

Synthesis, characterization, thermolysis and performance evaluation studies on alkali metal salts of TABA and NTO

P.B. Kulkarni, G.N. Purandare, J.K. Nair, M.B. Talawar*, T. Mukundan*, S.N. Asthana

High Energy Materials Research Laboratory (HEMRL), Pune 411021, India

Received 3 September 2004; received in revised form 13 December 2004; accepted 16 December 2004

Available online 25 January 2005

Abstract

The lithium (Li) and potassium (K) salts of 3-nitro-1,2,4-triazol-5-one (NTO) and 2,4,6-trinitroanilino benzoic acid (TABA) were prepared and characterized during this work. The synthesis was carried out by addition of a solution of lithium/potassium hydroxide to the aqueous solution of NTO and TABA, respectively. The products were characterized by elemental analysis, metal content determination and Fourier Transform Infrared (FTIR) Spectrum. Differential scanning calorimetry (DSC) profile indicated that Li and K salts of NTO and TABA undergo exothermic decomposition in the temperature range of 257–360 °C suggesting their energetic nature. The thermo gravimetric (TG) weight loss pattern revealed loss of water for Li/K salts of NTO and TABA in the temperature range of 115–155 °C. Sensitivity results revealed that the compounds are insensitive to impact and friction (impact sensitivity—height of 50% explosion > 170 cm and friction insensitivity up to 36 kg) stimuli despite even the parent molecule of NTO salts (NTO) being HEM in the hazard category of 1.1. The FTIR spectra of the gaseous products evolved during TGA of NTO and TABA salts indicated the release of NO₂. The formation of products such as LiNCO and KNCO was also observed in case of NTO salts, whereas that of CO₂ and NH containing products was indicated in case of TABA salts during this study. In order to assess the performance as energetic ballistic modifiers (EBMs), NTO and TABA salts were incorporated in the ammonium perchlorate-hydroxyl terminated polybutadiene (AP-HTPB) composite propellants. The potassium salts enhanced the burning rate of the propellant. The best catalytic effect was obtained with K-TABA salt, which increased the burning rate to the extent of ~81% as well as brought down the *n*-value to 0.15 (pressure 2–9 MPa).

© 2004 Elsevier B.V. All rights reserved.

Keywords: Energetic ballistic modifiers; Trinitroanilino benzoic acid; Nitrotriazolone, (NTO); Metal salts of NTO; Hazardous materials

1. Introduction

Problems associated with catastrophic mishaps and sympathetic detonations have made current explosives such as 2,4,6-trinitrotoluene (TNT), 1,3,5-trinitro hexahydro-s-triazine (RDX) and 1,3,5,7-tetranitro-1,3,5,7-tetrazocine (HMX) less attractive for specific applications, wherein the materials are subjected to extreme conditions while being transported or stored and used in operations. In this context, 3-nitro-1,2,4-triazol-5-one (NTO) has emerged as a potential high performance insensitive explosive, which is being ex-

plored as a substitute for RDX in munitions [1]. NTO is a unique high energy material (HEM), which despite belonging to UN hazard category of 1.1 is insensitive to most of the stimuli. The metal salts of NTO are reported [2] as potential primary explosives as well as ballistic modifiers [3]. They fit in the class of energetic ballistic modifiers (EBM), as they are envisaged to achieve the catalytic effect on burning rate without much adverse effect on the energetics of the propellants.

Owing to unique characteristic, EBMs are preferable to transition metal oxides and ferrocenes currently used as catalysts for improving the burning rate of composite propellants. Although, metal oxides like ferric oxide and copper chromite are highly effective ballistic modifiers, they impose a penalty on the energetics of propellant system due to inert nature.

* Corresponding authors. Tel.: +91 20 25869303; fax: +91 20 25869316.

E-mail addresses: mbtalawar@yahoo.com (M.B. Talawar), t.mukan@yahoo.com (T. Mukundan).

The ferrocene based ballistic modifiers offering high burn rate propellants, are beset with the additional problem of migration.

Synthesis of metal salts of NTO has been widely reported in the literature [2–5]. The acidic nature of NTO favours the formation of a large number of salts [6]. Transition metal salts of 2,4,6-trinitroanilinobenzoic acid (TABA) were found promising for double base system in the studies conducted by Pundlik et al. [7].

Authors of this paper have recently reported the evaluation of transition metal salts of NTO and TABA in composite propellant formulation [8]. In continuation of our work on EBMs, it was planned to examine the effect of addition of alkali metal salts of NTO and TABA in composite propellants. In addition to Li/K salts of NTO, the new Li/K salts of TABA were synthesized during this work. The compounds were characterized and subjected to sensitivity tests to assess their hazardous nature. The synthesized Li and K salts were subjected to thermal studies in simultaneous thermogravimetry cum differential thermal analyzer (SDTA) and differential scanning calorimetry (DSC). An attempt was made to characterize the decomposition products by FTIR coupled with TG. The burning rates of metal salts incorporated composite propellants were determined to assess their potential application in composite propellants.

2. Experimental

2.1. Synthesis

The starting materials of AR grade required for the synthesis of TABA and NTO salts were used as purchased from trade.

