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Hydroxylammonium nitrate: synthesis, cocrystals, and properties

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Hydroxylammonium nitrate (HAN) is a high-performing, less-toxic alternative to hydrazine in liquid propellants. HAN also possesses many desirable qualities for use as an oxidizer in solid propellant formulations, where a chlorine-free replacement for ammonium perchlorate is urgently required; however, the extreme hygroscopicity of HAN precludes it from consideration for this role. Ionic cocrystallization, the combination of a salt and a neutral molecular solid within a crystal lattice, is demonstrated here to overcome this limitation for the first time. Solid HAN, synthesized *via* salt metathesis in ethanol and purified *via* sublimation, provides an ideal starting point for cocrystallization. Melt fusion at 50 °C readily generated the first examples of HAN cocrystals. The cocrystals feature dramatically reduced hygroscopicity, stabilizing HAN against ambient moisture for the first time. Three of nine cocrystals were formed between HAN and molecules with proposed or realized applications in propellants or explosives, and these possess calculated specific impulse and detonation velocity exceeding those of both HAN and the respective cofomer molecules.

Introduction

In liquid rocket propellants, hydrazine and its derivatives are widely used for in-space monopropellant propulsion systems as well as certain in-atmosphere bipropellant launch vehicles.¹ However, these compounds pose severe health hazards (acute and chronic) upon exposure,^{2,3} eliciting substantial research promoting less hazardous “green” replacement fuels.^{4–6} Hydroxylammonium nitrate (HAN) (Fig. 1) has received significant attention as an alternative to hydrazine in the next generation of liquid propellants thanks to its increased oxygen content and reduced toxicity.^{7,8} HAN has been applied for in-space propulsion^{9–11} and is being investigated as an oxidizer in electrically ignited gelled propellant formulations.^{12,13} Parallel to the search for less hazardous liquid propellants, a similar search is ongoing in the realm of solid propellants where toxic and environmentally damaging ammonium perchlorate (AP) continues to reign as the state-of-the-art oxidizer.^{14–16} In spite of its strong qualifications as a component in liquid propellants, oxygen content on-par with AP and existing production infrastructure in the United States, HAN has yet to become a serious contender as an AP replacement in composite formulations. HAN is almost categorically

disqualified for its extreme hygroscopicity, which is such that it deliquesces (forms a solution with atmospheric moisture) nearly immediately at ambient conditions. Further, the solid-state properties of HAN are poorly studied in general,¹⁷ especially in comparison to other proposed AP alternatives including ammonium nitrate (AN) and ammonium dinitramide (ADN).^{18–21}

Maturing HAN to the point of serious consideration as a composite propellant component requires overcoming its hygroscopicity and establishing the ground-level characterization required for safety evaluation of the solid form. Towards the former, ionic cocrystallization (the combination of a salt and a neutral molecular solid in a crystal lattice) has been established as an effective route for reducing the hygroscopicity of oxidizing salts.^{22,23} With respect to the latter, the hazards and

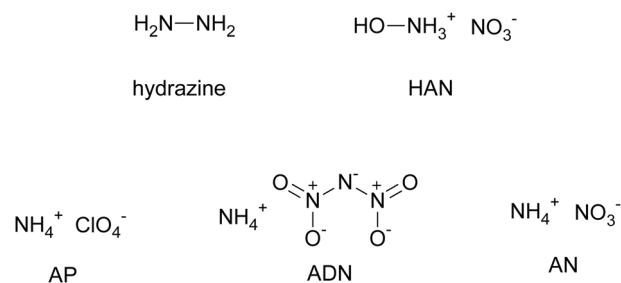


Fig. 1 Chemical structures of hydrazine and oxidizing salts: hydroxylammonium nitrate (HAN), ammonium perchlorate (AP), ammonium dinitramide (ADN), and ammonium nitrate (AN).

