (**165–172**) were designed and synthesized by the neutralization or ion exchange method (Scheme 31). Through theoretical calculation and experimental measurement, the potassium salt of compound **164** was found as high as 2.036 g/cm³, the sensitivity of compound **172** was satisfying (*IS* = 20 J, *FS* = 360 N), and the calculated detonation velocity and detonation pressure of hydroxylaminium salt (**166**) were the highest among the products (9174 m/s and 39.1 GPa). The hydroxylaminium salt **166** with high sensitivity (*IS* = 2 J, *FS* = 40 N) also has potential for becoming a green primary explosive.



Scheme 31. Synthetic routes for energetic salts 165–172.

2.2.3. Triazole-1-Oxides

The synthesis of 1,2,3-Triazolo [4,5-e]fuzano [3,4-b]pyrazine-6-oxide (177) and its energetic ionic salts (179–183) was reported by Thottempudi et al. [64]. Using 3,4-diaminofurazan (46) as the starting material, diaminofurazano [3,4-b]pyrazine 175 was obtained by a three-step process of condensation-cyclization, chlorination, and ammoniation. Then, triazole-1-oxide (176) was synthesized using the nitration-cyclization of HNO₃/TFAA. Due to the acidity of compound 176, a series of energetic ionic salts (177–181) were synthesized by the neutralization reaction with a yield ranging between 85% and 98% (Scheme 32). Compound 176 and ionic salts 177–181 display outstanding energy density and detonation properties (Table 3). Moreover, these compounds exhibit extremely low impact sensitivity, making them suitable for insensitive explosives.

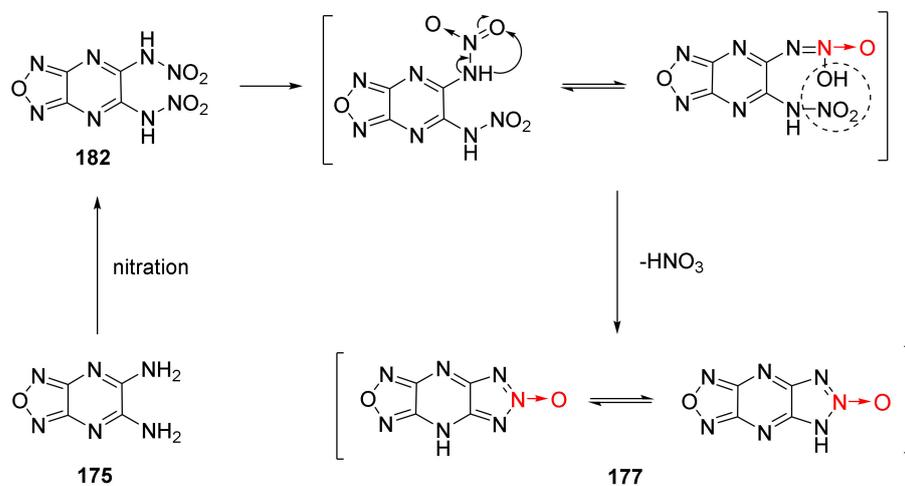


Scheme 32. Synthetic routes for compounds 177–181.

Table 3. Physical and detonation properties of compounds 177–181.

| Compound | $\rho/g\cdot cm^{-3}$ | $D/m\cdot s^{-1}$ | P/GPa | IS/J | $T_d/^\circ C$ |
|-----------|-----------------------|-------------------|-------|------|----------------|
| 176 | 1.85 | 8532 | 32.4 | 32 | 281 |
| 177 | 1.73 | 8079 | 26.3 | >40 | 270 |
| 178 | 1.76 | 8378 | 30.0 | 38 | 141 |
| 179 | 1.74 | 8518 | 30.3 | 35 | 157 |
| 180 | 1.70 | 7972 | 25.0 | >40 | 274 |
| 181 | 1.69 | 7871 | 24.0 | >40 | 301 |
| TNT [63] | 1.65 | 6881 | 19.5 | 15 | 295 |
| PETN [63] | 1.77 | 8564 | 31.3 | 5 | 150 |

Li Yanan et al. discussed the nitration-cyclization reaction mechanism of triazole-1-oxide **175** in 100% HNO_3 /TFAA system [65] (Scheme 33). Two nitro groups in compound **175** were first converted into nitroamino groups through nitration to obtain intermediate **182**. One nitroamino group in intermediate **182** was rearranged into a hydroxyoxyazo group, and the rearranged intermediate **182** was stripped of a molecule of HNO_3 to produce compound **177**.