2.1.1. Synthesis of TABA salts

TABA was synthesized by refluxing picryl chloride with *p*-amino benzoic acid at 70–75 °C, on the lines of reported method [9]. TABA-IR spectrum (Perkin-Elmer FTIR-1600 spectrophotometer-KBr pellet) (Fig. 1) band at 3600 cm⁻¹ (O–H), 3380 cm⁻¹ (N–H), 1674 cm⁻¹ (C=O), 1534 cm⁻¹, 1348 cm⁻¹ (NO₂). DTA—*T*_i: 300 °C, *T*_{max}: 340 °C.

Alkali metal salts of TABA [Li(TABA)(H₂O)₂, K(TABA)(H₂O)₂] were prepared on the lines of the method established in HEMRL for transition metal salts [9,10] (Scheme 1). In order to obtain K-TABA, 0.56 g of (0.01 mol) KOH was dissolved in 15 cm³ of distilled water in a beaker. It was kept under stirring and heated up to 55–60 °C. Subsequently, 3.48 g (0.01 mol) of TABA was added to the above solution over a period of 15 min at 55–60 °C under continuous stirring. The reaction mixture was maintained at 55–60 °C for about 30 min. Subsequently, it was digested for 30 min and solvent was evaporated to dryness to obtain yellow coloured K salt of TABA. The product was washed successively with cold water as well as ethanol and dried at room temperature for 48 h. Yield of the

product was 90% (3.80 g). Li-TABA was also synthesized on the similar lines (yield: 3.47 g, 89%). The IR spectral assignments of the Li and K salts of TABA are presented in Table 1. IR spectra of TABA and the newly synthesized Li-TABA and K-TABA are given in Fig. 1.

2.1.2. Synthesis of NTO salts

NTO was synthesized by refluxing semicarbazide hydrochloride with formic acid to obtain triazolone followed by nitration with the nitric acid as per the reported method [11]. Yield was 80%. IR Spectrum (Perkin-Elmer 1600 spectrophotometer-KBr pellet) (Fig. 2) band at 3210 cm⁻¹ (N–H), 1716 cm⁻¹ (C=O), 1542 cm⁻¹, 1354 cm⁻¹ (NO₂), 1278 cm⁻¹ (N–H), 1010 cm⁻¹ (ring) and 730 cm⁻¹ (C–NO₂). DTA: 254 °C (initial temperature, *T*_i), *T*_{max}: 264 °C. DSC: *T*_i: 251 °C, *T*_{max}: 269 °C.

The [Li(NTO)(H₂O)₂ and K(NTO)(H₂O)] were prepared on the lines of the reported procedure [2] (Scheme 2). In order to obtain K-NTO, aqueous solution of NTO was stirred with potassium hydroxide to obtain dark yellow coloured K-NTO monohydrate salt. The yield of the product was 90% (33.5 g). Li-NTO was also synthesized similarly. Yield—89% (30.6 g). IR spectral assignments of the Li and K salts of NTO are presented in Table 1. IR spectra of NTO, Li-NTO and K-NTO are given in Fig. 2.

3. Characterization

3.1. Metal content and elemental analysis

An atomic absorption spectrophotometer (Chemito 2001) was used to determine the metal content of the salts. The elemental analysis was carried out on a Perkin-Elmer elemental analyzer (Model no. 240).

3.2. Spectral characterization

Structural features were confirmed by Fourier transform-infrared spectrophotometer (FTIR, Perkin-Elmer 1600).

3.3. Thermal studies

Thermal decomposition pattern of the salts was studied thermogravimetrically at a heating rate of 10 °C/min, using a thermal analysis system of Mettler Toledo make (TG/SDTA-8551) in nitrogen atmosphere (sample mass of ~1 mg). The gaseous decomposition products were characterized by FTIR (Bruker make—Equinox 55) in conjunction with TG. The DTA profiles were recorded using 1 mg sample by means of an in-house assembled differential thermal analyzer. DSC was recorded on Perkin-Elmer make (DSC-7) instrument under similar experimental conditions (heating rate of 10 °C/min and nitrogen atmosphere).

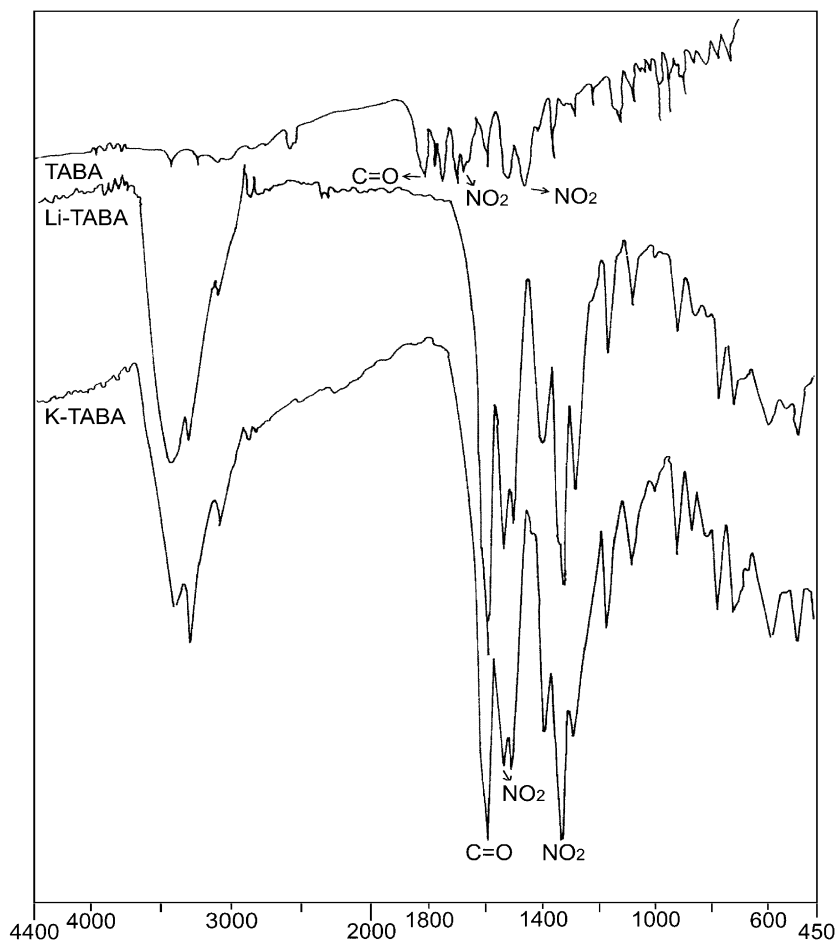
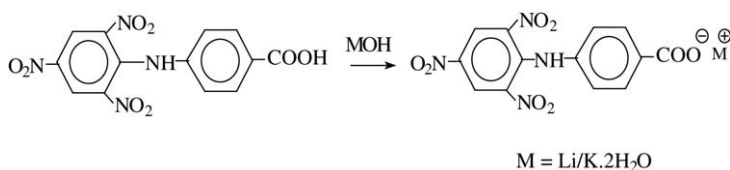