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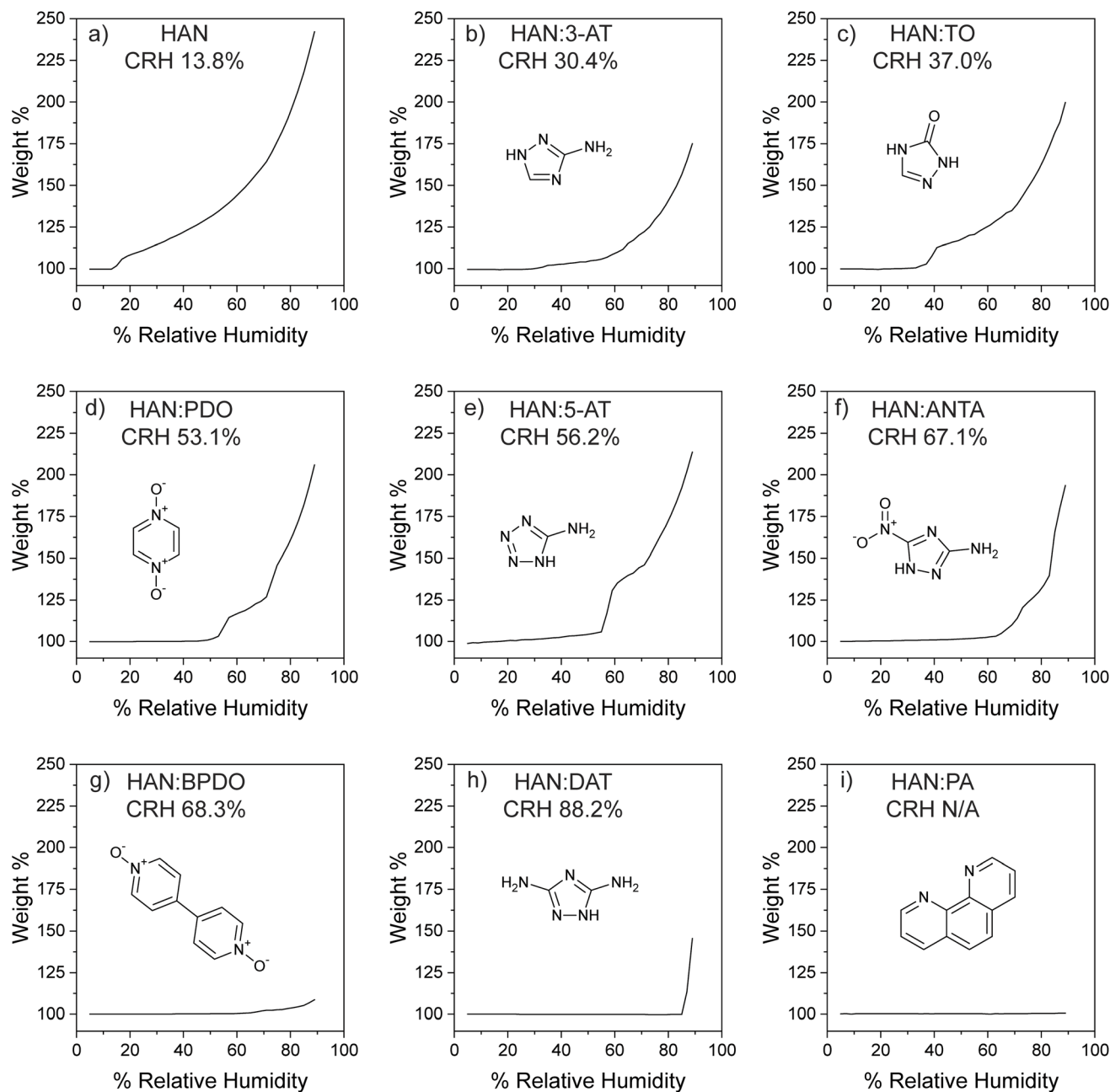


Fig. 4 DVS plots of (a) HAN, and the cococrystals (b) HAN:3-AT, (c) HAN:TO, (d) HAN:PDO, (e) HAN:5-AT, (f) HAN:ANTA, (g) HAN:BPDO, (h) HAN:DAT, and (i) HAN:PA.

chloride, barium sulfate and calcium sulfate have negligible vapor pressure^{32,33} and should remain as solid residue during sublimation, especially with the gentle conditions employed in this work.