Scheme 33. Synthetic route for compound 177.

3. Conclusions

N-oxides can be synthesized by either direct N-oxidation or cyclization with N→O coordination bonds. As for the second approach, the N→O coordination bonds in energetic N-oxides could be introduced into the cyclization process, avoiding the pollution of the N-oxidation reaction, shortening the synthetic route, and improving efficiency. In this study, the synthetic methods towards two kinds of N-oxides (nine energetic N-oxides) are introduced in detail. The reaction mechanisms towards cyclization reaction are also discussed to clarify the formation of N→O coordination bonds. The physicochemical properties and detonation performances of typical N-oxides are also introduced, laying a foundation for future applications.

The synthesis of N-oxides by cyclization is one of the most important directions of energetic materials. At present, the industrialized manufacturing process of heat-resistant explosive LLM-105 has been found based on its synthetic method. With improved synthetic methods and technological advancements, new N-oxides with excellent performance are expected to emerge, and the manufacturing process for more N-oxide energetic materials will be improved to meet the need of mass production.

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References

1. Gao, H.X.; Shreeve, J.M. Azole-based energetic salts. *Chem. Rev.* **2011**, *111*, 7377–7436. [[CrossRef](#)] [[PubMed](#)]
2. Badgujar, D.M.; Talawar, M.B.; Asthana, S.N.; Mahulikar, P.P. Advances in science and technology of modern energetic materials: An overview. *J. Hazard. Mater.* **2008**, *151*, 289–305. [[CrossRef](#)] [[PubMed](#)]
3. Wang, Y.; Liu, Y.; Song, S.W.; Yang, Z.J.; Qi, X.J.; Wang, K.C.; Liu, Y.; Zhang, Q.H.; Tian, Y. Accelerating the discovery of insensitive high-energy-density materials by a materials genome approach. *Nat. Commun.* **2018**, *9*, 2444. [[CrossRef](#)]
4. Tang, Y.X.; Kumar, D.; Shreeve, J.M. Balancing excellent performance and high thermal stability in a dinitropyrazole fused 1,2,3,4-tetrazine. *J. Am. Chem. Soc.* **2017**, *139*, 13684–13687. [[CrossRef](#)] [[PubMed](#)]
5. Zhai, L.J.; Bi, F.Q.; Huo, H.; Luo, Y.F.; Li, X.Z.; Chen, S.P.; Wang, B.Z. The ingenious synthesis of a nitro-free insensitive high-energy material featuring face-to-face and edge-to-face π -interactions. *Front. Chem.* **2019**, *7*, 559. [[CrossRef](#)] [[PubMed](#)]
