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Insensitive high explosives: IV. Nitroguanidine – Initiation & detonation

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ABSTRACT

This paper reviews the detonative properties of low bulk density (LBD), high bulk density (HBD) Nitroguanidine (NGu)(1), CAS-No: [556-88-7] and 82 explosive formulations based on NGu reported in the public domain. To rank the performance of those formulations they are compared with 15 reference compositions containing both standard high explosives such as octogen (HMX)(2), hexogen (RDX)(3), pentaerythritol tetranitrate (PETN)(4), 2,4,6-trinitrotoluene (TNT)(5) as well as insensitive high explosives such as 3-nitro-1,2,4-triazolone (NTO)(6), 1,3,5-triamino-2,4,6-trinitrobenzene (TATB)(7), 1,1-diamino-2,2-dinitroethylene (FOX-7)(8) and N-Guanylurea dinitramide (FOX 12)(9). NGu based formulations are superior to those based on FOX-12 or TATB and are a close match with FOX-7 based explosives, the latter just having higher Gurney Energies (~10%) and slightly higher detonation pressure (+2%). NGu based explosives even reach up to 78% of the detonation pressure, 82% Gurney energy and up to 95% of detonation velocity of HMX. LBD-NGu dissolves in many melt cast eutectics forming dense charges thereby eliminating the need for costly High Bulk Density NGu. Nitroguanidine based formulations are at the rock bottom of sensitiveness among all the above-mentioned explosives which contributes to the safety of these formulations. The review gives 132 references to the public domain. For a review on the synthesis spectroscopy and sensitiveness of Nitroguanidine see Ref. [1].

1. Introduction

Nitroguanidine is an important ingredient in triple base and insensitive, low erosion gun propellants, rocket propellants, gas generators for automobile restraint systems, smoke free pyrotechnics and shock insensitive high explosives [2]. Though its use in high explosives is referred to in the literature [3–5] there lacks a comprehensive and contemporary overview of the detonative performance of nitroguanidine and its formulations and an assessment of the sensitiveness of these formulations and the response of munitions containing those formulations to insensitive munitions tests in accordance with NATO AOP-39 [6]. Fig. 1 displays the valence bond structures of nitroguanidine (1) and the reference explosives octogen (HMX)(2), hexogen (RDX)(3), pentaerythritol tetranitrate (PETN)(4), 2,4,6-trinitrotoluene (TNT)(5) as well as insensitive high explosives such as 3-nitro-1,2,4-triazolone (NTO)(6), 1,3,5-triamino-2,4,6-trinitrobenzene (TATB)(7), 1,1-diamino-2,2-dinitroethylene (FOX-7)(8) and N-Guanylurea dinitramide (FOX 12)(9). Table 1 list the basic properties of NGu and the main reference explosives.

2. Thermochemistry

2.1. Enthalpy of formation and enthalpy of vaporisation

The solid-state enthalpy of formation of NGu ($\Delta_f H^\circ$) has been determined several times by combustion calorimetry [7–10]. There is considerable scatter of data ($\Delta_f H = -92$ kJ/mol to -100 kJ/mol) and in Ref. 8 some variation of $\Delta_f H$ is attributed to different grain sizes with larger grains leading to lower combustion enthalpy. The gas phase enthalpy of formation has been estimated and calculated [11,12]. The calculated value ($\Delta_f H(g) = +44{,}77$ kJ/mol) [12] fits the experimental data for the condensed state with the experimentally determined vaporisation enthalpy ($\Delta_{vap} H = 142.7$ kJ/mol) [13] adding up nicely according to

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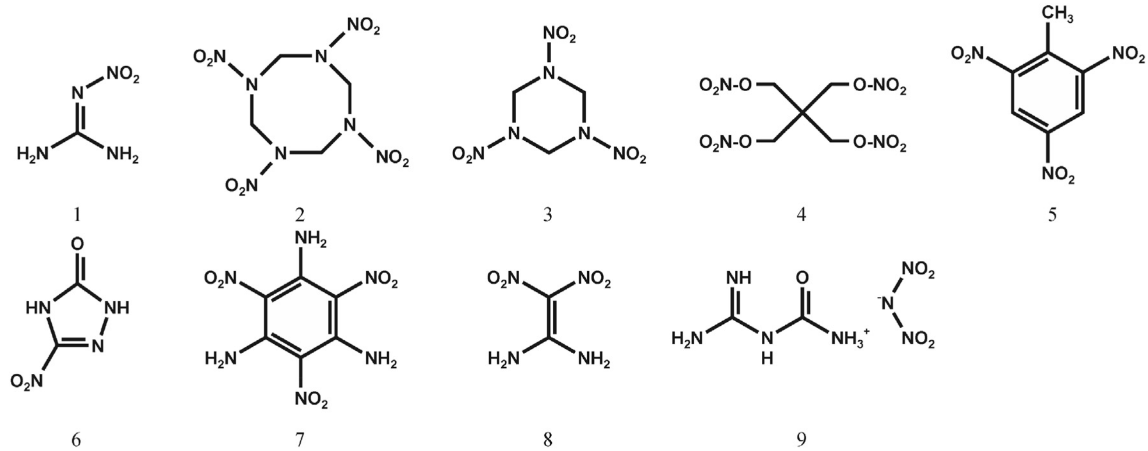

Fig. 1. Structures of Nitroguanidine (1) and the reference explosives, HMX (2), RDX (3), PETN (4), TNT (5), NTO (6), TATB (7), FOX-7 (8), FOX-12 (9) dealt with in this review.

Table 1
Basic thermochemical properties of the reference explosives dealt with in this report after Ref. [59].