The severe hygroscopicity of pure HAN precludes its use in traditional composite propellants and is a significant impediment to research on the properties of its anhydrous form. Cococrystallization has been shown to reduce the hygroscopicity of other chlorine-free oxidizing salts AN and ADN and has therefore been applied to HAN in the present study. Solid HAN is ideal for rapid cococrystal discovery. A low melting point of around 48 °C makes HAN an excellent candidate for melt fusion

(nomenclature surrounding melt techniques varies^{34–36}), a powerful cococrystallization technique in which the molten form of the low-melting cofomer (cococrystallization partner) solvates and fuses with a solid cofomer, which bypasses the need for individual design of solvent systems. Using melt fusion, a set of HAN cococrystals with nine different cofomers was generated as the first example of HAN cococrystallization in the literature (Fig. 3). Raman spectroscopy was used to identify successful cococrystallization by shifts in the known peaks of HAN and the cofomers (Fig. S12). In every case, single crystals of sufficient quality for structure determination by single crystal X-ray diffraction (SCXRD) were formed directly by melt fusion.



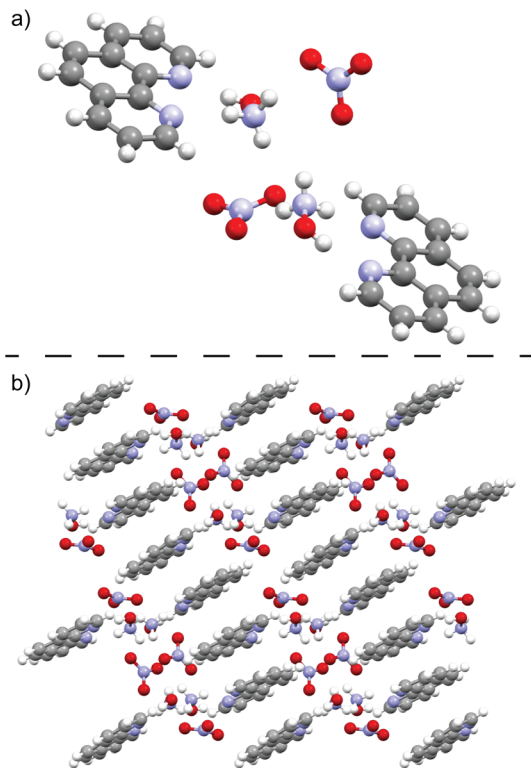


Fig. 5 (a) Asymmetric unit of HAN:PA and (b) crystal packing structure of HAN:PA.

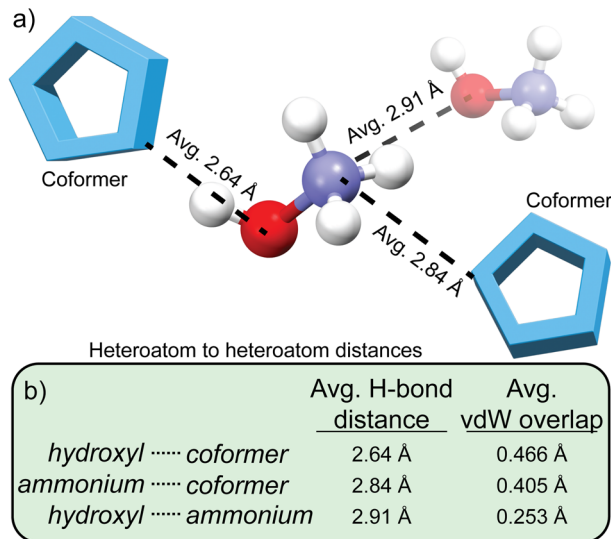


Fig. 6 (a) Illustration depicting the average hydrogen bond distances between hydroxylammonium and the cofomers and (b) average van der Waals overlap of the same interactions. All distances are between heteroatoms.

However, melt fusion is best employed as a screening technique, and in some cases once a cocrystal had been identified, recrystallization by evaporation or slurry techniques was necessary to produce higher quality crystals for publication-quality structures. All nine cocrystals are also accessible by

grinding HAN with the cofomers under a dry atmosphere; although laborious as a screening technique, this was our preferred method for obtaining pure samples for thermal analysis. The purity of the samples was verified with powder X-ray diffraction (Fig. S10).

Eight out of nine cocrystals have drastically reduced hygroscopicity compared to HAN, qualitatively apparent by their continued solidity at ambient. These cocrystals are the first instances of solid HAN showing stability towards atmospheric moisture. HAN:urea, which deliquesces under ambient conditions, was not studied further. Dynamic vapor sorption (DVS) was used to quantify the hygroscopicity of the remaining eight cocrystals and HAN by determining the critical relative humidity (CRH) for each. The CRH is the relative humidity at which the sample begins to deliquesce (Fig. 4).