Fig. 1. IR spectra of TABA, Li-TABA and K-TABA.



Scheme 1. Synthesis of alkali metal salts of TABA.

Table 1
Characterization of salts of NTO and TABA

	Li-TABA	K-TABA	Li-NTO	K-NTO
Molecular formula	(C ₁₃ H ₇ N ₄ O ₈) ⁻ Li ⁺ 2H ₂ O	C ₁₃ H ₇ N ₄ O ₈) ⁻ K ⁺ 2H ₂ O	(C ₂ HN ₄ O ₃) ⁻ Li ⁺ 2H ₂ O	(C ₂ HN ₄ O ₃) ⁻ K ⁺ H ₂ O
Colour	Orange	Yellow	Faint yellow	Dark yellow
IR (cm ⁻¹) C=O	1600	1600	1634	1640
NO ₂	1542, 1334	1540, 1334	1516, 1316	1508, 1308
C–N	1408	1396	1385	1388
Metal content (%) ^a	1.77 (1.79)	9.10 (9.24)	3.86 (4.07)	21.6 (21.00)
Elemental C ^a	39.51 (40.00)	36.58 (36.96)	14.04 (13.95)	13.00 (12.90)
Analysis H	2.81 (2.82)	2.50 (2.60)	2.81 (2.91)	1.59 (1.61)
(%) N	14.21 (14.35)	13.43 (13.27)	32.60 (32.56)	30.45 (31.10)
Impact sensitivity height of 50% explosion (cm)			>170	
Friction sensitivity (kg)			>36	

^a The metal content and elemental analysis values given in bracket are theoretically calculated figures.

