
AMMONIUM NITRATE AS AN OXIDIZER IN SOLID COMPOSITE PROPELLANTS

G. B. Manelis and D. B. Lempert

Despite the fact that ammonium nitrate (AN) has the highest hydrogen content and fairly high oxygen balance (compared to other oxidizers), its extremely low formation enthalpy and relatively low density makes it one of the worst power oxidizers in solid composite propellants (SCP). Nevertheless, AN has certain advantages — the combustion of the compositions containing AN is virtually safe, its combustion products are ecologically clean, it is very accessible and cheap, and also very thermostable (far more stable than ammonium dinitramide (ADN)). Besides, its low density stops being a disadvantage if the propellant has to be used in deep space and therefore, must be carried there with other rocket carriers. The low cost of AN may also become a serious advantage in the AN application even in lower stages of multistage space launchers as well as in one-stage space launchers with low mass fraction of the propellant. The main specific features relevant to the creation of AN-based SCPs with the optimal energetic characteristics are discussed. The use of metals and their hydrides and proper fuel-binders as well as the recent successes in phase stabilization of AN are described.

1 INTRODUCTION

Ammonium nitrate is the cheapest and most available oxidizer for SCPs. It was AN that the early solid propellants were based on. Ammonium nitrate combines a favorable element composition (5% hydrogen, 60% oxygen, absence of halides), high thermal stability, and sufficient compatibility with a number of other constituents. However, its low enthalpy of formation (-4514 kJ/kg) and relatively low density (1.725 g/cm³) make AN not competitive in energy potential to a majority of other known oxidizers.

Still, the attractive features of AN (environmentally friendly combustion products, low cost, very low sensitivity to mechanical loading, high thermal stability) can revive interest to this oxidizer for the applications with special requirements.

2 THE OBJECTS AND CRITERIA FOR COMPARISON

In this work, the energetic potential of AN-based SCPs are compared with analogous formulations based on the more frequently used oxidizers: ammonium perchlorate (AP) and ADN. All thermodynamic calculations for the specific impulse (I_{sp}) were performed for the combustion chamber pressure (P_c) of 40 bar and at the nozzle exit pressure (P_a) of 1 bar. Since these three oxidizers have different density (AP — 1.95; ADN — 1.80–1.82; and AN — 1.725 g/cm³) and the propellant density (ρ) substantially affects the ballistics, the formulations were compared not only by I_{sp} but also by the so-called ballistic efficiency. In this paper, the ballistic efficiency [1] of the i th launcher stage (E_i) defined as $E_1 = I_{sp}\rho^{0.6}$; $E_2 = I_{sp}\rho^{0.4}$; and $E_3 = I_{sp}\rho^{0.2}$ is considered. The exponents values (0.2, 0.4, and 0.6) correspond to three-stage rocket launchers with optimized stage masses and tank volumes of every stage. Using these equations, one can affirm that, e.g., if there are two different propellants (the first one possessing I_{sp1} and ρ_1 while the second one possessing I_{sp2} and ρ_2), the usage of the first propellant in the first stage would provide a higher speed growth than the usage of the second propellant (propellants used in the 2nd and 3rd stages being equal) if $I_{sp1}\rho_1^{0.6} > I_{sp2}\rho_2^{0.6}$. Naturally, the density exponents depend on the volume-to-mass ratio for each stage and can differ substantially. Since AN has lower density than ADN and AP, its efficiency is worst for the first stage.

The choice of a binder is important to materialize the potential of oxidizers. Four different binders were used in the calculations, namely:

- (1) hydrocarbon binder (HB), $\Delta H_f = -390$ kJ/kg, $\rho = 0.91$ g/cm³, hydrogen content $\sim 12\%$;
- (2) poly(methylvinyltetrazole) (PMVT) — $(C_4N_4H_6)_n$, a high-enthalpy polymer with high content of nitrogen ($\sim 46\%$), $\Delta H_f = +1255$ kJ/kg, $\rho = 1.28$ g/cm³;
- (3) active binder (AB), a model binder analogous to practical ones, 20% poly(vinylmethyltetrazole), plasticized with a mixture of trinitroglycerol with 2,4-dinitro-2,4-diazo-pentane; its gross formula is close to $C_{19}H_{34.5}N_{19}O_{29.5}$; $\Delta H_f = -757$ kJ/kg, $\rho = 1.49$ g/cm³, oxygen content $\sim 47\%$; and
- (4) poly(vinylmethoxydiazene-N-oxide) (PVMDO) $(C_3H_6N_2O_2)_n$, $\Delta H_f = 0$ kJ/kg, $\rho = 1.31$ g/cm³, a model binder rich in hydrogen ($\sim 6\%$) and oxygen ($\sim 31\%$).

3 ENERGY POTENTIAL OF THE FORMULATIONS

Formulations containing energetic components (aluminum, beryllium, or aluminum hydride (AH)) and simple pairs of oxidizer + binder were considered. The lower the formation enthalpy of an oxidizer, the more the oxidizer needs an additive of energetic component [2]. For the sake of brevity, only the calcu-