	1	2	3	4	5	6	7	8	9
Formularowhead	$CH_4N_4O_2$	$C_4H_8N_8O_8$	$C_3H_6N_6O_6$	$C_5H_8N_4O_{12}$	$C_6H_5N_3O_6$	$C_2H_2N_4O_3$	$C_6H_6N_6O_6$	$C_2H_4N_4O_4$	$C_2H_7N_7O_5$
CAS-No.	556-88-7	2691-41-0	121-82-4	78-11-5	118-96-7	932-64-9	3058-38-6	145250-81-3	217464-38-5
$\rho/(g \cdot cm^{-3})$	1.770	1.906	1.806	1.778	1.654	1.930	1.937	1.907	1.760
$m_r/(g \cdot mol^{-1})$	104.068	296.156	222.117	316.138	227.133	130.063	258.150	148.080	209.121
$\Delta_f H/(kJ \cdot mol^{-1})$	−98.74	84.01	66.94	−462.00	−67.07	−97.00	−154.00	−134.00	−356.00
Ω/(wt.%)	−30.75	−21.61	−21.61	−10.12	−73.96	−24.60	−55.78	−21.61	−19.13
M_p/°C	–	–	–	–	80.8	–	448.0 (D_p)	–	–
D_p/°C	257	280	204	192	240	264		225	215

ρ = density; m_r = molecular weight; $\Delta_f H$ = enthalpy of formation, Ω = oxygen balance, M_p = melting point; D_p = decomposition point.

$$\Delta_f H(s) = \Delta_f H(g) + \Delta_{vap} H = -97.93 \text{ kJ/mol}$$

which is within the range of $\Delta_f H(s)$ determined experimentally above (Table 2).

2.2. Enthalpy of detonation

From Kamlet's work it is known that the detonation velocity correlates with the fourth root of the detonation enthalpy,

$$v_D \sim \Delta_{det} H^{-0,25},$$

whereas the detonation pressure correlates with the square root of the detonation enthalpy [15–18],

$$p_{CJ} \sim \Delta_{det} H^{-0,50}.$$

Precise knowledge of $\Delta_{det}H$ is therefore essential to assess the detonative performance of a high explosive. However, this is difficult as the enthalpy of detonation is the heat released in the CJ-point and there is no way in experimentally determining this. Experimental determinations from detonation calorimeters using heavily confined charges (e.g. gold) hence rather correspond to the freeze-out region of the expansion isentrope and are correspondingly yield higher values than would be found exactly at the CJ point. $\Delta_{det}H$ can be calculated either based on semiempirical methods or based on the chemical composition of the post detonation residues from closed vessel detonations under an inert gas. In addition, $\Delta_{det}H$ can be determined in a detonation calorimeter from firing heavily confined (e.g. gold) charges [19].

Table 2
Enthalpy of formation of nitroguanidine at 298.15 K for both condensed and gas phase.

$\Delta_f H°/(kJ \cdot mol^{-1})$	Reference state	Method	Ref
−75.30	Solid	calorimetry	[7]
−97.40	Solid	calorimetry	[8]
−93.72 ± 1,67	Solid (1–3 mm grain)	calorimetry	[9]
−100.00 ± 2.51	Solid (0.2–0.8 mm grain)	calorimetry	[10]
−92.05 ± 2.47	Solid	calorimetry	[11]
−98.74	Solid	calorimetry	[14]
−1.00 ± 20	Gas	estimation[a]	[11]
+44.77	Gas	ab initio[b]	[12]

[a] Statistical mechanics.
[b] B3LYP/6-311G(d,p).

2.2.1. Semiempirical calculation of enthalpy of detonation

The enthalpy of detonation can be estimated [20] or calculated based on the rules presented by Cooper [21].

$$CH_4N_4O_2 \rightarrow 2N_2 + 2H_2O(g) + C(s) \tag{1}$$

Based on Krien's value [10] for the enthalpy of formation using Cooper's method yields

$$\Delta_{det}H(NGu) = -391.55 \text{ kJ/mol} \tag{2}$$

Taking into account the molar mass of NGu (m_r: 104.068 g/mol) this equals

$$\Delta_{det}H(NGu) = -3.762 \text{ kJ/g}. \tag{3}$$

2.2.2. Calculation of enthalpy of detonation based on detonation products

Pure NGu with low porosity is relatively hard to initiate and small charges ($\phi < 40$ mm) do not detonate ideally due to having a large critical diameter and quite a long run to detonation distance

[22]. Hence closed chamber ($V = 1.5\ m^3$) detonation experiments in Ar-atmosphere have been conducted with NGu/TNT-based melt cast charges (hereafter designated Nigutol) with NGu-contents ranging from 40 wt%~60 wt% [23,24]. Although the formal detonation according to Eq. (1) yields N_2, H_2O and C it is however observed upon analysis of the post detonation gases that significant amounts of both ammonia and hydrogen cyanide are formed. Table 3 shows the product composition for the detonation of both Comp B and various Nigutol charges in argon (0.1 MPa) highlighting the aforementioned.

Based on the above compositions the detonation enthalpy has been determined and is reproduced in Table 4.

In first approximation the enthalpy of detonation of a composition of two immiscible high explosives with both negative oxygen balance A and B the weight fractions n and m respectively is the sum of the enthalpy of detonation of its components.

$$\Delta_{det}H(n \times A + m \times B) = n \times \Delta_{det}H(A) + m \times \Delta_{det}H(B) \tag{4}$$

This assumes any chemical interaction of the individual explosive particles and their initial decomposition products does not occur until <u>after</u> reaching the CJ point. Table 5 compares the measured detonation enthalpy for RDX, HMX, TNT, Comp B and Octol with those values calculated detonation enthalpy for Comp B and Octol from Ref. [19] based on Eq. (4). Evidently the measured and calculated values for both compositions are within 1% of error.

Rearrangement of Eq. (4) to resolve the enthalpy of detonation of NGu based from the detonation enthalpy of its composite Nigutol (TNT + NGu) with its weight fraction n yields Eq. (5):

$$\Delta_{det}H(\text{NGu}) = \{\Delta_{det}H(\text{Nigutol}) - m \times \Delta_{det}H(\text{TNT})\}/n \tag{5}$$

Inserting the individual figures from Table 3 and the value for TNT from Table 4 yields the $\Delta_{det}H$ (NGu) values depicted in Table 6.

The obtained value for $\Delta_{det}H$ (NGu) = −2,991 kJ/g is very close (−1%) to a value cited in Fedoroffs Encyclopedia of Explosives $\Delta_{det}H$ (NGu) = −3,016 kJ/g [3] giving some support for the latter.

3. Detonation

3.1. Detonation of neat NGu

3.1.1. High velocity detonation (HVD) of neat NGu

Gogyula et al. optically determined the detonation temperature for NGu ($\rho = 1.649\ g/cm^3$) to 2 562 K [27] which is in the same ball park as the temperature calculated for a charge with the same density 2 830 K.

3.1.1.1. Detonation velocity. Price et al. have investigated the detonation velocity and critical diameter for neat unconfined NGu charges [28,29]. The infinite diameter law for charges with densities ranging from $\rho_0 = 1.00–1.78\ g/cm^3$ accordingly reads

Table 4
Detonation enthalpy, H_2O(g), of various Nigutol composites.