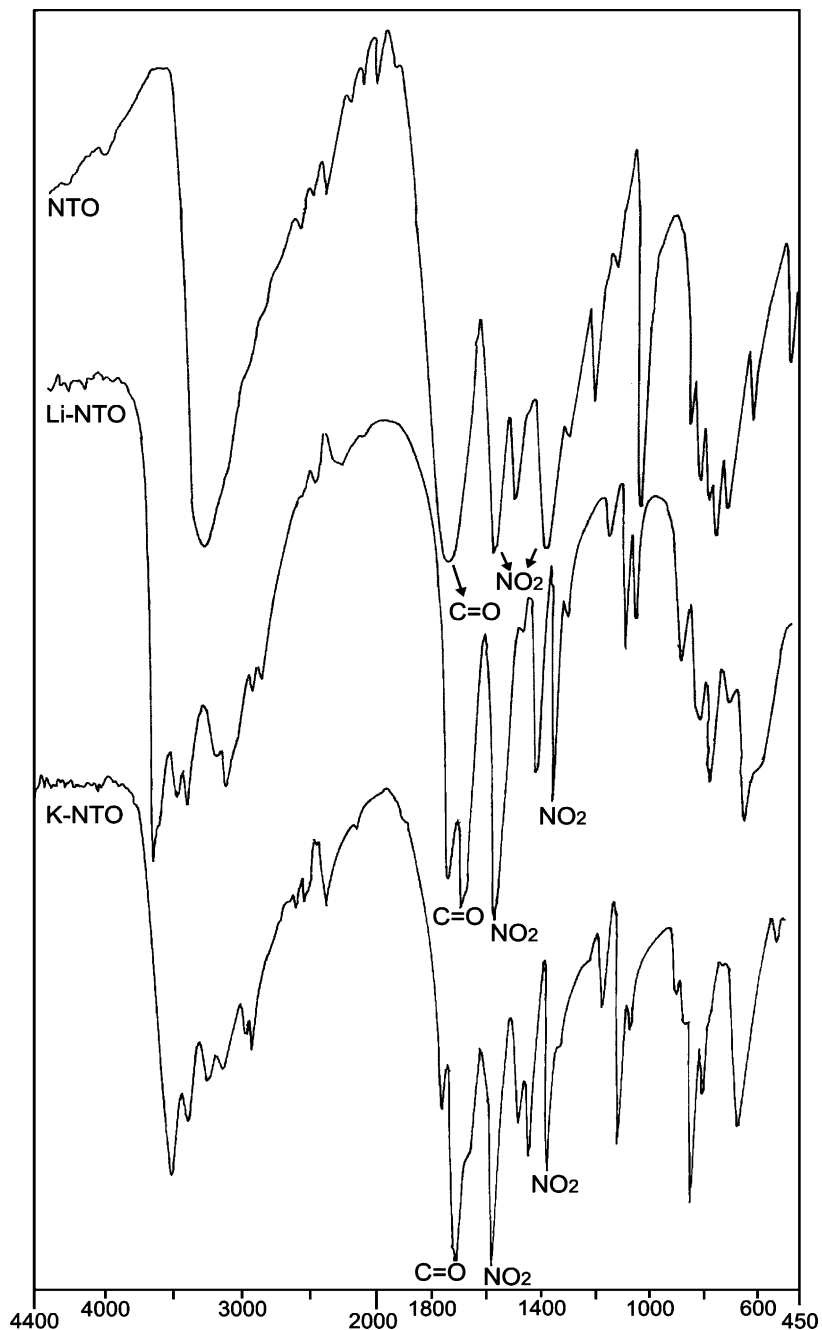


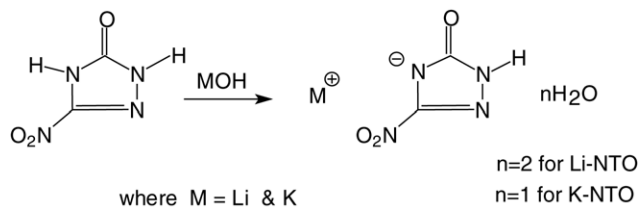
Fig. 2. IR spectra of NTO, Li-NTO and K-NTO.

3.4. Sensitivity characterization

The sensitivity of the synthesized compounds to impact stimuli was determined by applying standard Bruceton staircase method using a 2 kg drop weight and height for 50% probability of explosion ($h_{50\%}$) was determined statistically [12]. The figure of insensitivity (F of I) was computed by using tetryl (Composition Exploding-CE), as reference. The friction sensitivity of the compound was determined on a Julius Peters apparatus by incrementally increasing the load from 0.2 to 36 kg, till there was no ignition/explosion in five consecutive test samples.

3.5. Propellant formulation

Propellant compositions comprising 78% AP and 22% cross-linked polybutadiene binder along with two parts of



Scheme 2. Synthesis of alkali metal salts of NTO.

TABA/NTO salts over 100 parts of the composition (by weight) were prepared by slurry-cast technique [13]. Binder components sans curative [12% prepolymer-hydroxyl terminated polybutadiene (HTPB) and 8% plasticizer-dioctyl adipate (DOA) along with 0.3% processing aid-lecithin and 0.5% cross-linker cum antioxidant-pyrogallol] were added to a planetary mixer and heated to $55 \pm 3^\circ\text{C}$ by circulating water in its jacket oven. The contents were mixed for 20 min under vacuum (5–10 torr) for half an hour. AP [monomodal— $9\ \mu\text{m}$] was added to the binder in three installments and mixed for half an hour. Mixing was continued for an additional hour under vacuum (2–5 torr). The contents were allowed to cool to room temperature and the curative-toluene diisocyanate (TDI) was added (1.2%) in 1:1 (OH: NCO) stoichiometry with respect to HTPB. Final mixing was carried out for half an hour under vacuum (5–10 torr). The slurry was cast in evacuated mould (2–5 torr) and cured at 70°C for 8 days. HTPB (molecular weight, M_n 2200, hydroxyl value 42 mg KOH/g, functionality 2, viscosity < 70 Poises at 30°C) manufactured by NOCIL, India, was used for the present work.

The burning rates of the propellant were measured in a nitrogen pressurized (1.8–10.8 MPa) strand burner by sensing acoustics signals (transmitted through water) from deflagrating samples by piezoelectric transducer (resonance frequency 200 kHz) and recording the perturbation [14].

4. Results and discussion

4.1. Metal and C, H, N content

The experimentally determined metal and C, H, N contents (Table 1) of the salts were in close agreement with the theoretical values corresponding to the general formula of

$(\text{C}_{13}\text{H}_7\text{N}_4\text{O}_8)^- \text{M}^+ 2\text{H}_2\text{O}$ (where $\text{M} = \text{Li}, \text{K}$) for TABA salts and $(\text{C}_2\text{HN}_4\text{O}_3)^- \text{Li}^+ 2\text{H}_2\text{O}$ and $(\text{C}_2\text{HN}_4\text{O}_3)^- \text{K}^+ \text{H}_2\text{O}$ for NTO salts.

4.2. IR spectral analysis

The spectral patterns obtained for NTO and TABA are in close agreement with the reported data [1,9,10]. TABA displayed characteristic IR stretching frequency at 3600 and $1674\ \text{cm}^{-1}$ due to hydroxyl and carbonyl groups, respectively. The formation of Li/K salts of TABA was confirmed by the absence of $-\text{OH}$ frequency ($3600\ \text{cm}^{-1}$) and the negative shift in the carbonyl frequency from 1674 to $1600\ \text{cm}^{-1}$. The appearance of new IR bands at $500\text{--}600\ \text{cm}^{-1}$ may be attributed to $\text{O}^- \text{--} \text{M}^+$ linkage (Fig. 1)

In the metal salts of NTO (Fig. 2) negative shift in the $-\text{NO}_2$ absorption bands was observed. The carbonyl frequency also shifted from 1716 to $1634\text{--}1640\ \text{cm}^{-1}$ as in case of TABA salts (Table 1).