Table 1 Energy potential of metal-free formulations

Oxidizer	Binder		I_{sp} , s	ρ , g/cm ³	T_c , K	T_a , K	E_1 , g, cm ³ , s	E_2 , g, cm ³ , s	E_3 , g, cm ³ , s
	%(wt.)	%(vol.)							
AB + AN	25	27.8	219.3	1.660	2440	1297	297.2	268.6	242.7
	26	28.9	221.2	1.657	2476	1327	299.5	270.7	244.7
	27	30.0	223	1.655	2511	1358	301.7	272.8	246.6
HB + AN	10.5	18.2	209.8	1.577	2017	998	275.7	251.7	229.8
	11	19.0	208.5	1.570	1976	974	273.3	249.7	228.2
PMVT + AN	13	16.8	218.3	1.650	2348	1200	294.9	266.7	241.3
	14	18.0	217.1	1.645	2309	1172	292.7	264.9	239.8
	15	19.2	215.8	1.640	2268	1143	290.3	263.0	238.2
PVMDO + AN	14	17.7	221.5	1.652	2408	1276	299.3	270.7	244.9
	15	18.9	224.9	1.647	2460	1329	303.4	274.6	248.5
	16	20.1	226.3	1.642	2490	1338	304.7	275.9	249.9
AB + AP	25	30.4	214.8	1.810	2663	1457	306.7	272.4	241.9
	26	31.5	216.7	1.805	2697	1490	308.9	274.4	243.9
	27	32.6	218.5	1.800	2730	1525	310.9	276.4	245.8
	28	33.7	220.4	1.795	2762	1560	313.1	278.5	247.8
HB + AP	9.5	18.4	239.8	1.759	2989	1953	336.5	300.6	268.5
	10	19.2	240.6	1.750	3003	1910	336.6	301.0	269.1
	11	20.9	240.5	1.732	3007	1793	334.4	299.6	268.4
PMVT + AP	20	27.6	238.2	1.765	3004	1770	335.0	299.0	266.9
	21	28.8	234.7	1.757	2994	1709	329.1	294.0	262.7
	22	30.1	236.5	1.749	2975	1651	330.7	295.7	264.5
PVMDO + AP	22	29.6	239.7	1.761	3005	1927	336.6	300.6	268.4
	23	30.8	241.8	1.753	3025	1983	338.6	302.7	270.5
AB + ADN	26	30.0	239.3	1.721	2930	1714	331.4	297.3	266.7
	27	31.1	240.6	1.717	2950	1743	332.8	298.7	268.1
HB + ADN	10	18.2	250.9	1.655	3017	1660	339.4	306.9	277.5
	11	19.8	249	1.640	2967	1580	335.0	303.5	274.9
PMVT + ADN	14	17.5	250	1.596	3025	1894	331.0	301.4	274.5
	15	18.5	250.4	1.583	3038	1833	329.8	300.9	274.5
	16	19.6	250	1.569	3043	1774	327.6	299.4	273.6
PVMDO + ADN	20	25.8	254	1.689	3073	1945	347.8	313.2	282.1
	21	27.0	254.3	1.682	3082	1904	347.5	313.1	282.2
	22	28.2	254.3	1.676	3088	1865	346.7	312.7	282.0

Table 2 Energy potential of the formulations with 20% Al

Formulation	Binder		I_{sp} , s	ρ , g/cm ³	T_c , K	T_a , K	E_1 , g, cm ³ , s	E_2 , g, cm ³ , s	E_3 , g, cm ³ , s
	%(wt.)	%(vol.)							
Al 20% + AB + AN	20	24.1	247.3	1.798	3498	2429	351.7	312.7	278.1
	21	25.3	247.5	1.795	3500	2426	351.6	312.8	278.2
	22	26.5	247.7	1.792	3503	2421	351.5	312.8	278.4
Al 20% + HB + AN	10	18.6	245.7	1.696	2965	1881	337.3	303.5	273.1
	11	20.3	245.1	1.681	2896	1804	334.7	301.7	271.9
Al 20% + PMVT + AN	10	14.0	245.2	1.792	3295	2300	348.0	309.6	275.5
	11	15.3	245.4	1.786	3271	2260	347.5	309.5	275.6
	12	16.7	245.5	1.779	3245	2216	346.9	309.1	275.5
Al 20% + PVMDO + AN	16	21.5	248.7	1.763	3334	2326	349.5	312.0	278.6
	17	22.8	249.1	1.757	3322	2304	349.4	312.1	278.8
	18	24.1	249.4	1.752	3309	2282	349.1	312.1	279.0
Al 20% + AB + AP	24	30.8	245.5	1.915	3859	2901	362.5	318.3	279.6
	25	32.0	246	1.909	3860	2897	362.6	318.6	280.0
	26	33.2	246.5	1.903	3860	2893	362.6	318.9	280.4
Al 20% + HB + AP	8	16.5	249.2	1.882	3716	2681	364.2	321.0	282.8
	9	18.4	250.1	1.862	3670	2604	363.2	320.7	283.2
Al 20% + PMVT + AP	10	15.3	250.8	1.956	3810	2840	375.1	328.0	286.8
	11	16.7	251.1	1.946	3800	2814	374.4	327.7	286.9
	12	18.1	251.2	1.936	3787	2784	373.4	327.2	286.7
Al 20% + PVMDO + AP	20	28.6	251.7	1.871	3762	2721	366.6	323.4	285.3
	21	29.9	252.3	1.862	3748	2694	366.4	323.6	285.7
	22	31.1	252.8	1.854	3733	2666	366.1	323.6	286.0
Al 20% + AB + ADN	15	18.9	255.3	1.880	3884	2888	372.9	328.6	289.7
	16	20.1	255.6	1.876	3884	2885	372.8	328.7	289.9
	17	21.4	255.9	1.872	3884	2881	372.7	328.8	290.1
	18	22.6	256.1	1.867	3884	2877	372.5	328.8	290.2
	19	23.8	256.4	1.863	3884	2873	372.4	328.9	290.4
	20	25.0	256.6	1.859	3884	2867	372.2	328.8	290.5
	21	26.1	256.9	1.855	3884	2861	372.2	328.9	290.7
Al 20% + HB + ADN	8	15.8	262	1.793	3695	2507	372.0	331.0	294.5
	9	17.6	262.1	1.776	3642	2420	369.9	329.8	294.0
	10	19.3	262	1.759	3584	2331	367.6	328.4	293.3
Al 20% + PMVT + ADN	12	17.3	259.7	1.847	3785	2640	375.3	331.9	293.6
	13	18.7	259.9	1.839	3763	2596	374.6	331.6	293.6
Al 20% + PVMDO + ADN	14	20.0	260	1.831	3738	2550	373.8	331.2	293.4
	13	18.3	260.2	1.847	3763	2596	376.0	332.6	294.2
	14	19.7	260.7	1.840	3738	2550	375.8	332.7	294.5
	15	21.0	261.1	1.832	3710	2503	375.5	332.7	294.7
	16	22.3	261.5	1.825	3679	2455	375.2	332.7	294.9
	17	23.6	261.9	1.818	3645	2405	374.9	332.7	295.2
18	24.9	262.2	1.811	3608	2358	374.5	332.5	295.3	