Composition	1	2	3
NGu/(wt.%)	40	50	60
TNT/(wt.%)	60	50	40
Density/($g \cdot cm^{-3}$)	1.62	1.63	1.64
$\Delta_{det}H$/($kJ \cdot g^{-1}$)	−3.909	−3.742	−3.536

Table 5
Enthalpy of detonation of TNT, RDX and Comp B.

Item	TNT	RDX	HMX	Comp B	Comp B Calc.	Octol[a]	Octol Calc.
$\Delta_{det}H$/($kJ \cdot g^{-1}$)	4.477	6.075	6.188	5.527	5.436	5.694	5.736

[a] 73.58 wt% HMX, 26.42 wt% TNT.

Table 6
Enthalpy of detonation of NGu from various Nigutol-composites.

Item	1	2	3	Mean
$\Delta_{det}H$/($kJ \cdot g^{-1}$)	−3,057	−3,007	−2,909	−2,991

$$v_{D\infty}(\text{experiment}) = 1440 + 4015 \times r_0(\text{m/s}) \qquad (3.2\ \ -1)$$

Predictions with Cheetah 7.0 [30] based on an enthalpy of formation of NGu of $\Delta_f H = -98.74$ kJ/mol call for a significant steeper slope

$$v_{D\infty}(\text{Cheetah 7.0}) = -747.5 + 5388 \times r_0(\text{m/s}) \qquad (3.2\ \ -2)$$

and overshoot the actual performance at ρ0 > 1.6 g/cm3, while predictions with Cheetah 2.0 [25].

Using the same enthalpy of formation show a slope more alike the experimentally determined one but undershoot the actual performance nearly constantly by 3%~4% in the range between $\rho_0 = 1.55–1.78\ g/cm^3$ (Fig. 1).

$$v_{D\infty}(\text{Cheetah 2.0}) = 836.1 + 4220 \times r_0(\text{m/s}) \qquad (3.2\ \ -3)$$

Experimental and calculated data on neat FOX-12 [31] shown in Fig. 2 indicate that FOX-12 has a lower detonation velocity than NGu at given density.

Fig. 3 shows the influence of density on fixed diameter charges. With decreasing density, the detonation velocity of the individual diameter charges fans away from the infinite diameter line (Fig. 3) as is also observed with many group 1 high explosives [32].

Table 3
Composition and enthalpy of formation of experimentally measured and calculated [25] post-detonation products from Comp B and Nigutol-50 [26].

Product	$\Delta_f H°$/($kJ \cdot mol^{-1}$)	Comp B		Nigutol-40(1)		Nigutol-50(2)		Nigutol-60(3)	
Density/($g \cdot cm^{-3}$)		1.69	[a]	1.62	[a]	1.63	[a]	1.64	[a]
N_2/(mol%)	0	23.4	24.0	21.8	17.9	23.1	18.4	24.8	18.8
H_2/(mol%)	0	5.5	1.4	3.7	0.5	3.3	0.4	2.4	0.2
CO/(mol%)	−110	20.4	17.7	16.5	7.0	14.9	4.9	11.8	3.3
CO_2/(mol%)	−294	10.8	9.5	10.9	5.0	14.3	4.0	11.6	3.2
CH_4/(mol%)	−75	0.2	1.6	0.3	1.0	0.2	0.8	0.3	0.1
HCN/(mol%)	+130	0.6	–	2.3	–	2.9	–	2.7	–
NH_3/(mol%)	−46	2.9	0.1	6.2	0.7	11.4	0.1	11.6	0.1
H_2O/(mol%)	−285	19.6	23.1	17.2	19.4	13.7	19.5	16.3	19.6
C(s)/(mol%)	0	16.6	16.8	21.1	21.5	16.3	19.1	16.5	16.9
NO/ppm	+90	25		116		66		4 000	

[a] Mol/Mol explosive.

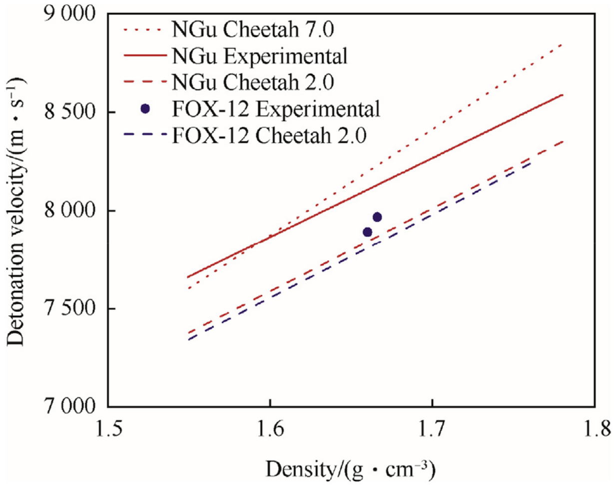

Fig. 2. Experimental and calculated infinite diameter detonation velocity of NGu and FOX-12.

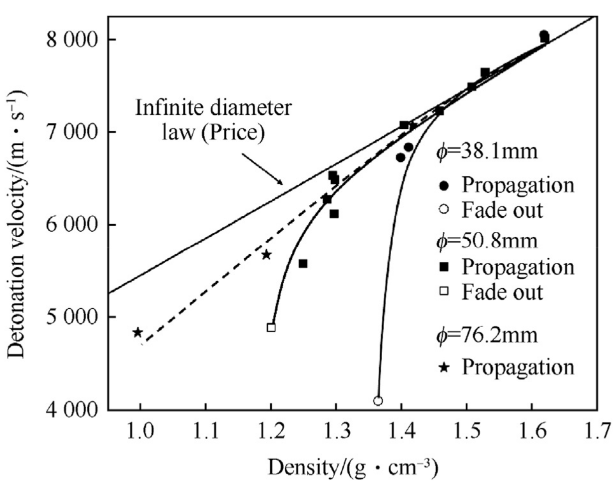

Fig. 3. Effect of Density on Detonation Velocity at two fixed diameters.