To our knowledge the hygroscopicity of solid HAN (CRH 13.8%) has not been quantified previously. Most of the cocrystals have CRH values between 30–88%, a significant reduction in hygroscopicity which allows these materials to stay dry within typical laboratory conditions. This consistent reduction in hygroscopicity, even in the presence of hydrophilic cofomers, argues for a low lattice energy of HAN leading to anomalously high hygroscopicity. This notion is supported by its relatively low melting temperature relative to hydroxylammonium chloride (48 °C for HAN versus 155 °C for hydroxylammonium chloride) as well as significantly reduced volatility of the cocrystals relative to HAN (*vide infra*). Notably, HAN:PA did not deliquesce at any point during the experiments. This can potentially be explained by the crystal packing structure of the cocrystal, in which hydrophilic HAN is mostly caged in by bulky hydrophobic phenanthroline while participating in hydrogen bonding interactions with the sp^2 nitrogens of the latter (Fig. 5). The cocrystals were also assessed for phase stability under humid conditions by examining the powder X-ray patterns of the samples after DVS experiments (Fig. S11), and most reformed after drying the solution resulting from deliquescence (*i.e.* pure cocrystal with no hydrates or cofomers) with three exceptions. After exposure to 90% relative humidity: HAN:5-AT is partially converted to 5-aminotetrazole monohydrate, HAN:DAT breaks down into a mixture of cocrystal and diaminotriazole monohydrate, and HAN:3-AT decomposes to form a nitrate salt of the cofomer 3-aminotriazole.

Cofomers for this study were selected based on our previous work with hydroxylammonium chloride (HACl), in which we found that hydroxylammonium is prone to hydrogen bonding with *N*-oxides and sp^2 nitrogen atoms, with the hydroxyl functionality consistently forming closer contacts (greater van der Waals overlap) with the cofomer molecules than the ammonium functionality.³⁷ The reliability of these interactions makes them an ideal choice for HAN cocrystal design, and therefore every cofomer in the present work features *N*-oxide or sp^2 nitrogen functionality. Consistent with our previous work involving HACl, in HAN cocrystals the hydroxylammonium cation donates one or more hydrogen bonds to an *N*-oxide or sp^2 nitrogen of the cofomer molecule and the hydroxyl functionality forms closer contacts with cofomers than the ammonium functionality (Fig. 6). In addition to its two hydrogen bond



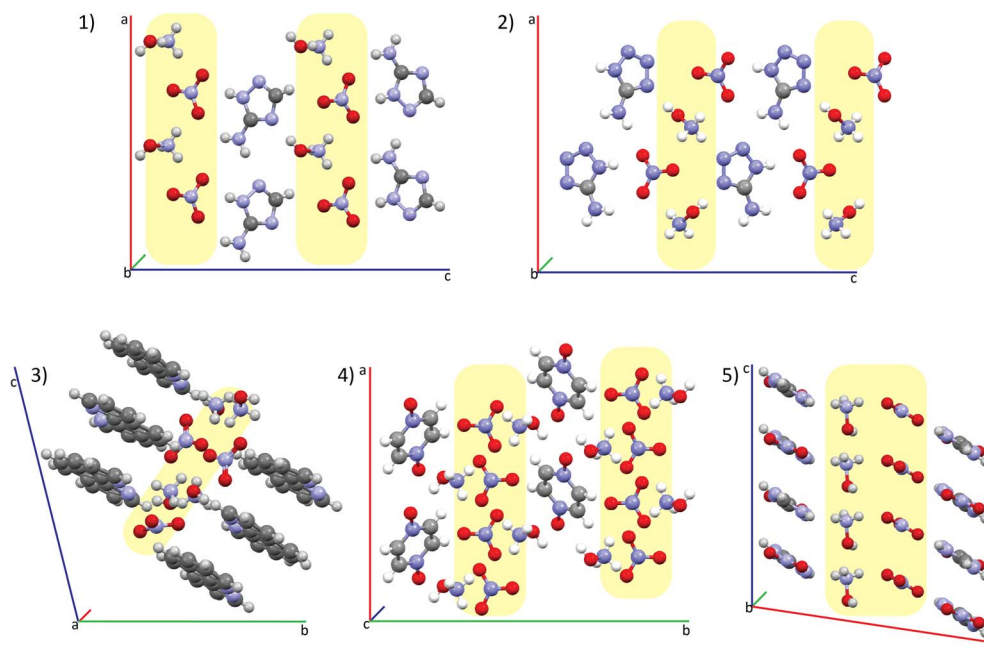


Fig. 7 Lamellar packing structures of (a) HAN:3-AT, (b) HAN:5-AT, (c) HAN:PA, (d) 2HAN:PDO, and (e) HAN:ANTA. Salt lamellae are highlighted.