Table 3 Energy potential of the formulations with 13% Be

Formulation	Binder		I_{sp} , s	ρ , g/cm ³	T_c , K	T_a , K	E_1 , g, cm ³ , s	E_2 , g, cm ³ , s	E_3 , g, cm ³ , s
	%(wt.)	%(vol.)							
Be 13% + AB + AN	23	25.9	262.2	1.679	3469	2789	357.8	322.6	290.8
	24	27.0	262.5	1.676	3471	2788	357.9	322.8	291.1
	25	28.1	262.8	1.674	3473	2787	358.0	322.9	291.3
	26	29.2	263.1	1.671	3475	2785	358.0	323.1	291.6
Be 13% + AB + AP	25	30.2	254.8	1.799	3893	2961	362.4	322.2	286.5
	26	31.3	255.3	1.793	3891	2954	362.5	322.5	286.9
	27	26.8	255.8	1.788	3889	2949	362.1	321.4	285.3
Be 13% + AB + ADN	15	17.8	265.7	1.765	3899	2949	373.6	333.5	297.7
	16	18.9	265.9	1.761	3898	2945	373.4	333.5	297.8
	17	20.1	266.2	1.758	3897	2941	373.4	333.6	298.0
	18	21.2	266.5	1.754	3896	2937	373.3	333.6	298.2
	19	22.3	266.7	1.750	3895	2933	373.1	333.6	298.3
	20	23.4	267	1.746	3893	2927	373.1	333.7	298.5
	21	24.6	267.2	1.743	3891	2921	372.9	333.7	298.6
	22	25.7	267.4	1.739	3889	2916	372.7	333.6	298.7
Be 13% + HB + AN	10	17.5	270.5	1.596	3038	2260	358.1	326.1	297.0
	11	19.1	271.2	1.583	2990	2190	357.2	325.9	297.3
	12	20.7	271.8	1.570	2941	2120	356.3	325.5	297.5
Be 13% + HB + AP	12	22.5	266.2	1.704	3554	2787	366.6	329.5	296.2
	13	24.1	267.8	1.687	3500	2727	366.6	330.1	297.3
	14	25.7	269.3	1.671	3441	2661	366.4	330.7	298.4
	15	27.3	270.4	1.655	3374	2581	365.8	330.7	299.1
	16	28.8	270.7	1.639	3290	2477	364.1	329.8	298.8
Be 13% + HB + ADN	14	24.6	269.3	1.599	3295	2426	357.0	325.0	295.8
	15	26.1	270.4	1.586	3153	2344	356.5	325.1	296.5
Be 13% + PMVT + AN	17	21.8	268.4	1.642	3145	2378	361.5	327.3	296.4
	18	23.0	268.9	1.637	3124	2345	361.4	327.5	296.8
	19	24.2	269.1	1.632	3102	2311	361.0	327.3	296.8
	20	25.4	269.7	1.626	3080	2276	361.1	327.6	297.2
	21	26.6	270	1.621	3057	2240	360.8	327.5	297.4
	22	27.8	270.3	1.616	3034	2205	360.5	327.5	297.5
Be 13% + PMVT + AP	20	27.4	263	1.754	3630	2850	368.5	329.3	294.3
	21	28.6	264.3	1.746	3598	2827	369.2	330.3	295.5
	22	29.9	264.7	1.738	3561	2791	368.8	330.2	295.6
	23	31.1	265.3	1.730	3518	2747	368.6	330.3	296.0
Be 13% + PMVT + ADN	19	25.1	276	1.688	3603	2812	377.9	340.3	306.5
	20	26.3	276.4	1.682	3559	2772	377.6	340.3	306.7
	21	27.5	276.1	1.675	3489	2666	376.3	339.4	306.1

(Continued)

Table 3 Energy potential of the formulations with 13% Be (Continued)

Formulation	Binder		I_{sp} , s	ρ , g/cm ³	T_c , K	T_a , K	E_1 , g, cm ³ , s	E_2 , g, cm ³ , s	E_3 , g, cm ³ , s
	%(wt.)	%(vol.)							
Be 13% + PVMDO + AN	21	26.1	270.1	1.631	3269	2531	362.2	328.5	297.9
	22	27.3	270.7	1.626	3259	2514	362.4	328.8	298.3
	23	28.5	271.2	1.621	3249	2497	362.4	329.0	298.7
Be 13% + PVMDO + AP	20	26.9	261.1	1.765	3786	2851	367.2	327.7	292.5
	21	28.2	261.9	1.757	3773	2851	367.3	328.2	293.2
	22	29.4	262.7	1.750	3760	2851	367.5	328.6	293.8
Be 13% + PVMDO + ADN	19	25.7	274.1	1.773	3765	2851	386.5	344.7	307.4
	20	26.9	274.6	1.765	3751	2850	386.2	344.7	307.6
	21	28.2	275.2	1.757	3736	2850	386.0	344.8	308.0
	22	29.4	275.8	1.750	3721	2850	385.8	345.0	308.4
	23	30.6	276.4	1.742	3706	2850	385.6	345.1	308.9

lated data for the formulations with a constant content of energetic component, 20% Al, 13% Be, or 25% AlH₃ are presented herein. At these concentrations, the formulations are close to optimal in energy, although it is known that, owing to two-phase losses, higher stages require a somewhat lower metal content. Tables 1 to 5 and Figs. 1 to 8 present the main results of the calculations.

The calculations were performed for a widely varied content of binders. Tables 1 to 3 show the formulations with the binder fraction exceeding 18–19%(vol.) (at lower content of binders, a formulation with satisfactory mechanical properties cannot be obtained).

Figures 1 to 12 show that for the active binder and PVMDO, possessing relatively high oxygen content, the optima in I_{sp} and E_i are achieved at a higher volume content of binders as compared to the hydrocarbon binder and PMVT. Table 4 summarizes the maximum attainable E_i , provided the volume fraction of a binder is not less than 19%.