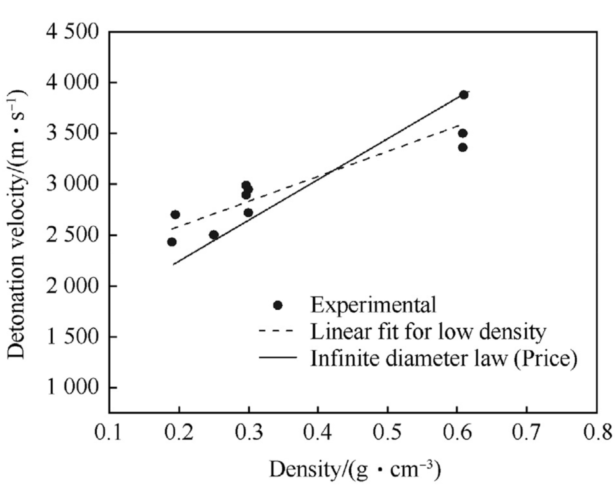

Fig. 4. Effect of Density on Detonation Velocity of confined charges at low ρ.

Even at densities, much lower than $\rho < 0.6\ g/cm^3$, the detonation velocity of NGu about follows Price's law (Fig. 4) but can be fitted more appropriately with the expression

$$v_{D\infty}(\text{experiment}) = 2091 + 2464 \times r_0(\text{m/s}) \qquad (3.2\ \ -4)$$

The inverse diameter detonation velocity relationship for unconfined $\rho_0 = 1.51\ g/cm^3$ is depicted in Fig. 5. Below charge diameters of $\phi = 14$ mm the detonation fades out. Depending on the particle type of NGu LBD or HBD [1] the fade-out diameter for charges of varying density appears to differ as is depicted in Fig. 6. Thus, in the considered density range LBD can be assigned a group 1 HE whereas HBD behaves like a group 2 material [29].

In comparison the critical diameter for FOX-12 with densities $1.60 \leq \rho \leq 1.67$ ranges from 24–54 mm [31].

3.1.1.2. Detonation pressure. Mader reasoned that the plate dent test typically applied to probe the p_{CJ}-pressure is an inadequate tool for Nitroguanidine and its formulation as NGu fails to correlate with its P_{CJ} pressure due to its low energy and the resulting steep isentrope compared to most other explosives [33]. Poor plate dent results for NGu in turn have fed the unsubstantiated "reputation" that NGu is an inferior explosive. Hence the data referred to in this review exclusively stem from copper cylinder tests unlike otherwise stated.

The experimentally determined detonation pressure for charges with densities ranging from 0.19 g/cm^3 to 1.7 g/cm^3 are given in Table 7 [27, 34–38] and depicted in Fig. 7 together with the detonation pressure of neat FOX-12 [39] (p_{CJ} ($\rho = 1.666$ g/cm^3) = 26.11 GPa) and the calculated p_{CJ} for both NGu and FOX-12. Mader also reasoned that though NGu has only half the detonation enthalpy of Comp B (see Table 5 and Table 6) it still performs comparable due to its favourable particle density of the detonation products due to the high hydrogen content in the explosive and consequently the water content in the final products [33].

3.1.1.3. Gurney Energy. The Gurney energy, E_G (J/g) and Gurney velocity, $\sqrt{2E_G}$ (m/s), dealt with in the context of this review relate to the corresponding energies and velocities determined for the relative expansion of copper cylinders ($ID = 25.4$ mm, wall thickness 2.54 mm) at $r_a = 5–7$ mm and $r_a = 19–26$ mm respectively. Table 8 displays the $\sqrt{2E_G}$ or NGu [40,41], FOX-12 [42] and several reference high explosives [41,43]. The Gurney Energy typically drops with decreasing density for a given explosive [41,43]. Hence

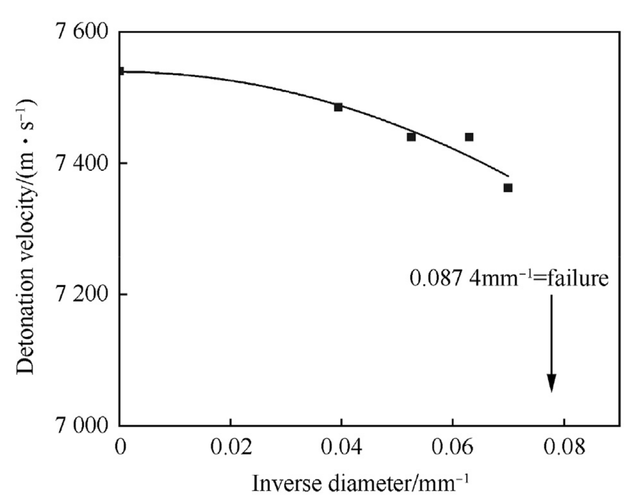

Fig. 5. Diameter Effect on Detonation Velocity at $\rho_0 = 1.514$ g/cm^3.

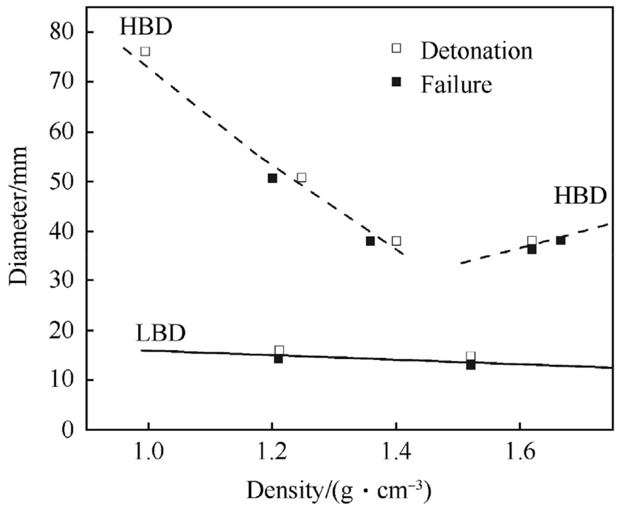

Fig. 6. Diameter effect on detonation velocity of LBD and HBD.

Table 7
Experimental p_{CJ} of NGu at different densities.