Table 1 Calculated detonation velocity (V_d), detonation pressure (P_{Cj}), specific impulse (I_{sp}), oxygen balance (OB_{CO}), and density (ρ) for three energetic HAN cocrystals. HAN and RDX are included for comparison

	V_d (km s ⁻¹)	P_{Cj} (GPa)	I_{sp} (s)	OB_{CO} (%)	ρ (g cm ⁻³)
2HAN:PDO	8.21	25.8	247	0.00	1.67
HAN:ANTA	8.83	30.8	242	3.55	1.77
HAN:5-AT	8.98	29.6	236	-4.42	1.71
HAN	7.50	23.8	149	33.0	1.84
ANTA	8.33	30.3	207	-18.6	1.820
RDX	8.84	35.8	266	0.00	1.82

donating functionalities, the hydroxylammonium cation is capable of simultaneously accepting hydrogen bonds *via* lone pair electrons on the oxygen atom. This interaction appears to occur preferentially with itself. In six of nine cocrystals, hydroxylammonium accepts a hydrogen bond from the ammonium functionality of an adjacent hydroxylammonium cation. However, in none of the HAN cocrystals reported here does the hydroxyl functionality accept a hydrogen bond from a coformer molecule. Among the coformers selected for screening are six which were previously found to cocrystallize with HAN: BPDO, PDO, DAT, PA, isoquinoline *N*-oxide, and 4-picoline *N*-oxide. Of those six, four successfully cocrystallized with HAN, while two (isoquinoline *N*-oxide and 4-picoline *N*-oxide) did not. Isoquinoline *N*-oxide is protonated by HAN to form a nitrate salt whereas 4-picoline *N*-oxide reacts on contact with HAN to yield a liquid. HAN cocrystals are, therefore, a fair predictor for HAN cocrystal formation; however, subtleties arising from pK_a differences (chloride *versus* nitrate) must be considered.³⁸ Four of nine cocrystals feature lamellar architecture, a crystal packing motif defined by alternating sheets of salt

and coformer “sandwiched” and extending infinitely along two axes (Fig. 7). Previous work has explored salt lamellae as a potential route towards achieving variable salt stoichiometry in ionic cocrystals,³⁹ although no examples of varied stoichiometry for a given coformer were discovered for the cocrystals featuring lamellar architecture in the present work.

Three of the cocrystals in this set warrant closer examination as potentially promising energetic materials: HAN:ANTA, HAN:5-AT, and 2HAN:PDO. 3-Amino-5-nitro-1*H*-1,2,4-triazole (ANTA) is an insensitive high explosive that has attracted significant attention for its potential applications in insensitive munitions (IMs) and as a precursor for a variety of other energetic molecules.^{40,41} 5-AT is a high-energy nitrogen-rich heterocycle with demonstrated applications as a fuel in liquid and gelled propellant formulations, some of which also include HAN.^{42–44} PDO is a common coformer in energetic cocrystals due to its high energy content and powerful hydrogen bond accepting capability.^{45,46} Energetic performance properties were calculated using CHEETAH 7.1 thermochemical analysis software (Table 1). The calculated detonation velocities for the cocrystals are comparable to, or in the case of HAN:5-AT, slightly exceed that of the benchmark explosive hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX). Oxygen balance (OB_{CO}), which compares the oxygen content of a given chemical or formulation to the amount required for its complete oxidation, is slightly negative (oxygen deficit) for HAN:5-AT, neutral for 2HAN:PDO, and slightly positive (oxygen excess) for HAN:ANTA. Using an in-house drop height apparatus described in previous work,⁴⁷ impact sensitivity was determined for the first time for solid HAN and compared to that of the cocrystals and coformers. Impact sensitivity is here described as Dh_{50} , the height from which a dropped weight will cause the sample to detonate 50% of the time. Anhydrous HAN is mildly sensitive to impact (Dh_{50}