A careful analysis of the results shows that in metal-free compositions, AN is inferior to AP and ADN for all launcher stages. Introduction of aluminum, and even more so beryllium, substantially decreases the loss. The higher the stage, the better AN performs compared to AP and ADN. For the 3rd stage, AN is not worse than AP and only a little worse than ADN.

The use of AH in the formulations with AB (the other binders are substantially less efficient with AH) results in the enhancement of E_2 and E_3 over the corresponding values for the formulations based on aluminum (with any binder). AlH₃ values become close to those for Be-containing formulations. Table 5 shows the calculated data. The binder content of the formulations with AH must be substantially higher compared to the metal-based formulations because the small hydride particles have large surface area, and the formulations with the binder

Table 4 Maximum attainable E_i for different compositions

Oxidizer	Binder			
	HB	AB	PMVT	PVMDO
Metal-free — E_1				
AN	272	300	293	303
AP	335	310	338	335
ADN	335	335	331	345
Metal-free — E_2				
AN	250	275	262	275
AP	300	275	299	300
ADN	305	298	301	311
Metal-free — E_3				
AN	224	248	238	250
AP	264	245	268	270
ADN	278	268	274	283
20% Al — E_1				
AN	337	354	345	350
AP	363	362	372	366
ADN	368	372.5	374	375
20% Al — E_2				
AN	303	312.5	308	312
AP	321	315.5	326	321
ADN	328	327	331	332
20% Al — E_3				
AN	272	278	275	278
AP	283	275	286	280
ADN	293	291	293	294
13% Be — E_2				
AN	326	322	327	329
AP	331	321	330	328
ADN	323	333	340	344
13% Be — E_3				
AN	297.5	291	297	295
AP	299	287	296	298
ADN	296.5	299	307	308

content less than 28%–33% do not exhibit satisfactory physicochemical and rheological properties.

Table 6 summarizes the calculated maximum attainable E_2 and E_3 performances. These data are also presented in Fig. 13.

The above data show that upon the replacement of Al with AlH_3 or Be, the maximum attainable E_2 and E_3 become less sensitive to the oxidizer na-

Table 5 Energy potential of the formulations with AH (25%) and the AB

Formulation	Binder		I_{sp} , s	ρ , g/cm ³	T_c , K	T_a , K	E_1 , g, cm ³ , s	E_2 , g, cm ³ , s	E_3 , g, cm ³ , s
	%(wt.)	%(vol.)							
AlH ₃ 25% + AB + AN	25	26.8	267.4	1.596	3208	2125	354.0	322.4	293.6
	27	28.8	267.6	1.591	3206	2117	353.6	322.3	293.7
	29	30.9	267.9	1.587	3204	2109	353.4	322.2	293.8
AlH ₃ 25% + AB + ADN	25	27.4	277.6	1.636	3564	2345	372.9	338.0	306.3
	27	29.5	277.4	1.629	3548	2327	371.8	337.2	305.8
	28	30.6	277.4	1.626	3540	2327	371.3	336.9	305.7
AlH ₃ 25% + AB + AP	25	28.3	270.3	1.686	3589	2466	369.8	333.1	300.1
	27	30.4	270.5	1.677	3573	2438	368.9	332.6	300.0
	29	32.5	270.8	1.668	3557	2410	368.1	332.3	300.0

ture, although the order of relative efficiency of the oxidizers remains the same: ADN > AP > AN.

The use of AN instead of AP and ADN can be justified in systems where the overall content of oxidizers is low, e.g., in the formulations based on the AB with a high content of HMX (usually, 50%–55%, whereas AP content amounts to $\sim 10\%$). Since further increase of HMX content deteriorates combustion properties, one should replace AP with AN at the expense of a minor loss in energy potential (Table 7). Such formulations become environmentally safe as compared to AP-based propellants and much more thermally stable than the ADN-based propellants. These AN formulations surpass AP in energy potential and are virtually the same as the ADN-based formulations.

4 STABILITY OF AMMONIUM NITRATE, ITS COMPATIBILITY WITH OTHER COMPONENTS OF SOLID COMPOSITE PROPELLANTS, AND THE PROBLEM OF PHASE STABILITY

Ammonium nitrate is a sufficiently stable compound. The rate constant [3] for its solid-phase decomposition (i.e., below 166 °C) is

$$k = 2.2 \cdot 10^{12} \exp\left(-\frac{45,000}{RT}\right), \text{ s}^{-1};$$

so, even at 140 °C, $k = 3.4 \cdot 10^{-12} \text{ s}^{-1}$. This stability exceeds by orders of magnitude general requirements. The thermal decomposition proceeds via the