Density/ (g·cm^{-3})	0.195	0.500	0.720	0.850	1.000	1.100	1.250	1.400	1.635	1.720
p_{CJ}/GPa	0.63	1.48	2.39	3.28	4.20	4.87	10.30	15.80	28.63	24.50
Ref	[34]	[35]	[36, 37]	[36, 37]	[36, 37]	[36, 37]	[36, 37]	[36, 37]	[27]	[38]

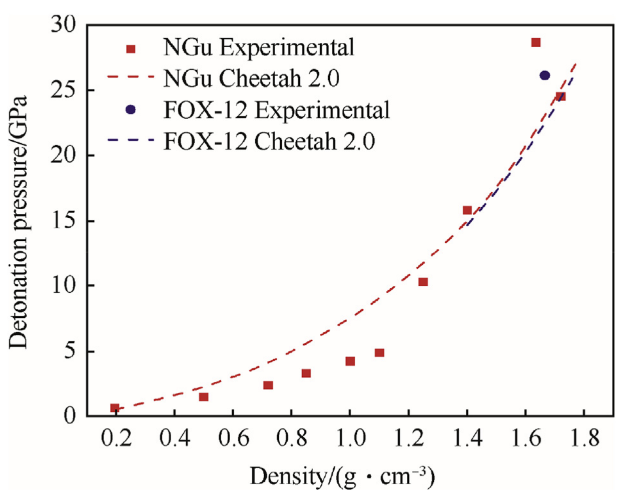

Fig. 7. Experimental and calculated p_{CJ} for NGu and FOX-12.

the low figure measured with NGu is not unusual. The Gurney energies of various formulations are presented further down in § 3.2.

3.1.2. Low velocity detonation (LVD) of neat NGu

At charge densities below $\rho_0 = 1.2$ g/cm^3, HBD shows a stable low velocity detonation (LVD). Fig. 8 depicts the observed velocities and Fig. 6 shows the critical diameter for LVD with charges based on HBD after Price [32].

The effect of density on LVD has been tested by Montesi in the context of investigations on the water arm air safe detonator (WARAS) [45,46].

In low density charges ($\rho = 0.5$ g/cm^3) of NGu the gas pressure of the pockets has a distinct influence on the propagation of LVD and high pressures diminish propagation velocity and eventually inhibit propagation (Fig. 9) [47].

3.1.3. Shock wave Hugoniot data on neat NGu

Hugoniot curve data for neat NGu of different particle density are presented as $U_s - u_p$ and $p - V$ diagram in Figs. 10 and 11 [4,48].

3.2. Detonation of NGu-based formulations

3.2.1. Melt-castable formulations

3.2.1.1. NGu-TNT (Nigutol). By far the most thoroughly studied NGu-based high explosives mixtures are those based on TNT as melt cast binder. NGu/TNT mixtures (Nigutol), were initially developed as high explosives in wartime Germany [49,50] and were then used as an insensitive filler for armour piercing naval artillery shells. Research into Nigutol was resumed in Germany in the 1980s and the US in the early 1990s when new cheap insensitive high explosives were sought. This research was also motivated by new crystallisation processes developed then which allowed to produce NGu with high spherical high bulk density >1.0 g/cm^3 [1]. Also, the first nanodiamonds formed by detonation were found by Volk et al. in the detonation soot of Nigutol and TATB/TNT mixtures [51].

The detonation enthalpy of various Nigutol formulations has been determined by Volk and Schedlbauer [23,24] and is already given above in Table 6. Fig. 12 compares the experimental and calculated detonation enthalpy at given experimental density for Nigutol. The free-standing charges ($\phi = 50$ mm) yield about 88% of the calculated enthalpy whereas the charge confined in 9 mm glass yields 92% of the calculated enthalpy.

The critical diameter has been determined for Nigutol-50 with different particle types and size distributions as is indicated in Table 9 [52,53]. The general observation is that small particle sizes yield smaller critical diameters.

Schedlbauer [54], and Lungenstraβ [55] investigated a large

Table 8
Gurney Velocity for various neat high explosives.

High Explosive	Density/(g·cm^{-3})	TMD/%	$\sqrt{2E_G}$ (m·s^{-1})		v_w/(m·s^{-1})	$V/V_0 = 9.0$/(kJ·cm^{-3})	Ref
			5~7 mm	19–26 mm			
PETN	1.765	99.3		3 030		−8.68	[43]
	1.500	84.4		2 900		−6.79	[43]
	1.270	71.4		2 690		−5.33	[43]
HMX	1.891	99.2		3 110		−9.74	[43]
	1.190	62.4		2 740		−5.02	[43]
	1.810	95.0			2 130	−9.12	[44]
NGu	1.440	81.0	1 896			−4.54	[40, 41]
	1.635	92.9			1 780	−5.46	[44]
TNT	1.610	97.3	2 097			−5.54	[41]
	1.630	98.5	2 039	2 462		−5.65	[41]
FOX-12	1.666	94.7		2 374		−5.84	[42]

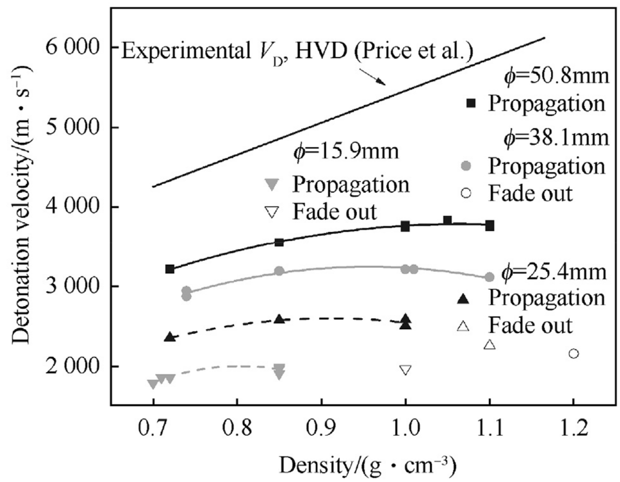

Fig. 8. Diameter Effect on LVD HBD at different diameters.

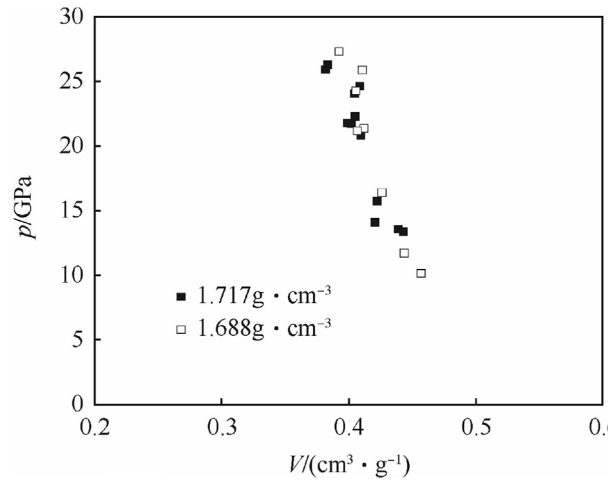

Fig. 11. p–V plane for pure NGu.