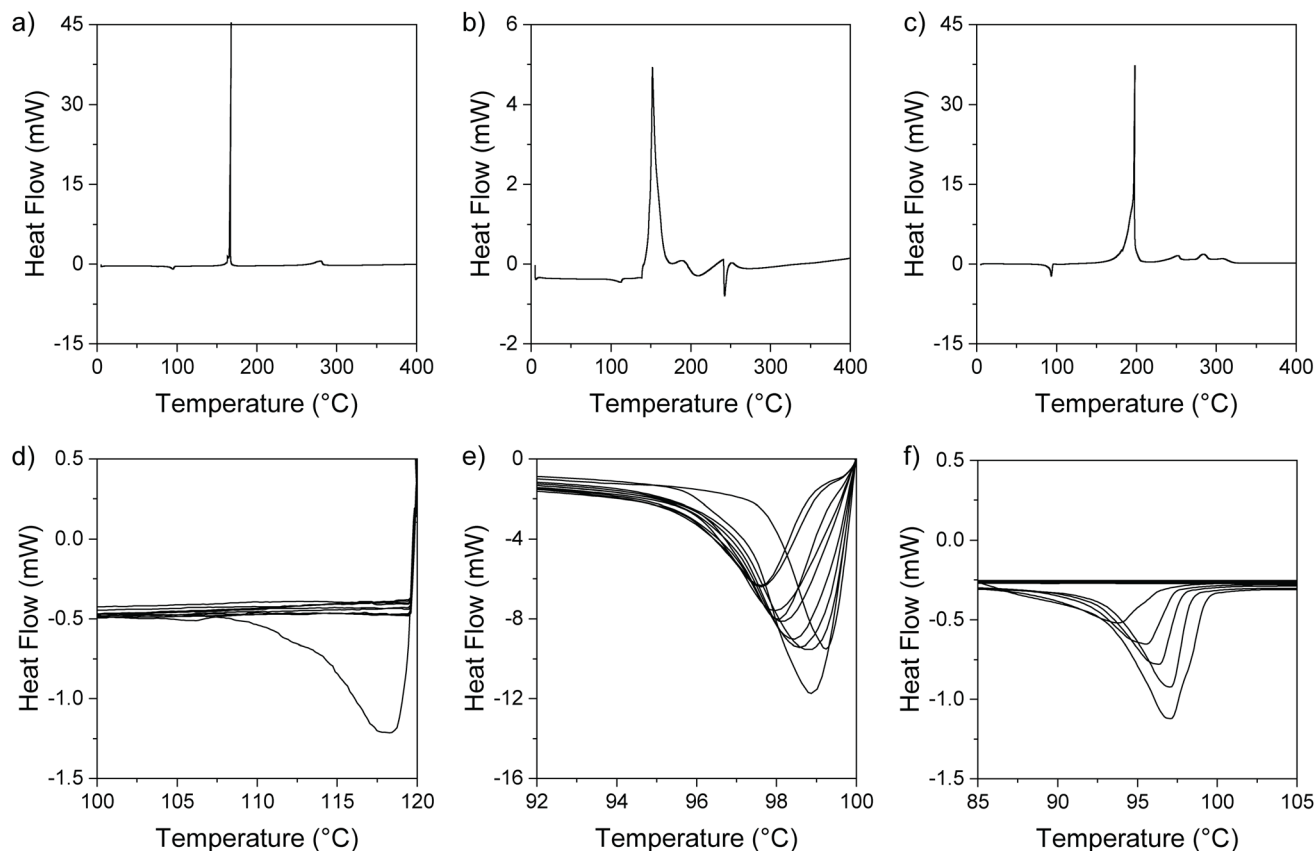


Fig. 8 DSC traces for (a) HAN:ANTA, (b) 2HAN:PDO, and (c) HAN:5-AT. Cyclic traces are depicted for (d) HAN:ANTA, (e) 2HAN:PDO, and (f) HAN:5-AT.