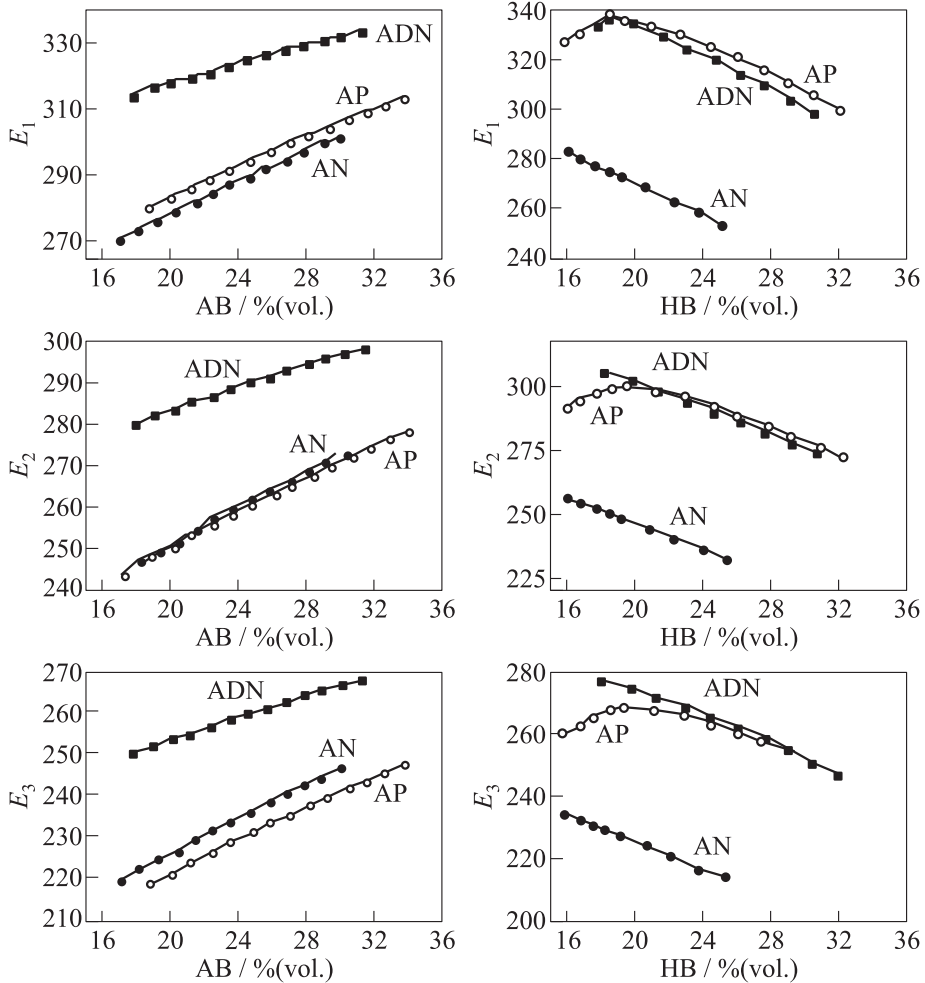


Figure 1 Ballistic efficiency of AB + oxidizer compositions

Figure 2 Ballistic efficiency of HB + oxidizer compositions

salt dissociation with the formation of free nitric acid. Therefore, a compound having acidic nature, e.g., oxalic acid, catalyzes AN decomposition. This catalysis depends upon various properties, in particular, upon component acidity, e.g., organic acids that are considerably weaker than oxalic do not affect AN decomposition [4]. To date, the stability of AN-based formulations (if one means that “stability” is the “absence of other substances formation”) is a solved problem.

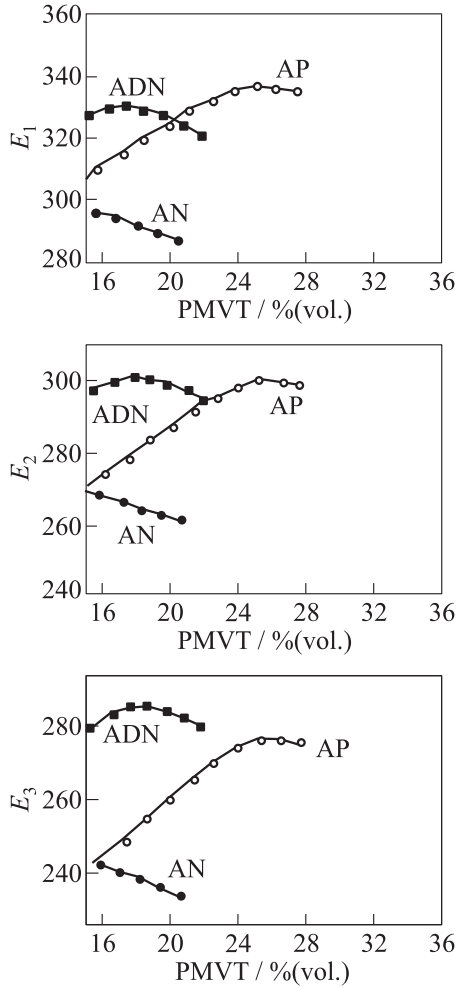


Figure 3 Ballistic efficiency of PMVT + oxidizer compositions

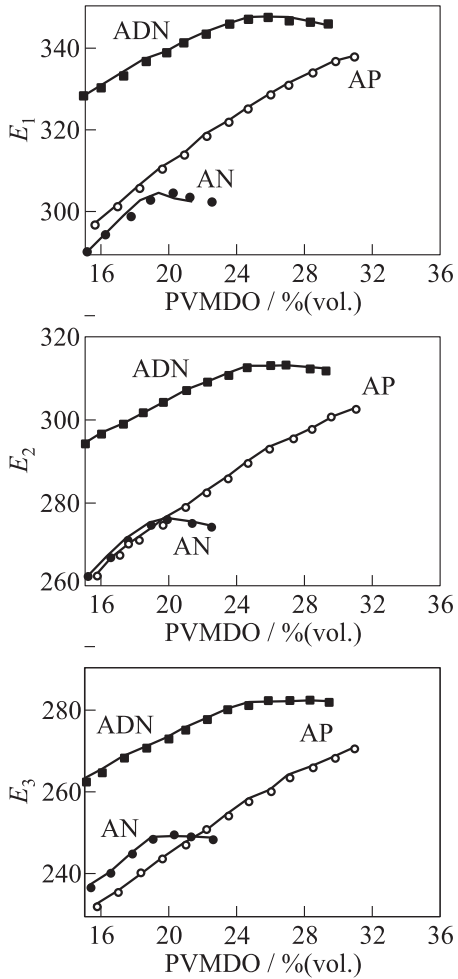


Figure 4 Ballistic efficiency of PVMDO + oxidizer compositions

However, AN has a specific drawback, i.e., the occurrence of three-phase transitions accompanied by changes in density, in the temperature range of normal solid propellant operation (V–IV transition at $-17\text{ }^\circ\text{C}$, IV–III at $+32\text{ }^\circ\text{C}$, and III–II at $+82\text{ }^\circ\text{C}$). These transitions cause mechanical degradation of propellants during storage. A known method to suppress these phase transitions is to add over 8% potassium nitrate [5]. A number of studies aimed at phase stabilization