4.3. Thermal studies

Both the NTO and TABA salts underwent multistage decomposition.

4.3.1. $M(\text{NTO})(\text{H}_2\text{O})$ ($M = \text{Li}, \text{K}$)

The representative DSC result obtained for Li-NTO salt is depicted in Fig. 3 and TG results are given in Fig. 4. In DSC, Li-NTO salt exhibited two-stage decomposition. The first stage was endothermic, whereas exothermicity was observed in the second stage. The endotherm was recorded in the temperature range of $97\text{--}124^\circ\text{C}$ and the exotherm appeared in the temperature range of $270\text{--}320^\circ\text{C}$ with peak decomposition temperature (T_{max}) at 295°C . In TG, weight loss

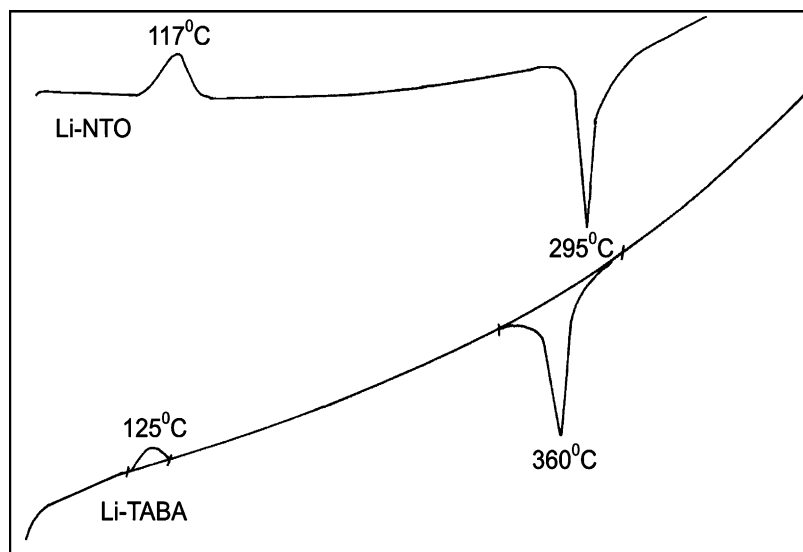


Fig. 3. DSC of Li-TABA and Li-NTO.

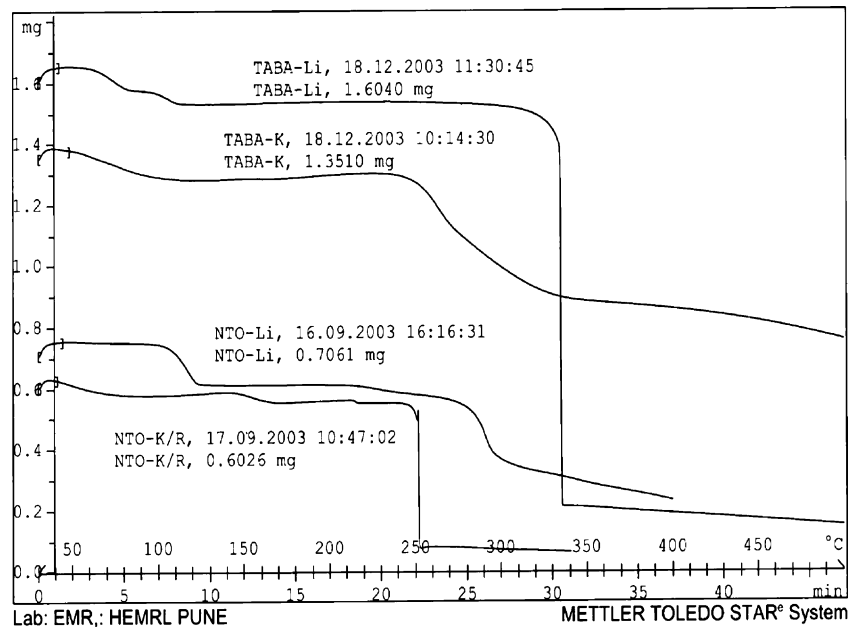


Fig. 4. TG of NTO and TABA salts.