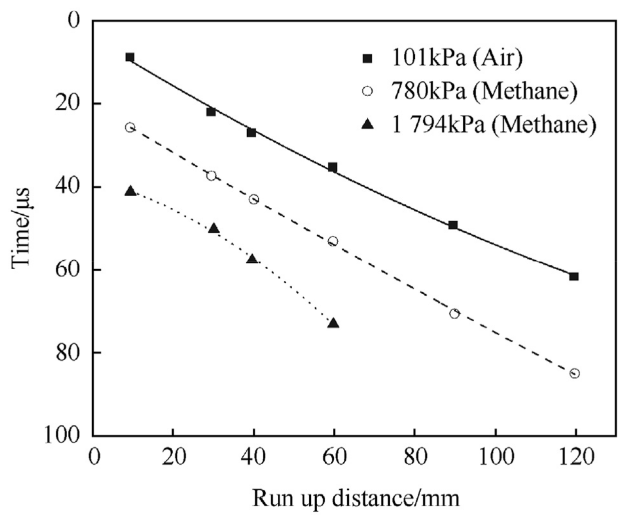

Fig. 9. Influence of gas pressure on propagation of 11,11 mm diameter NGu-charges at $\rho = 0.5$ g/cm^3.

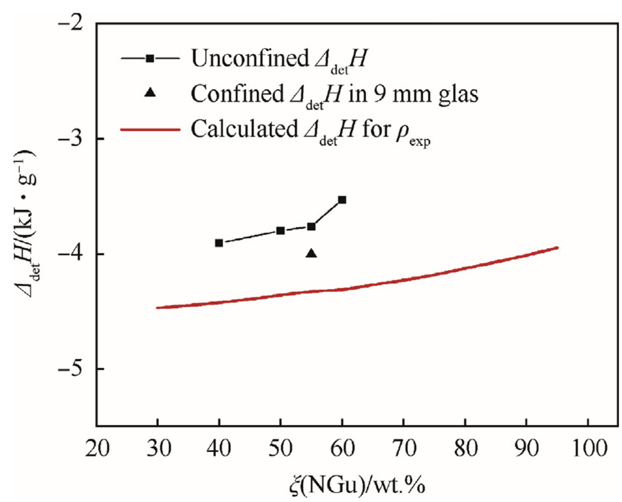

Fig. 12. Detonation enthalpy of Nigutol.

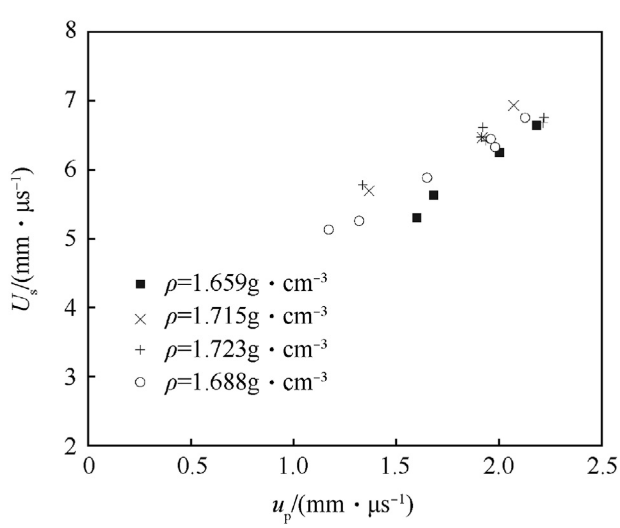

Fig. 10. $U_s - u_p$ plane for pure NGu.

array of Nigutol formulations (Table 10). Fig. 13 depicts the experimental detonation velocity, the calculated detonation velocity at TMD the calculated detonation velocity at the experimental density for Nigutol and Guntol (FOX-12/TNT) [56] and the baseline experimental detonation velocity of Comp B at $\rho = 1.71$ g/cm^3 for comparison. In general, the experimental detonation velocities for Nigutol with ξ(NGu) < 80 wt% undershoot the calculations in average by 2% whereas at ξ(NGu) = 80 wt% and beyond the experimental detonation velocities are higher than calculated at given experimental density and supersede the Comp B baseline performance. The few Guntol (FOX-12/TNT) formulations investigated exhibit lower experimental detonation velocities at corresponding stoichiometries.

The experimental detonation velocity of aluminized Nigutol and one single aluminized Guntol (Guntonal) [56]. Is shown in Table 11 [54,57].

The detonation pressure determined by cylinder tests has been reported by Hornberg for Nigutol-35, -50 (Fig. 14) and aluminized Nigutol [58]. Table 12 displays those values together with formulations based on FOX-12.

The Gurney-Velocities of Nigutol and Guntol modified with either or both nitramine and aluminium are presented in Table 13. In essence Gurney-Energy for Nigutol is between 10%~17% higher

Table 9
Critical diameter of Nigutol- 50 with SHBD and HBD [52,53].

	d_p/(μm)	ϕ_{cr}/(mm)	ρ/(g·cm^{-3})	% TMD 1.710/(g·cm^{-3})	v_D/(m·s^{-1})
HBD	105–210	<19	1.663	97.25	7400
HBD	297–420	29 ± 3	1.643	96.08	7280
SHBD	105–210	<19	1.638	95.79	7620
SHBD	297–420	25 ± 3	1.636	95.67	7430

Table 10
Detonation velocity of various Nigutol (unconfined ϕ = 50 mm) and two Guntol (Cu-confined, ϕ = 60 mm) formulations.