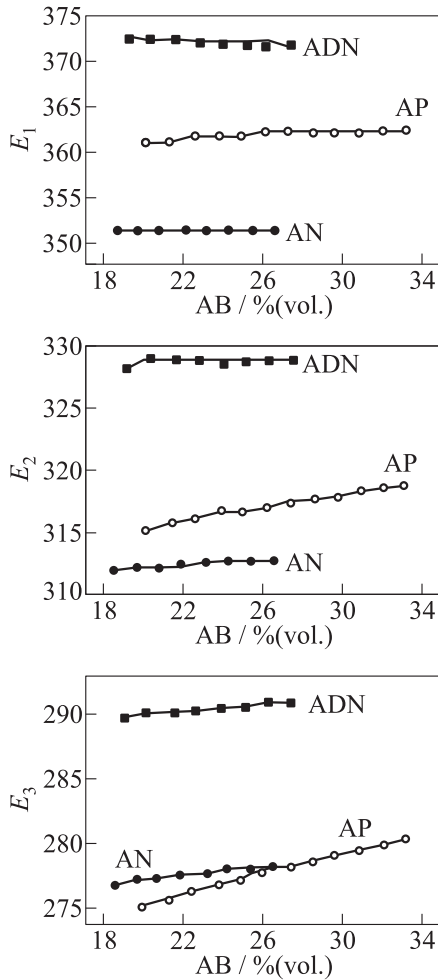


Figure 5 Ballistic efficiency of AB + oxidizer + 20% Al compositions

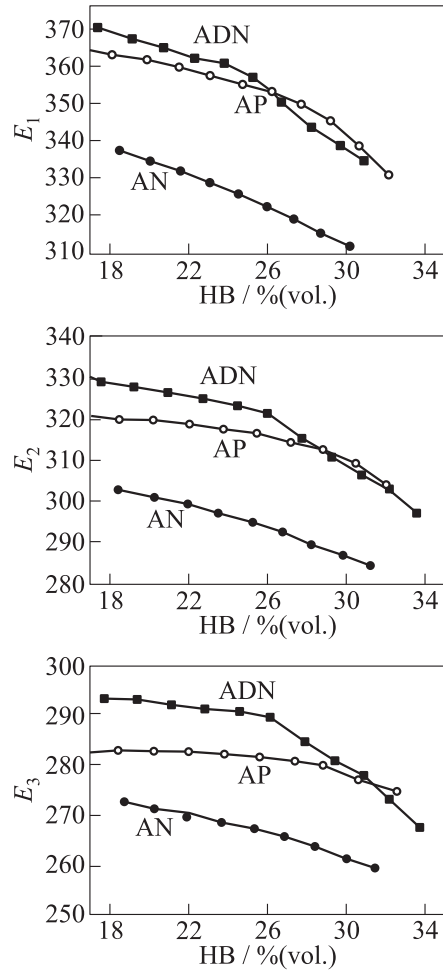


Figure 6 Ballistic efficiency of HB + oxidizer + 20% Al compositions

of AN with additives that contain neither metals nor halides were performed by the present authors. It seemed possible to achieve stabilization by introducing anions of close dimensions into AN lattice. However, the choice of anions commensurate with the nitrate is limited; NO_2^- and CO_3^{2-} do not fit due to poor stability of ammonium nitrite and carbonate. Azide, cyanate, and oxalate anions could not be introduced into AN lattice by alloying or by crystallization from solution. This occurs apparently due to substantial differences in the anion

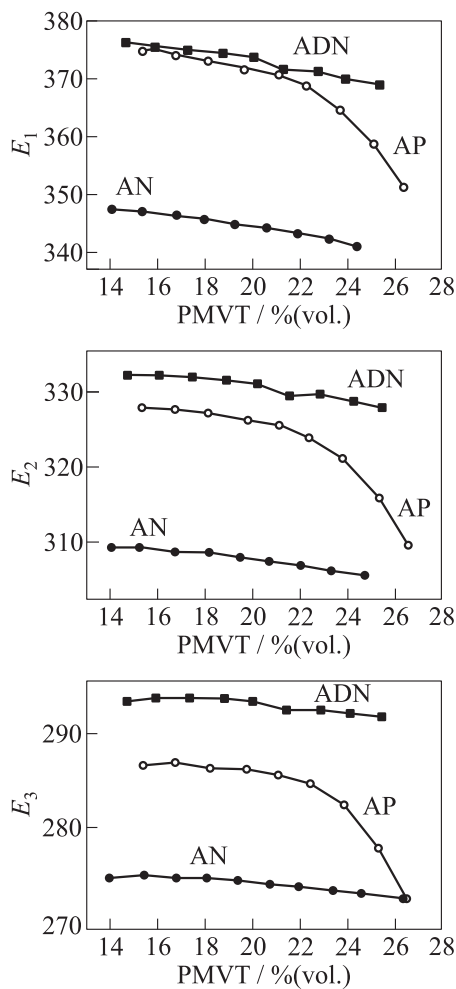


Figure 7 Ballistic efficiency of PMVT + oxidizer + 20% Al compositions

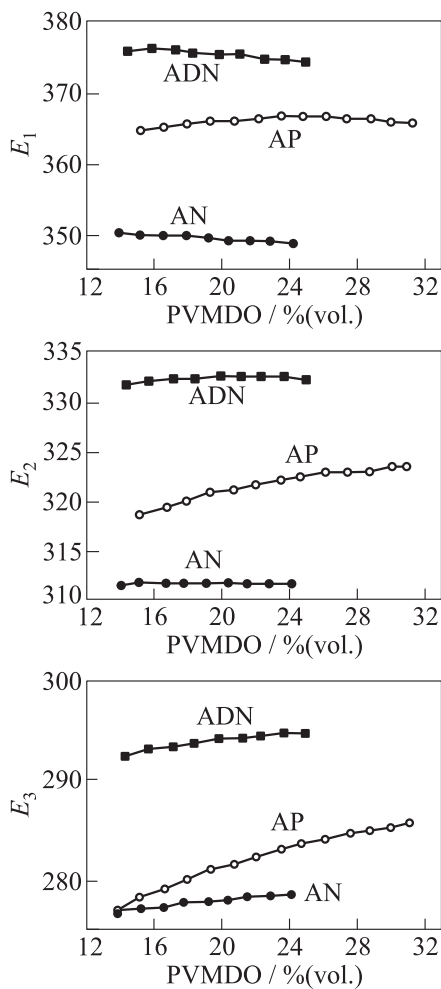


Figure 8 Ballistic efficiency of PVMDO + oxidizer + 20% Al compositions

structure. Only formate anion proved capable of forming isomorphous alloys in AN lattice in both cocrystallization and alloying [6]. Unfortunately, the phase stabilization could be achieved only at a high content of formate, so the resulting compound made little sense as an oxidizer. Authors' studies showed that a number of compounds, namely, derivatives of five- or six-member nitrogen-containing heterocycles with carbonyl, amine, or imine groups, have a stabilizing effect on