6. Huo, H.; Zhang, J.L.; Dong, J.; Zhai, L.J.; Guo, T.; Wang, Z.J.; Bi, F.Q.; Wang, B.Z. A promising insensitive energetic material based on a fluorodinitromethyl explosophore group and 1,2,3,4-tetrahydro-1,3,5-triazine: Synthesis, crystal structure and performance. *RSC Adv.* **2020**, *10*, 11816–11822. [[CrossRef](#)]
7. Xu, Y.G.; Shen, C.; Lin, Q.H.; Wang, P.C.; Jiang, C.; Lu, M. 1-Nitro-2-trinitromethyl substituted imidazoles: A new family of high performance energetic materials. *J. Mater. Chem. A* **2020**, *4*, 17791–17800. [[CrossRef](#)]
8. Barton, L.M.; Edwards, J.T.; Johnson, E.C.; Bukowski, E.J.; Sausa, R.C.; Byrd, E.F.C.; Orlicki, J.A.; Sabatini, J.J.; Baran, P.S. Impact of stereo- and regiochemistry on energetic materials. *J. Am. Chem. Soc.* **2019**, *141*, 12531–12535. [[CrossRef](#)] [[PubMed](#)]
9. Ma, H.X.; Chen, X.; Zhang, C.; Zheng, W.W.; Tian, H.W.; Bai, Y. Research on the S-Tetrazine-based Energetic Compounds. *Chin. J. Explos. Propellants* **2021**, *44*, 407–419. (In Chinese)
10. Han, Y.Z.; Yang, Y.Z.; Du, Z.M.; Zhang, Y.H.; Yao, Q. Progress of Study on Thermal Behaviors of Nitrogen-rich Compounds as Azole, Triazine and Furazan. *Chin. J. Explos. Propellants* **2016**, *39*, 1–11. (In Chinese)
11. Liu, Y.; Gong, L.S.; Yi, X.Y.; He, P.; Zhang, J.G. Tunable 1,2,3-triazole-N-oxides towards high energy density materials: Theoretical insight into structure-property correlations. *New J. Chem.* **2022**, *46*, 11741–11750. [[CrossRef](#)]
12. Tang, Y.X.; Zhang, J.H.; Mitchell, L.A.; Parrish, D.A.; Shreeve, J.M. Taming of 3, 4-Di(nitramino)furazan. *J. Am. Chem. Soc.* **2015**, *137*, 15984–15987. [[CrossRef](#)] [[PubMed](#)]
13. Chavez, D.; Klapötke, T.M.; Parrish, D.; Piercey, D.G.; Stierstorfer, J. The Synthesis and Energetic Properties of 3, 4-Bis(2,2,2-trinitroethylamino)furazan (BTNEDAF). *Propellants Explos. Pyrotech.* **2010**, *35*, 1–9. [[CrossRef](#)]
14. Li, J.; Ma, Q.; Tang, S.H.; Fan, G.J. Crystal Structure and Thermal Decomposition Properties of *N,N'*-Bis(2-fluoro-2,2'-dinitroethyl)-3,4'-dinitraminefurazan. *Chin. J. Energ. Mater.* **2019**, *27*, 41–46. (In Chinese)
15. Xiao, X.; Ge, Z.X.; Wang, W.; Liu, Q.; Su, H.P.; Li, T.Q.; Bi, F.Q.; Ji, X.T. Progress of 3-Azido-1,2,4-Triazole and Its Derivatives. *Chin. J. Energ. Mater.* **2014**, *22*, 100–107. (In Chinese)