NGu/ (wt.%)	FOX-12/ (wt.%)	TNT/ (wt.%)	ρ_{exp}/ (g·cm^{-3})	v_{Dexp}/ (m·s^{-1})	at 20 mm diameter [55]
95		5	1.69	8056	
92		8	1.70	–	8100
90		10	1.70	8022	
85		15	1.70	8029	
80		20	1.69	7833	
75		25	1.70	7721	
70		30	1.69	7687	
65		35	1.67	7600	
60		40	1.68	7431	7140
55		45	1.63	7224	
50		50	1.63	7255	
40		60	1.63	7106	
30		70	1.61	7002	
	50	50	1.652	7120	
	45	55	1.63	6860	

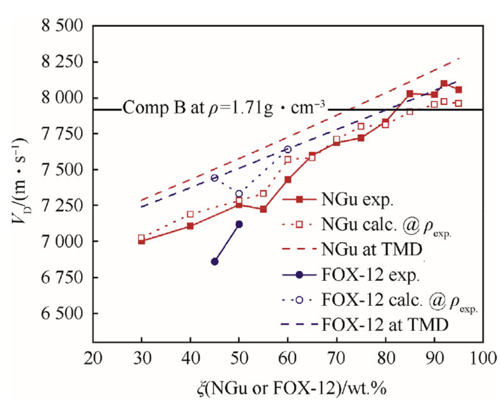

Fig. 13. Detonation velocity of Nigutol and Guntol as function of respective NGu and FOX-12 content.

than for Guntol. Remarkable is that Nigutol-50 is equally powerful as Guntol (35/40) modified with 25 wt% HMX (sic). While adding aluminium has no pronounced effect on Nigutol-35 the Gurney velocities of Guntol apparently decreases.

3.2.1.2. IMX-101 and ALIMX-101. Two important NGu-based melt cast formulations comprising NTO as an additional insensitive filler are IMX-101 [63] (formerly known as OSX-CAN) and its aluminised derivative ALIMX-101 [64]. Table 14 displays the disclosed composition for IMX-101 and the alleged formulation for ALIMX-101, Table 15 shows the performance. Due to the large critical diameter of IMX-101 neither plate dent nor aquarium test have been conducted so far. The values used in Refs. [66,68] are based on a Cheetah 4.0 calculation at ρ = 1.63 g/cm^3.

The unreacted Hugoniot data for IMX was obtained by Roth et al. [68] and is displayed in Fig. 15.

3.2.1.3. PrNGu-NGu-HMX. *n*-Propylnitroguanidine (PrNGu) (m_p: 98.5 °C) is a substance currently investigated as potential melt-cast base for high explosives [69]. As a crystal density is unknown its density has been estimated using Ammon's procedure [70] to ρ = 1.35 g/cm^3. A ternary formulation comprising about equal amounts PrNGu, NGu and HMX has been investigated by Samuels et al. (Tables 16 and 17) [71].

3.2.1.4. Eutectic systems based on NGu. NGu forms a series of eutectic systems with other explosive materials and dissolves nicely in many energetic ionic liquids. Hence highly dense charges can be obtained entirely without using costly SHBD.

Manuelli and Bernadini were the first to claim eutectic melt-castable formulations named Albite, based on NGu, ammonium nitrate and guanidinium nitrate with melting points below 130 °C [72]. Urbanski and Skrzynecki found that a formulation.

3.2.1.4.1. NGA

- Nitroguanidine 17.5 wt%
- Guanidinium nitrate 22.5 wt%
- Ammonium nitrate 60.0 wt%

Would melt as low as 113.2 °C [73]. In addition, they found two other binary eutectic mixtures.

Table 11
Detonation velocity of various aluminized Nigutol (unconfined ϕ = 50 mm) and one aluminized Guntol (*Guntonal*) (Cu-confined, ϕ = 60 mm) formulations.

NGu/(wt.%)	FOX-12/(wt.%)	TNT/(wt.%)	Al/(wt.%)	ρ_{exp}/(g·cm^{-3})	v_{Dexp}/(m·s^{-1})
50		35	15	1.76	7143
45		45	10	1.72	7171
40		50	10	1.72	7109
35		50	15	1.75	7072
35		45	20	1.81	6828
33		42	25	1.89	6881
31		42	27	1.86	6952
30		50	20	1.78	6841
30		45	25	1.89	6881
30		40	30	1.88	6991
28		45	27	1.85	6901
28		42	30	1.88	6904
26		47	27	1.86	6803
25		45	30	1.87	6794
25		40	35	1.89	6800
23.5		46.5	30	1.87	6677
22		48	30	1.86	6617
	42.5		15	1.77	7160

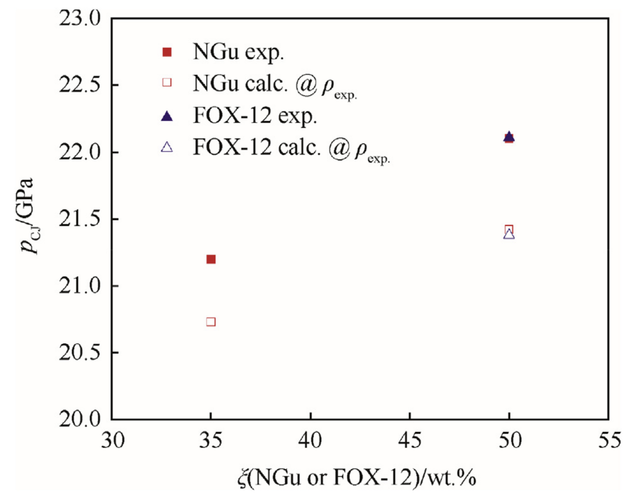

Fig. 14. Detonation pressure of TNT/NGu and TNT/FOX-12 as a function of stoichiometry.

- Nitroguanidine 20 wt%
- Ammonium nitrate 80 wt%
  m_p: 131.5 °C
- Nitroguanidine 41 wt%
- Guanidinium nitrate 59 wt%
  m_p: 166.5 °C

Table 14
Composition of NGu-based melt cast insensitive high explosives.

Component	CAS-no	IMX-101	ALIMX-101
TMD/($g\cdot cm^{-3}$)		1.688	1.800
NGu/(wt.%)	556-88-7	36.8 ± 2	~32
Aluminum/(wt.%)	7429-90-5	–	~24
2,4-DNAN/(wt.%)	119-27-7	43.5 ± 2	~34
NTO/(wt.%)	932-64-9	19.7 ± 2	~10

While neither Manuelli nor Urbanski have reported any data on the performance of NGA or any of the other formulations, Akts &Herskovitz have tested blends of NGA with other HE (Table 18 and Table 19) [74]. The critical diameter in steel confinement is well below 9.65 mm for NGA/AN/RX while NGA/AN has a limiting diameter well above 9.65 mm. Though the detonation pressure nicely correlates with calculations for NGA/AN/RDX the detonation velocity falls dramatically short by 16% against predictions with Cheetah 2.0.