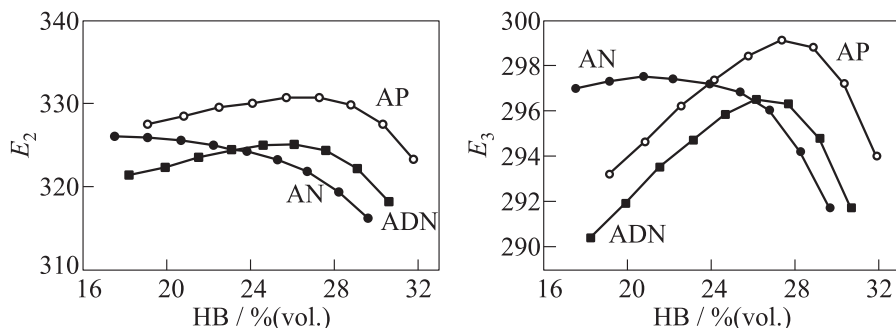


Figure 9 Ballistic efficiency of HB + oxidizer + 13% Be compositions

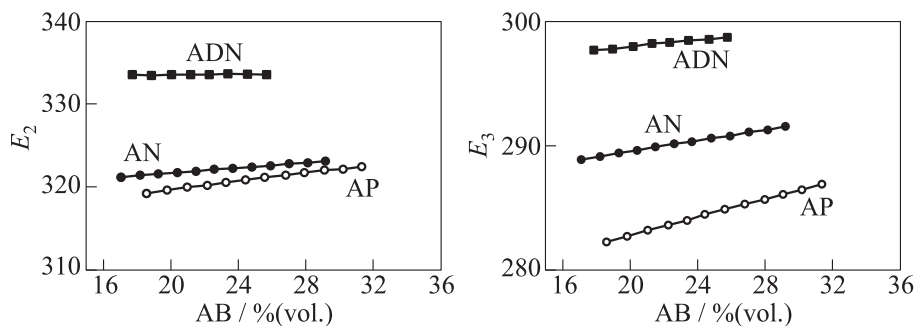
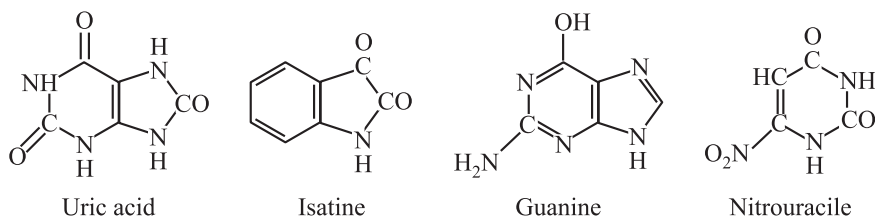


Figure 10 Ballistic efficiency of AB + oxidizer + 13% Be compositions

AN. In some cases, phase structure stabilization occurred at an additive content of only 3%–4%. Some stabilizers are shown below:



However, this stabilization is not complete: one phase transition, IV–II at +50 °C or so persists. Nevertheless, this incomplete stabilization increases dramatically the mechanical stability of AN items at cyclic shock heating. Figure 14 demonstrates pressed AN tablets after such tests.

Note that the cracks arising after 40 heating cycles (Fig. 14, right) are due to very fast cycling (in 20–30 min) and therefore, wide range of temperature

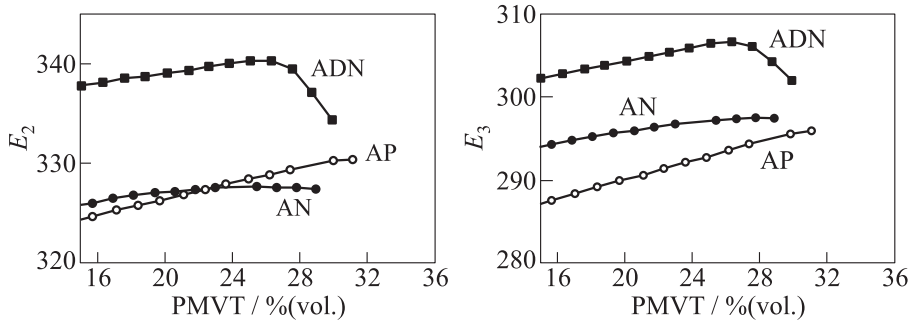


Figure 11 Ballistic efficiency of PMVT + oxidizer + 13% Be compositions

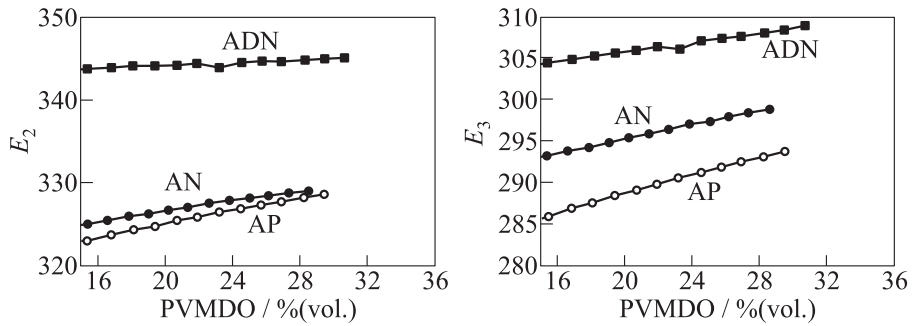


Figure 12 Ballistic efficiency of PVMDO + oxidizer + 13% Be compositions

Table 6 Calculated maximum attainable E_2 and E_3 for the compositions with AB, oxidizer, and energetic component: Al (not exceeding 20%), or Be (not exceeding 14%), or AlH_3 (not exceeding 25%)