110 cm) and all three coformer molecules are insensitive to the limits of our apparatus (141 cm). **HAN:ANTA** is also insensitive to the limits of the apparatus, but **HAN:5-AT** (Dh_{50} 49 cm) and **2HAN:PDO** (Dh_{50} 38 cm) are drastically more sensitive than either mildly sensitive **HAN** or the insensitive cofomers. Particular caution must be observed with **2HAN:PDO** which occasionally detonated from drop heights as low as 19 cm, within the range of primary explosives. Although only a few have been reported previously, this result is unique among energetic ionic cocrystals. Previous examples of sensitive ionic cocrystals (**2ADN:PDO**, **2ADN:DNBT**, **AP:1HT**)^{23,48,49} contain at least one component with high impact sensitivity, and the sensitivity of the resulting cocrystals is similar to the sensitive component(s) rather than significantly increased. This work complements earlier findings on an energetic cocrystal less sensitive than either component (**DADP:TITNB**).⁵⁰

The low melting point of anhydrous **HAN** may present another potential barrier to incorporation in solid formulations. Therefore, differential scanning calorimetry (DSC) was used to assess the thermal properties of the cocrystals (Fig. 8). All three energetic ionic cocrystals feature elevated melting points around 100 °C, above typical operating temperatures and well below their respective decomposition points. The potential for melt casting capability warranted further study of the cocrystal melting behavior. Each cocrystal was repeatedly cycled

from 25 °C to just above its respective melting point to assess the stability of the molten cocrystal. In each case the melting point shifts with every cycle, indicating some instability and potential chemical degradation of the cocrystal. An optical melting temperature apparatus was then used to inspect the melting points visually. Upon reaching the supposed melting temperature, the cocrystals appear “wet” and partially melted but do not melt fully. At this point we suspected that **HAN** was melting out of the cocrystals at elevated temperatures and investigated the matter with thermogravimetric analysis (TGA). The cocrystals were held at 100 °C under continuous N_2 flow for 48 hours (Fig. S15). Initially, the samples lost mass rapidly (3–5 wt% per hour) but stabilized in the latter half of the experiment, supporting the idea that **HAN** is being liberated from the cocrystals and decomposing or vaporizing. PXRD analysis of the same samples after TGA experiments confirm that this is the case. Although not reported previously, solid **HAN** is highly volatile as evidenced by the ease of sublimation in this work. Previous work has demonstrated the effectiveness of cocrystallization in suppressing the volatility of energetic cofomers, and so isothermal TGA experiments were then carried out at 80 °C and 60 °C for 10 hours to gain a more complete picture of the thermal stability of the cocrystals (Fig. 9). Mass loss rates at 80 °C are close to 1% per hour for all three cocrystals. At 60 °C, mass loss occurs at less than 0.1% per hour for each cocrystal.