16. Lai, Y.; Liu, Y.; Huang, W.; Zeng, Z.Z.; Yang, H.W.; Tang, Y.X. Synthesis and Characterization of Pyrazole- and Imidazole- Derived Energetic Compounds Featuring Ortho Azido/nitro Groups. *FirePhysChem* **2022**, *2*, 160–164. [[CrossRef](#)]
17. Wu, B.; Yang, L.F.; Zhai, D.D.; Ma, G.M.; Pei, C.H. Facile Synthesis of 4-Amino-3,5-dinitropyrazolated Energetic Derivatives via 4-Bromopyrazole and Their Performances. *FirePhysChem* **2021**, *1*, 76–82. [[CrossRef](#)]
18. Vishnevskiy, Y.V.; Tikhonov, D.S.; Schwabedissen, J.; Stammler, H.G.; Moll, R.; Krumm, B.; Klapötke, T.M.; Mitzel, N.W. Tetranitromethane: A nightmare of molecular flexibility in the gaseous and solid States. *Angew. Chem. Int. Edit.* **2017**, *56*, 9619–9623. [[CrossRef](#)]
19. Zhai, L.J.; Zhang, J.L.; Zhang, J.R.; Wu, M.J.; Bi, F.Q.; Wang, B.Z. Progress in Synthesis and Properties of High Energy Density Compounds Regulated by N-F Bond. *Chin. J. Org. Chem.* **2020**, *40*, 1484–1501. (In Chinese) [[CrossRef](#)]
20. Zhou, J.; Zhang, J.L.; Wang, B.Z.; Qiu, L.L.; Xu, R.Q.; Sheremete, A.B. Recent Synthetic Efforts towards High Energy Density Materials: How to Design High-Performance Energetic Structures? *FirePhysChem* **2022**, *2*, 83–139. [[CrossRef](#)]
21. Yuan, J.; Long, X.P.; Zhang, C.Y. Influence of N-Oxide Introduction on the Stability of Nitrogen-Rich Heteroaromatic Rings: A Quantum Chemical Study. *J. Phys. Chem. A* **2016**, *120*, 9446–9457. [[CrossRef](#)] [[PubMed](#)]
22. Politzer, P.; Lane, P.; Murray, J.S. Computational analysis of relative stabilities of polyazine N-oxides. *Struct. Chem.* **2013**, *24*, 1965–1974. [[CrossRef](#)]
23. Lai, W.P.; Lian, P.; Ge, Z.X.; Liu, Y.Z.; Yu, T.; Lv, J. Theoretical study of the effect of N-oxides on the performances of energetic compounds. *J. Mol. Model.* **2016**, *22*, 1–11. [[CrossRef](#)] [[PubMed](#)]
24. Liu, S.; Shi, W.; Wang, Y.; Zhang, Q.H. Research Progress of Nitrogen-rich Fused-ring N-oxides. *Chin. J. Energ. Mater.* **2021**, *29*, 567–578. (In Chinese)
25. Zhu, J.P.; Ren, J.; Han, X.Y.; Li, Y.X.; Wang, J.L.; Cao, R.L. Study on Structures and Detonation Performance for Polynitropyrazine-N-oxides by Density Functional Theory. *Chin. J. Explos. Propellants* **2010**, *33*, 47–51. (In Chinese)
26. Churakov, A.M.; Ioffe, S.L.; Strelenko, Y.A.; Tartakovskii, V.A. 1,2,3,4-tetrazine 1,3-dioxides—a new class of heterocyclic compounds. *Bull. Acad. Sci. USSR Div. Chem. Sci.* **1990**, *39*, 639–640. [[CrossRef](#)]
27. Bi, F.Q.; Wang, B.Z.; Li, X.Z.; Fan, X.Z.; Xu, C.; Ge, Z.X. Progress in the Energetic Materials Based on 1,2,3,4-Tetrazine 1,3-Dioxid. *Chin. J. Energ. Mater.* **2012**, *20*, 630–637. (In Chinese)
28. Klapötke, T.M.; Piercey, D.G.; Stierstorfer, J.; Weyrauther, M. The Synthesis and Energetic Properties of 5,7-Dinitrobenzo-1,2,3,4-tetrazine-1,3-dioxide (DNBTDO). *Propellants Explos. Pyrotech.* **2012**, *37*, 527–535. [[CrossRef](#)]
29. Christie, K.O.; Dixon, D.A.; Vasiliu, M.; Wagner, R.I.; Haiges, R.; Boatz, J.A.; Ammon, H.L. Are DTTO and iso-DTTO Worthwhile Targets for Synthesis? *Propellants Explos. Pyrotech.* **2015**, *40*, 463–468. [[CrossRef](#)]