Energetic component	Oxidizer	E_2	E_3
		g, cm ³ , s	
Al	AN	312	278
	AP	321	286
	ADN	332	294
Be	AN	329	297
	AP	331	299
	ADN	334	308
AlH_3	AN	322	294
	AP	333	300
	ADN	338	306

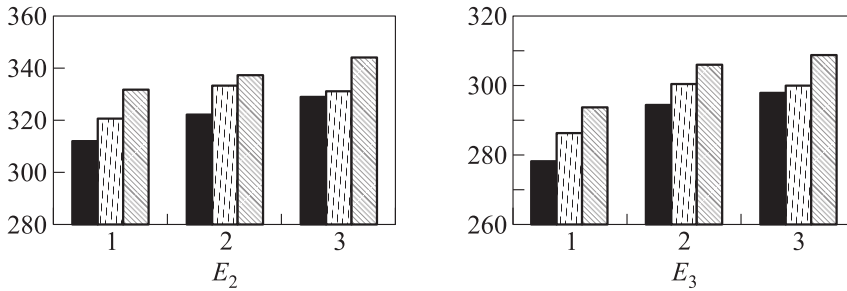


Figure 13 The calculated maximum attainable E_2 and E_3 . 1 — formulations with Al; + — formulations with AlH_3 ; 3 formulations with Be. In each group the left bar corresponds to AN, the middle — to AP, and the right — to ADN

Table 7 Energy potential of compositions containing 18% AB, 20% Al, 50% HMX, and 12% oxidizer

Oxidizer	I_{sp} , s	ρ , g/cm ³	T_c , K	E_1	E_2 g, cm ³ , s	E_3
AP	259.6	1.924	3790	384.4	337.3	295.9
ADN	261.9	1.905	3780	385.5	338.9	297.9
AN	262.3	1.895	3760	384.9	338.7	298.1

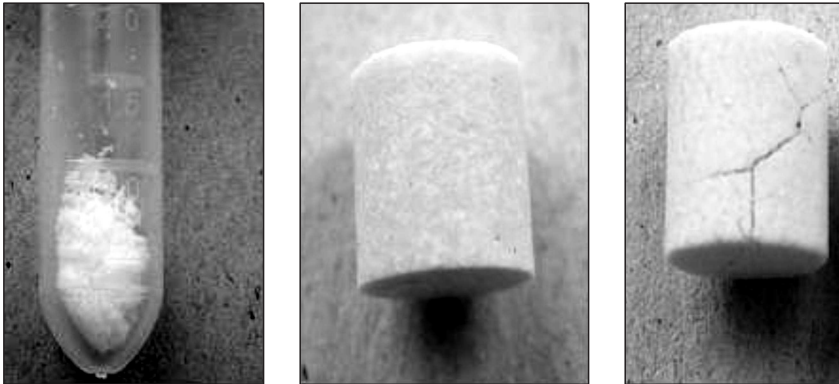


Figure 14 Samples of pressed AN tablets after multiple cyclic shock heating from -40 to $+90$ °C. Left to right: neat AN after two cycles; AN stabilized with uric acid after 10 cycles; and the latter after 40 cycles. Initial dimensions of the tablets: height $\sim 8-10$ mm, diameter 6.0 mm

sweep in small samples. The tests were aimed at application of stabilized AN in gas-generating compositions for airbag inflators. The temperature storage conditions for SCPs are substantially milder. Additionally, the remaining IV–II phase transition occurs at ~ 50 rather than at the $32\text{ }^{\circ}\text{C}$ IV-to-III phase transition often found for AN samples. Therefore, the gap between average storage temperature and phase transition has been substantially increased. The number of cases when the temperature could reach the phase transition point during years of storage has been reduced by orders of magnitude. Still, despite this optimistic assessment, a search for further phase stabilization of AN is necessary to get rid of any transition within the range of -40 to $+70\text{ }^{\circ}\text{C}$. The work is underway at the Institute for Problems of Chemical Physics of the Russian Academy of Sciences.

5 CONCLUDING REMARKS

1. Despite the fact that AN is less energetic oxidizer compared to AP and ADN, it may compete them in cases when cost plays an important role, when environmental impact of combustion products is limiting (advantage over AP) and when storage in a wider temperature range is required (advantage over ADN).
2. Upon addition of energetic components (Al, Be, hydrides), the ballistic efficiency of AN-based formulations increases more rapidly than for compositions using other oxidizers.

REFERENCES

1. Nechiporenko, G. N., and D. B. Lempert. 1998. An analysis of energy potentials of composite solid propellants containing beryllium or beryllium hydride as an energetic component. *Chem. Phys. Rep.* 17:1927–47.
2. Lempert, D. B., G. N. Nechiporenko, G. P. Dolganova, and L. N. Stesik. 1998. Specific impulse of optimized solid propellants (binder + metal + oxidizer) as a function of metal and oxidizer properties. *Chem. Phys. Rep.* 17:1547–56.
3. Rubtsov, Yu. I., A. I. Kazakov, L. P. Andrienko, I. I. Strizhevskii, and E. B. Moshkovich. 1987. Rate of thermodestruction of solid ammonium nitrate in presence of water and excess of nitric acid. *Rus. J. Appl. Chem.* 60:3–7.
4. Rubtsov, Yu. I., A. I. Kazakov, D. B. Lempert, and G. B. Manelis. 2006. Kinetic regularities of heat release in interaction of some organic compounds with ammonium nitrate. *Propellants Explosives Pyrotechnics* 31(6):421–34.
5. Campbell, A. N., and J. R. Campbell. 1946. *Can. J. Res., Sect. B* 24:93–108.
6. Lempert, D. B., G. N. Nechiporenko, N. I. Golovina, G. V. Shilov, G. P. Dolganova, and G. G. Nemtsev. 2004. Ammonium nitrate cocrystallites as a way to eliminate phase transitions in ammonium nitrate crystal lattice. 7th “Airbag-2004” (*International*) Proceedings. Karlsruhe, Germany. 44/1–44/4.