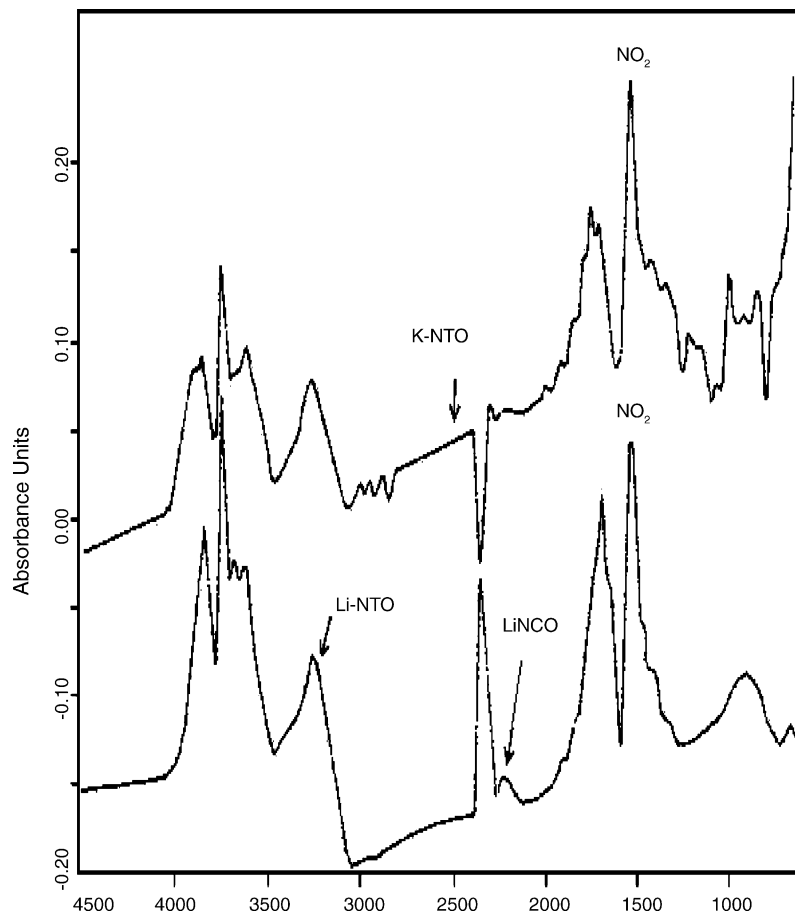


Fig. 5. TG-FTIR of NTO salts.

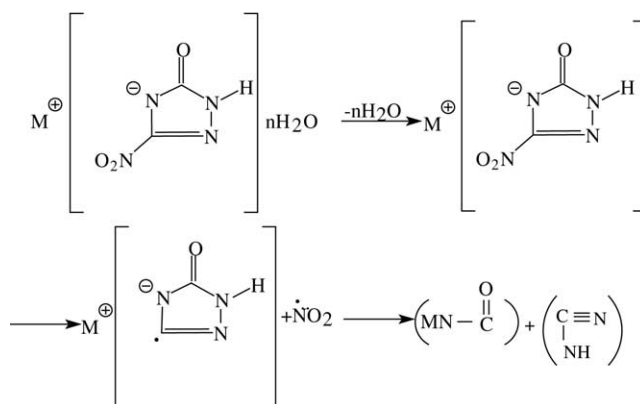
corresponding to DSC endotherm was 20%, which can be co-related with the loss of two water molecules. The weight loss recorded in the second stage corresponding to exotherm in DSC was 36%.

K-NTO exhibited three-stage decomposition in DSC. The first and second stages were endothermic and occurred almost consecutively in the temperature range of 135–180 and 180–200 °C, respectively. The exothermic decomposition was exhibited in the third stage in the temperature range of 247–268 °C with T_{\max} at 257 °C. The total weight loss of 9% observed in the TG corresponding to endothermic stages in DSC, is in close agreement with the calculated loss of water molecules. The weight loss corresponding to DSC exotherm amounted to 78% and occurred in the temperature range of 241–260 °C with maxima at 251 °C.

The FTIR spectra of the decomposition products of NTO salts obtained during TG are given in Fig. 5. The gaseous products exhibited absorption bands attributable to NO_2 group at 1516 and 1312 cm^{-1} . The FTIR spectra also exhibited bands at 2239 and 2200 cm^{-1} suggesting the formation of LiNCO and KNCO, respectively (Scheme 3). This is in line with the decomposition pattern of NTO salts reported by Brill [15]. They observed sharp absorbing modes in IR spectra of gaseous products of Li-NTO and K-NTO at 2254 and 2185 cm^{-1} , respectively.

4.3.2. $M(\text{TABA})(\text{H}_2\text{O})$ ($M = \text{Li}, \text{K}$)

The representative DSC result obtained for Li-TABA salt is depicted in Fig. 3 and TG results are given in Fig. 4. In DSC,



Scheme 3. Decomposition pattern of metal salts of NTO.

both Li and K salts of TABA exhibited two-stage decomposition. The first endothermic decomposition occurred in the temperature range of 115–140 °C. The second exothermic stage was observed in the temperature range of 330–400 °C for Li-TABA with T_{\max} at 360 °C, whereas K-TABA, exhibited exothermic decomposition in the temperature range of 250–350 °C with T_{\max} at 274 °C. In TG, Li and K salts of TABA showed a weight loss of 8–9% corresponding to the endotherm in DSC, which can be accounted for the loss of water molecules. The weight loss corresponding to exotherm in DSC was 81% for Li TABA in the temperature range of 300–370 °C and 31% for K-TABA in the temperature range of 210–360 °C.