30. Khakimov, D.V.; Dzyabchenko, A.V.; Pivina, T.S. Computer simulation of the crystal structure of tetrazino-tetrazine tetraoxide (TTTO) isomers with one and two independent molecules in the unit cell. *Russ. Chem. Bull.* **2020**, *69*, 212–217. [[CrossRef](#)]
31. Mendoza-Cortes, J.L.; An, Q.; Goddard, W.A., III; Ye, C.; Zybin, S. Prediction of the crystal packing of di-tetrazine-tetroxide (DTTO) energetic material. *J. Comput. Chem.* **2016**, *37*, 163–167. [[CrossRef](#)] [[PubMed](#)]
32. Song, X.L.; Li, J.C.; Hou, H.; Wang, B.S. Extensive theoretical studies of a new energetic material: Tetrazino-tetrazine-tetraoxide (TTTO). *J. Comput. Chem.* **2009**, *30*, 1816–1820. [[CrossRef](#)]
33. Klenov, M.S.; Guskov, A.A.; Anikin, O.V.; Churakov, A.M.; Strelenko, Y.A.; Fedyanin, I.V.; Lyssenko, K.A.; Tartakovsky, V.A. Synthesis of Tetrazino-tetrazine 1,3,6,8-Tetraoxide (TTTO). *Angew. Chem. Int. Ed.* **2016**, *55*, 11472–11475. [[CrossRef](#)] [[PubMed](#)]
34. Frumkin, A.E.; Churakov, A.M.; Strelenko, Y.A.; Tartakovsky, V.A. Synthesis of 1,2,3,4-tetrazino[5, 6-g]benzo-1,2,3,4-tetrazine-1,3,7,9-tetraoxides. *Russ. Chem. Bull.* **2006**, *55*, 1654–1658. [[CrossRef](#)]
35. Frumkin, A.E.; Churakov, A.M.; Strelenko, Y.A.; Kachala, V.V.; Tartakovsky, V.A. Synthesis of 1,2,3,4-Tetrazino[5, 6-f]benzo-1,2,3,4-tetrazine-1,3,7,9-Tetra-N-oxides. *Org. Lett.* **1999**, *1*, 721–724. [[CrossRef](#)]
36. Churakov, A.M.; Loffe, S.L.; Tartakovsky, V.A. Synthesis of [1,2,5]Oxadiazolo [3,4-e][1,2,3,4]tetrazine-4,6-Di-N-oxide. *Mendeleev Commun.* **1995**, *6*, 227–228. [[CrossRef](#)]
37. Dong, L.L.; Zhang, G.Q.; Chi, Y.; Fan, G.J.; He, L.; Tao, G.H.; Huang, M. Synthesis of Furazano[3,4-e]-1,2,3,4-tetrazine-1,3-dioxide. *Chin. J. Energ. Mater.* **2012**, *20*, 690–692. (In Chinese)
38. Zelenov, V.P.; Lobanova, A.A.; Sysolyatin, S.V.; Sevodina, N.V. New syntheses of [1,2,5]oxadiazolo[3,4-e][1,2,3,4]tetrazine 4,6-dioxide. *Russ. J. Org. Chem.* **2013**, *49*, 455–465. [[CrossRef](#)]
39. Li, X.Z.; Wang, B.Z.; Li, H.; Li, Y.A.; Bi, F.Q.; Huo, H.H.; Fan, X.Z. Novel Synthetic Route and Characterization of [1,2,5]oxadiazolo-[3,4-e][1,2,3,4]tetrazine 4,6-Di-N-oxide (FTDO). *Chin. J. Org. Chem.* **2012**, *32*, 1975–1980. [[CrossRef](#)]
40. Voronin, A.A.; Zelenov, V.P.; Churakov, A.M.; Strelenko, Y.A.; Tartakovsky, V.A. Alkylation of 1-hydroxy-1H-[1,2,3]triazolo[4,5-e][1,2,3,4]tetrazine 5,7-dioxide. *Russ. Chem. Bull.* **2014**, *63*, 475–479. [[CrossRef](#)]
41. Voronin, A.A.; Zelenov, V.P.; Churakov, A.M.; Strelenko, Y.A.; Fedyanin, I.V.; Tartakovsky, V.A. Synthesis of 1,2,3,4-tetrazine 1,3-dioxides annulated with 1,2,3-triazoles and 1,2,3-triazole 1-oxides. *Tetrahedron* **2014**, *70*, 3018–3022. [[CrossRef](#)]
42. Wang, T.Y.; Zheng, C.M.; Liu, Y.; Gong, X.D.; Xia, M.Z. Theoretical studies of the structure, stability, and detonation properties of vicinal-tetrazine 1,3-dioxide annulated with a five-membered heterocycle. 1. Annulation with a triazole ring. *J. Mol. Model.* **2015**, *21*, 1–9.
43. Shvets, A.O.; Konnov, A.A.; Klenov, M.S.; Churakov, A.M.; Strelenko, Y.A.; Tartakovsky, V.A. Synthesis of 2-(6-nitrobenzofuroxan-4-yl)-2H-[1,2,3]triazolo-[4,5-e][1,2,3,4]tetrazine 4,6-dioxide. *Russ. Chem. Bull.* **2020**, *69*, 739–741. [[CrossRef](#)]