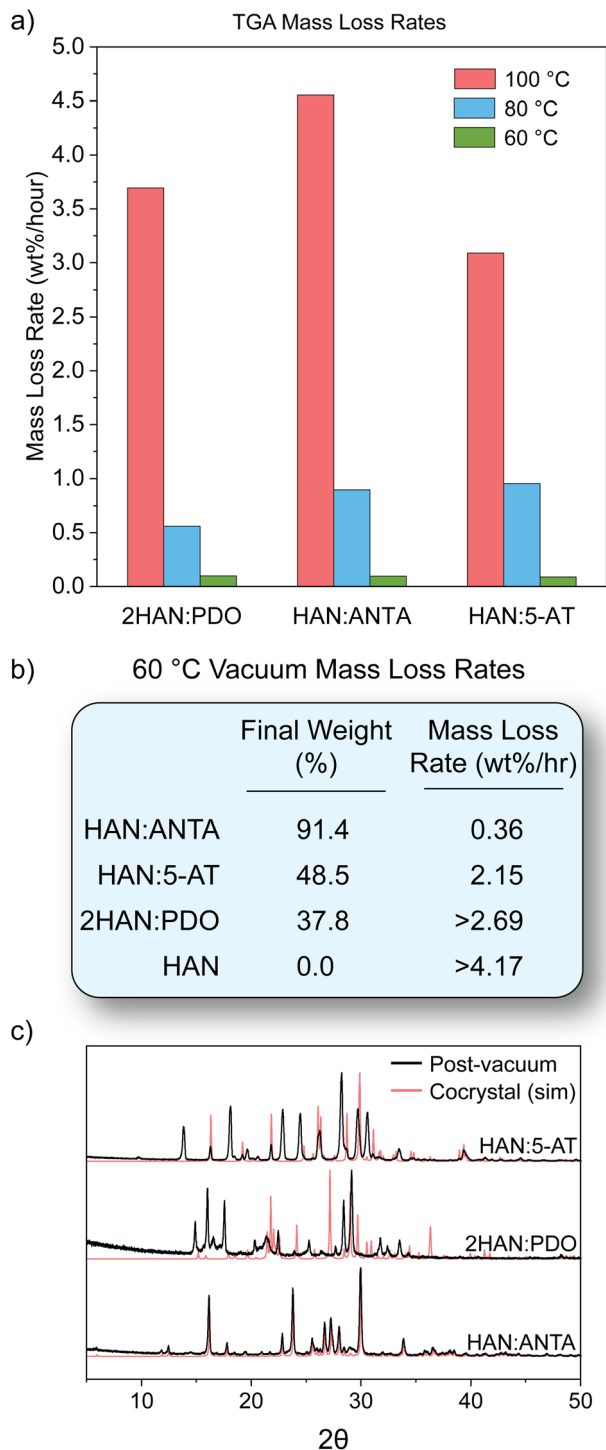


Fig. 9 (a) Bar plot showing mass loss rates of the energetic cocrystals during TGA experiments at 100 °C, 80 °C, and 60 °C. (b) Table of final mass percent and mass loss rates for the energetic cocrystals and HAN when held at 60 °C under vacuum for 24 hours, and (c) PXRD patterns of the samples after the vacuum experiment.

Inclusion of HAN as a comparison point proved difficult for TGA measurements, where uptake of atmospheric moisture prior to data collection threatens to skew the results of the experiment. Therefore a similar experiment was performed at elevated

temperature in a sealed vacuum chamber where HAN can be more easily included. HAN and the energetic cocrystals were held at 60 °C under vacuum for 24 hours. The initial and final masses of the samples were compared to calculate the rate of mass loss. HAN was observed to vaporize completely in under 30 minutes. Aside from 2HAN:PDO, the cocrystals show a marked improvement over HAN with a twofold suppression of volatility in the case of HAN:5-AT and nearly twelvefold for HAN:ANTA. These calculations were made with the minimum possible mass loss rate of HAN across the entire 24 hour experiment; taking into account the fact that HAN had visually vaporized entirely within 30 minutes, the actual improvement is likely many times greater.

Conclusion

Solid anhydrous HAN has been synthesized in one step from commercial reagents and purified via sublimation. This method is likely applicable to other HAN syntheses which struggle with metal contaminants. Solid HAN is ideal for cocrystallization, and purification from metal contaminants ensures thermal analysis uncomplicated by catalytic decomposition, an important consideration for applications in propellants. Rapid cocrystal screening can be achieved via melt fusion of solid HAN, bypassing complex solution methods which must be adjusted to suit the needs of individual cofomers. Through this method, the first set of HAN cocrystals have been reported. Eight of nine cocrystals have reduced hygroscopicity to the point of remaining stable as solids under ambient conditions, and one cocrystal, HAN:PA, eliminates the hygroscopicity of HAN entirely. The ability to stabilize HAN such that it is easily handled under ambient conditions without significant moisture uptake should enable research on HAN in the context of solid propellants, where it has not previously been studied in spite of its excellent oxygen content and existing production infrastructure. HAN:ANTA, HAN:5-AT, and 2HAN:PDO possess noteworthy energetic properties exceeding those of both HAN and the cofomer molecules. Ionic cocrystallization of oxidizing salts with organic cofomers necessarily results in reduced oxygen balance, and while the cocrystals presented are no exception, incorporation of more oxygen-rich cofomers or ones which can accommodate greater stoichiometric quantities of oxidizer in future work may mitigate the impact to oxidizing power as demonstrated in previous work with AN and ADN. While thermal stability remains a challenge, every cocrystal assessed shows a marked improvement over HAN in that regard. The potential of ionic cocrystallization as a route towards addressing the undesirable properties of HAN and thus enabling it for further study in solid applications is clearly demonstrated.

Author contributions

Andrew J. Bennett conceived research, designed experiments, performed experimental work and drafted the manuscript; Haley R. Froberg and Leila M. Foroughi performed experimental work and edited the manuscript; Michael K. Bellas conceived research and edited the manuscript; Adam J. Matzger



conceived research, edited the manuscript, and provided project administration, resources, and supervision.

Conflicts of interest

There are no conflicts to declare.

Data availability

Supplementary information (SI): experimental details, Raman spectra, powder X-ray patterns, crystallographic information, DSC and TGA thermograms, and ORTEP diagrams. See DOI: <https://doi.org/10.1039/d5ta08279j>.

CCDC 2483543–2483551 contain the supplementary crystallographic data for this paper.^{51a–i}

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