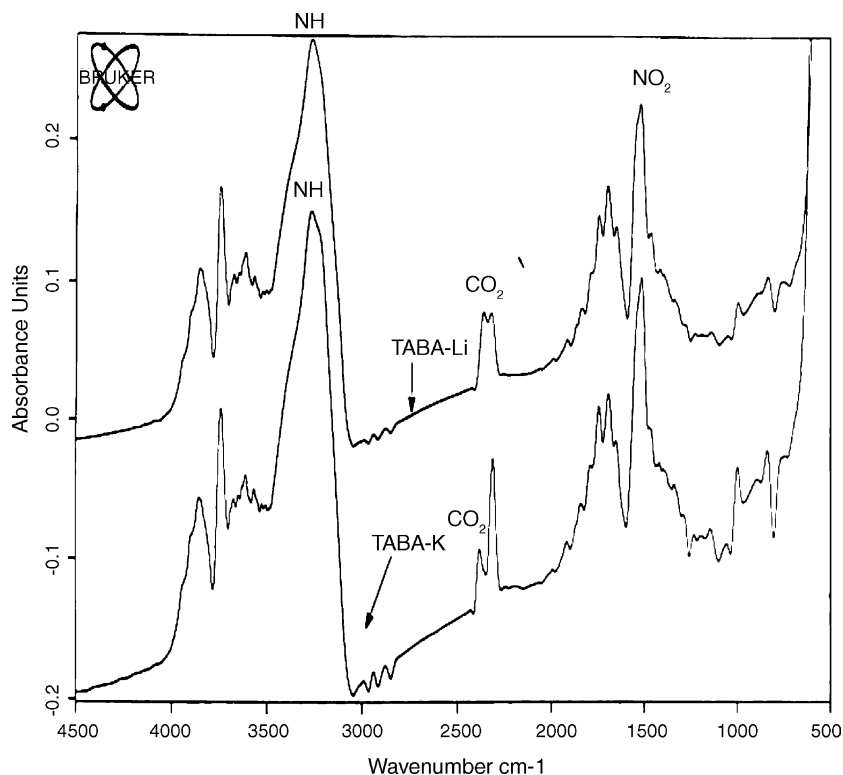


Fig. 6. TG-FTIR of TABA salts.

The FTIR spectrum (Fig. 6) of the decomposition products of the alkali metal salts of TABA also exhibited peaks corresponding to NO_2 (1517 cm^{-1}). In addition, IR bands corresponding to CO_2 (2377 cm^{-1}) and NH (3266 cm^{-1}) containing species were also observed. Formation of CO_2 might have occurred due to decomposition of COO^- group as reported earlier [8].

4.4. Sensitivity studies

The results of sensitivity tests are given in Table 1. Sensitivity test results revealed that the Li/K salts of NTO and TABA are insensitive to mechanical stimuli (impact sensitivity $h_{50\%} > 170\text{ cm}$ and friction insensitive up to 36 kg). However, the exothermic nature of the Li/K salts of NTO and TABA suggests their susceptibility to thermal hazards, entailing that these salts need to be handled by highly skilled HEMs chemists/scientists during their synthesis, characterization, scale up, storage, transport and evaluation. The unplanned accidental initiation of these materials can cause explosion.

4.5. Propellant formulation

The results of the burning rates of propellant formulations are given in Table 2. The influence of TABA and NTO salts on the burning rates of AP-HTPB composite propellant was determined in the pressure range of 2–9 MPa. Li-NTO incorporated propellant did not undergo sustained combustion in the experimental set up and Li-TABA did not exhibit any remarkable effect on the burning rates of control. On the other hand, K salts exhibited positive catalytic effect. Although, K-NTO enhanced the burning rates merely to the extent of 2–12% in the pressure range of 3–9 MPa, K-TABA produced 40–81% burn rate enhancement effect in the entire pressure region studied. The burning rates obtained for the K-

Table 2
Catalytic effect on burning rates of composite propellants

Composition	Burning rate (mm/s)					n (2–9 MPa)
	2 ^a	3 ^a	5 ^a	7 ^a	9 ^a	
Control	5.3	6.2	7.1	7.9	8.9	0.33
Control + Li-TABA (2 parts)	5.4	6.1	7.1	8.0	9.1	0.34
Control + K-TABA (2 parts)	9.6	10.2	10.9	11.1	12.4	0.15
Control + K-NTO (2 parts)	5.3	6.6	9.1	10.0	10.0	0.41
Control + Li-NTO (2 parts)	Extinguished					

Control: AP—78%, HTPB binder—22%, n : pressure index.

^a Pressure (MPa).

Table 3
DSC results of ballistically modified AP-HTPB propellants

Composition	Peak temperature ($^{\circ}\text{C}$)		
	Endo	Exo I	Exo II
Control	248	345	397
Control + Li-TABA (2 parts)	242	357	–
Control + K-TABA (2 parts)	242	334	–
Control + K-NTO (2 parts)	243	341	–

TABA incorporated composite propellant were of the order of 9.6–12.4 mm/s in the pressure range of 2–9 MPa compared to those of 5.3–8.9 mm/s for control. It also brought down the pressure exponent of burning rate (n) to 0.15 from 0.33 (control). This is an interesting observation, as alkali metal salts are widely known as burning rate suppressants [16,17].

NTO salts incorporated propellant formulations were also subjected to DSC studies (Table 3 and Fig. 7). In DSC, the control propellant exhibited an endotherm at $248\text{ }^{\circ}\text{C}$ followed by two exotherms with peak decomposition temperature

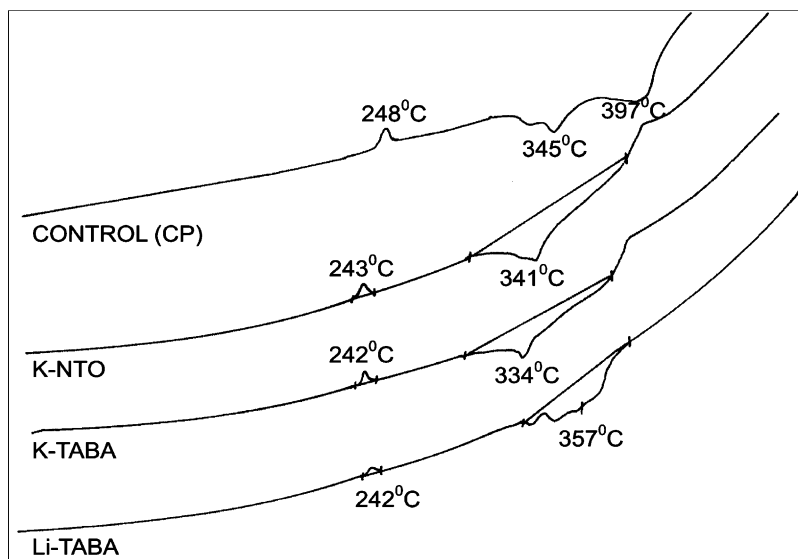


Fig. 7. DSC of NTO and TABA salts incorporated propellant.