44. Bian, C.M.; Dong, X.; Zhang, X.H.; Zhou, Z.M.; Zhang, M.; Li, C. The unique synthesis and energetic properties of a novel fused heterocycle: 7-nitro-4-oxo-4, 8-dihydro-[1,2,4]triazolo[5,1-d][1,2,3,5]tetrazine 2-oxide and its energetic salts. *J. Mater. Chem. A* **2015**, *3*, 3594–3601. [[CrossRef](#)]
45. Zhou, Z.M.; Bian, C.M. Energetic ionic salts of 7-nitryl-4-ketone-4,8-dihydro-[1,2,4]triazole[5,1-d][1,2,3,5]tetrazine-2-oxide and preparation method of energetic ionic salt. CN Patent 104447762, 25 March 2015. (In Chinese)
46. Zhao, B.J.; Wang, P.P.; Fu, W.; Li, C.; Zhou, Z.M. High Density of a New Fused Heterocycle: 7,8-Dinitro-4-oxo-4,6-dihydropyrazolo[5,1-d][1,2,3,5]tetrazine 2-oxide and Its Energetic Salts. *ChemistrySelect* **2018**, *3*, 4797–4803. [[CrossRef](#)]
47. Lei, C.J.; Cheng, G.B.; Yi, Z.X.; Zhang, Q.H.; Yang, H.W. A facile strategy for synthesizing promising pyrazole-fused energetic compounds. *Chem. Eng. J.* **2021**, *416*, 129190. [[CrossRef](#)]
48. Tang, Y.X.; Imler, G.H.; Parrish, D.A.; Shreeve, J.M. Energetic and fluorescent azole-fused 4-amino-1,2,3-triazine-3-N-oxides. *ACS Appl. Energy Mater.* **2019**, *2*, 8871–8877. [[CrossRef](#)]
49. Deng, M.C.; Feng, Y.G.; Zhang, W.Q.; Qi, X.J.; Zhang, Q.H. A green metal-free fused-ring initiating substance. *Nat. Commun.* **2019**, *10*, 1339. [[CrossRef](#)]
50. Deng, M.C.; Feng, Y.A.; Zhang, Q.H. Green environmental protection type primary explosive and preparation method thereof. CN Patent 108752349, 11 June 2018. (In Chinese)
51. Ogurtsov, V.A.; Dorovatovskii, P.V.; Zubavichus, Y.V.; Khrustalev, V.N.; Fakhrutdinov, A.N.; Zlotin, S.G.; Rakitin, O.A. [1,2,5]Oxadiazolo[3,4-d]pyridazine 1,5,6-trioxides: Efficient synthesis via the reaction of 3,4-bis(hydroxyimino)methyl-1,2,5-oxadiazole 2-oxides with a mixture of concentrated nitric and trifluoroacetic acids and structural characterization. *Tetrahedron Lett.* **2018**, *59*, 3143–3146. [[CrossRef](#)]
52. Liu, Y.G.; Huang, Z.; Yu, X.J. Progress of research of new insensitive energetic material LLM-105. *Expl. Shock Wave* **2004**, *24*, 465–469. (In Chinese)
53. Jing, S.M.; Liu, Y.C.; Yuan, J.M. New Synthesis of LLM-105 and Experimental Study of Replacement Process. *Initiat. Pyrotech.* **2012**, *2*, 34–36. (In Chinese)
54. Zhao, X.F.; Liu, Z.L.; Yao, Q.Z.; Chen, J.; Dong, Y. Synthesis of 2,6-Diamino-3,5-dinitropyrazine-1-oxide. *Chin. J. Explos. Propellants* **2012**, *35*, 15–17. (In Chinese) [[CrossRef](#)]