(T_{\max}) at 345 and 397 °C. These trends are in line with those well reported for AP in the literature [18]. The incorporation of K-NTO and K-TABA (Fig. 7) led to decrease in peak decomposition temperature of the exotherm suggesting their catalytic effect on the decomposition process in condensed/near surface gas phase of the propellant. The effect was relatively more pronounced with K-TABA (decrease by 11 °C). The relative shift in T_{\max} may be correlated with their overall catalytic effect of K-TABA and K-NTO salts on the burning rates of the composite propellants studied during this work.

5. Conclusions

Two new alkali (Li and K) metal salts of 2,4,6-trinitroanilino benzoic acid (TABA) have been synthesized and characterized in the present study on the lines of the methodology established in HEMRL. Li and K salts of NTO were synthesized on the lines of the reported procedure. Impact and friction sensitivity results of the synthesized salts revealed their insensitive nature towards mechanical stimuli. However, thermolysis indicated the exothermic decomposition in the temperature range of 257–360 °C. The burning rate studies on the alkali metal salt incorporated AP-HTPB composite propellant revealed a potential role of K salt of NTO and TABA as energetic ballistic modifiers in composite propellants. K-TABA salt was found superior in this regard in view of its remarkable effect on burning rate enhancement and reduction in pressure index value. K-TABA has more pronounced catalytic effect on decomposition of the propellant.

References

- [1] T. Mukundan, G.N. Purandare, J.K. Nair, S.M. Pansare, R.K. Sinha, H. Singh, *Defence Sci. J.* 52 (2002) 127.
- [2] Matthew W. Smith, Matthew D. Cliff, *NTO-Based Explosive Formulations: A Technology Review*, DSTO-TR-0796 March 1999.
- [3] G. Singh, S.P. Felix, *J. Hazard. Mater.* 90 (2002) 1.
- [4] Z. Tonglai, H. Rongzu, L. Fuping, Preparation, characterization and thermal decomposition mechanisms of metal salts of 3-Nitro-1,2,4-triazol-5-one, in: O. Yuxiang (Ed.), *Beijing International Symposium on Pyrotechnics and Explosives*, Beijing, China, 3rd ed., China Ordnance Society, Beijing, China, 1995, pp. 303–306.
- [5] Z. Tonglai, H. Rongzu, L. Yanjun, L. Fuping, *J. Therm. Anal.* 39 (1993) 827.
- [6] G. Singh, I.P.S. Kapoor, S.P. Felix, *Propellants, Explosives, Pyrotechnics* 27 (2002) 16.
- [7] S.M. Pundalik, R.S. Palaiah, J.K. Nair, T. Mukundan, S.N. Singh, H. Singh, *J. Energ. Mater.* 19 (2001) 339.
- [8] P.B. Kulkarni, T.S. Reddy, J.K. Nair, A.N. Nazare, M.B. Talawar, T. Mukundan, S.N. Asthana, *Studies on the thermal decomposition and catalytic effect of energetic ballistic modifiers: TABA and NTO salts*, Technical Report, HEMRL/EMR/TR/2004/4.
- [9] R.S. Palaiah, N.R. Bulakh, M.B. Talawar, T. Mukundan, *J. Energ. Mater.* 18 (2000) 207.
- [10] J.K. Nair, M.B. Talawar, T. Mukundan, *J. Energ. Mater.* 19 (2001) 155.
- [11] A. Becuwe, A. Delclos, *Propellants, Explosives, Pyrotechnics* 18 (1993) 1.
- [12] I. Arvani, R. Hutchinson, *The Sensitivity of Impact and Friction in Energetic Materials 2, Technology of the Inorganic Azide*, Plenum Press, New York, 1977, pp. 111–1589.
- [13] W.N. Christiansen, *AIAA/SAE*, in: *Fourteenth Joint Propulsion Conference*, Las Vegas, 1978, pp. 25–27.
- [14] L. An-Fang, A new method for measurement of burning rates of propellants and explosives—method of constant pressure in closed bomb, in: *Proceedings of the Nineteenth International Annual Conference of ICT on Combustion and Detonation Phenomenon*, 1988, pp. 49.1–49.11.
- [15] T.B. Brill, T.L. Zhang, B.C. Tappan, *Combust. Flame* 121 (2000) 662.
- [16] M. Shorr, Alfred Zachrinor, *Solid Rocket Technology*, John Wiley and Sons, New York, 1967.
- [17] Kenneth K. Kuo, M. Summerfield, *Fundamentals of Solid Rocket Combustion*, 1984, p. 106.
- [18] K. Kishore, G. Prasad, *Defence Sci. J.* 29 (1979) 39.