55. Wang, J.M.; Du, Y. Optimization of Synthetic Method of 2,6-Diamino-pyrazine-1-oxide. *Chin. J. Explos. Propellants* **2017**, *40*, 25–27. (In Chinese)
56. Li, Y.H.; Wang, Y.; Liao, L.Y.; Guo, Z.C.; Chen, L.P.; Wu, W.Q. Thermal Risk Analysis Based on Reaction Mechanism: Application to the 2,6-Diaminopyrazine-1-oxide Synthesis Process. *Org. Process Res. Dev.* **2021**, *25*, 849–857. [[CrossRef](#)]
57. Luo, Y.F.; Ma, L.; Wang, B.Z.; Zhou, Y.S.; Huo, H.; Jia, S.Y. Synthesis and Characterization of 3,3'-Dicyano-4,4'-azofuroxan. *Chin. J. Energ. Mater.* **2010**, *18*, 538–540. (In Chinese)
58. He, J.X.; Lu, Y.H.; Lei, Q.; Cao, Y.L. Synthesis and Properties of High Energetic Compound 3,3'-Dinitro-4,4'-azofuroxan. *Chin. J. Energ. Mater.* **2011**, *34*, 9–12. (In Chinese)
59. Ma, C.M.; Pan, Y.; Jiang, J.C.; Liu, Z.L.; Yao, Q.Z. Synthesis and thermal behavior of a fused, tricyclic pyridine-based energetic material: 4-amino-5-nitro-[1,2,5]oxadiazolo[3,4-e]tetrazolo[1,5-a]pyridine-3-oxide. *New J. Chem.* **2018**, *42*, 11259–11263. [[CrossRef](#)]
60. He, C.L.; Gao, H.X.; Imler, G.H.; Parrish, D.A.; Shreeve, J.M. Boosting energetic performance by trimerizing furoxan. *J. Mater. Chem. A* **2018**, *6*, 9391–9396. [[CrossRef](#)]
61. Sun, K.L.; Wu, N.; Yang, H.; Yang, X.F.; Li, H. Independent Component Analysis Combined with On-line Infrared Spectroscopy for Researching the Synthesis Reaction Mechanism of 3,4'-Bis(4'-aminofurazano-3')furoxan. *Chem. J. Chin. Univ.* **2014**, *35*, 244–249. (In Chinese)
62. Li, Y.; Huang, H.F.; Shi, Y.M.; Yang, J.; Pan, R.M.; Lin, X.Y. Potassium nitraminofurazan derivatives: Potential green primary explosives with high energy and comparable low friction sensitivities. *Chem. Eur. J.* **2017**, *23*, 7353–7360. [[CrossRef](#)]
63. Tang, Y.X.; He, C.L.; Shreeve, J.M. A furazan-fused pyrazole N-oxide via unusual cyclization. *J. Mater. Chem. A* **2017**, *5*, 4314–4319. [[CrossRef](#)]
64. Thottempudi, V.; Yin, P.; Zhang, J.H.; Parrish, D.A.; Shreeve, J.M. 1,2,3-Triazolo [4,5-e]furazano[3,4-b]pyrazine 6-Oxide—A Fused Heterocycle with a Roving Hydrogen Forms a New Class of Insensitive Energetic Materials. *Chem. Eur. J.* **2014**, *20*, 542–548. [[CrossRef](#)]
65. Li, Y.N.; Hu, J.J.; Chen, T.; Wang, B.; Chang, P.; Wang, B.Z. Synthesis and Properties of 4-Amino-1,2,3-triazolo[4,5-e]furazano[3,4-b]pyrazine 6-oxide. *Chin. J. Energ. Mater.* **2020**, *28*, 664–669. (In Chinese)