3.2.1.4.2. NGu-AN-ADNT. Ammonium 3,5-dinitro-1,2,4-triazolate, ADNT (Fig. 16) ($\rho = 1.75$ g/cm^3, m_p: 168 °C, $\Delta_f H$: +4 kJ/mol) forms a eutectic mixture with AN melting at 112 °C [75] which dissolves up to 12 wt% [76] of LBD-NGu. Two formulations with 33 and about 40% NGu (dissolved content plus HBD-NGu) have been formulated and tested (see Table 20 and Table 21). The experimental CJ-pressures exceed the predicted values by 6%~8%.

3.2.1.4.3. NGu-AN-EDDN. Ethylenediammonium dinitrate, EDDN (Fig. 17) ($\rho = 1.603$ g/cm^3, mp: 186 °C, $\Delta_f H$: 653 kJ/mol) forms a eutectic mixture with AN melting at 98 °C and freezing at 81 °C

Table 12
Detonation pressure of Nigutol and related formulations.

High Explosive	Density/($g\cdot cm^{-3}$)	p_{CJ} Cylinder test/GPa	p_{CJ} Plate dent/GPa	p_{CJ} Calculated/GPa	Ref
NGu/TNT/Al (31/42/27)	1.849	20.8		19.13	[58]
NGu/TNT/Al (35/50/15)	1.745	22.7		19.65	[58]
Nigutol-35	1.658	21.2		20.73	[58]
Nigutol-50	1.665	22.1		21.42	[58]
	1.663		20.9	21.35	[52,53]
	1.643		20.9	20.68	[52,53]
	1.638		21.1	20.52	[52,53]
	1.636		21.8	20.45	[52,53]
TNT		21.0			[59]
Guntol-45		20.6			[60]
Guntol-50	1.652	22.1		20.92	[60]
FOX-12/TNT/Al (42.5/42.5/15)	1.795	23.5		21.76	[60]
	1.771	21.2		20.94	[60]

Table 13
Gurney Velocity for various melt cast NGu-based explosives.

High Explosive	Density/($g\cdot cm^{-3}$)	$\sqrt{2E_G}$ ($m\cdot s^{-1}$)		$V/V_0 = 9.0$/($kJ\cdot cm^{-3}$)	Ref
		5–7 mm	19–26 mm		
Nigutol-35	1.658		2300	−5.81	[58]
Nigutol-50	1.665		2441	−5.83	[57]
Nigutol-60	1.690		2320	−5.95	[61]
NGu/TNT/Al (31/42/27)	1.849		2039	−6.27	[58]
NGu/TNT/Al (35/50/15)	1.745		2300	−6.09	[58]
NGu/TNT/RDX(40/40/20)	1.710		2500	−6.53	[61]
Comp B (60/40)	1.730		2730	−7.61	[59]
TNT	1.630	1950		−5.65	[59]
Guntol-45		1950	2070		[62]
Guntol-50	1.652	1951		−5.75	[60]
FOX-12/TNT/Al (42.5/42.5/15)	1.759	1942		−6.36	[56, 60]
FOX-12/TNT/RDX (35/40/25)		2050	2300		[56, 62]
FOX-12/TNT/RDX/Al (35/35/15/15)		1870	2230		[56, 62]
FOX-12/TNT/HMX (35/40/25)		2100	2440		[56, 62]
FOX-12/TNT/HMX/Al (35/35/15/15)		1855			[56, 62]

Table 15
Performance of IMX-101 and ALIMX-101 [65–67].

	IMX-101 TMD: 1.688 g/cm^3			ALIMX-101 TMD: 1.845 g/cm^3		
	exp.	calc. at	calc. at	exp.	calc.at	calc. at
ρ_{exp}./(g·cm^{-3}) (Δ)	1.63	1.63	TMD	1.81	1.81	TMD
v_D(exp.)/(m·s^{-1})	6885[a]	7032	7245	6825	7029	7183
ϕ_{cr}/mm	64–68			<127		
p_{CJ}/GPa		18.8	20.6		19.5	20.6
T_{CJ}/K		3084	3072		4916	4909
$\sqrt{2E_G}$(~26 mm)/(m·s^{-1})	2036			–		
$E(V/V_0 = 9.0)$/(kJ·cm^{-3})	−5.24	−5.20	−5.49		−7.11	−7.32
γ (–)	44.03					

[a] At 82 mm diameter.

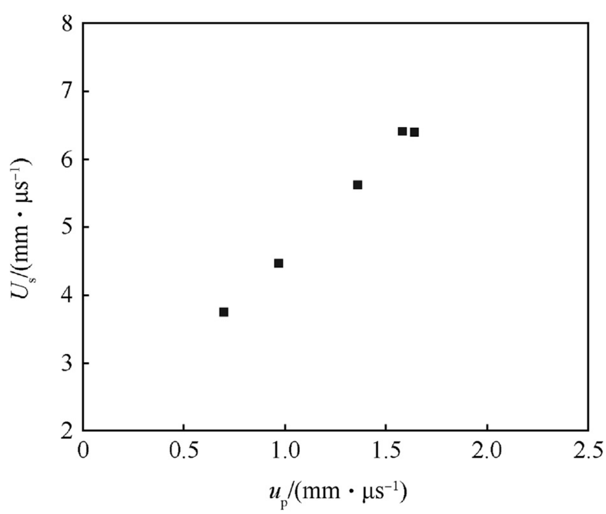

Fig. 15. $U_s - u_p$ plane for IMX-101 at ρ = 1.63 g/cm^3.

Table 16
Composition of NGu-based melt cast insensitive high explosives.

Component	CAS-no	
TMD/(g·cm^{-3})		1.524
NGu/(wt.%)	556-88-7	35
PrNGu/(wt.%)	35091-64-6	34
HMX/(wt.%)	2691-41-0	31

Table 17
Performance of NGu-PrNGu-HMX [71].

Unit	NGu-PrNGu-HMX		
ρ_{exp}./(g·cm^{-3}) (Δ)	1.59	TMD	TMD
v_D(exp.)/(m·s^{-1})	7710	7475	7716
ϕ_{cr}/mm			
p_{CJ}/GPa		20.42	22.52
T_{CJ}/K		2952	2932
$\sqrt{2E_G}$(~26 mm)/(m·s^{-1})			
$E(V/V_0 = 9.0)$/(kJ·cm^{-3})		−5.59	−5.90

[77] and dissolves LBD-NGu (Table 22 and Table 23).

3.2.1.4.4. NGu-AN-MeNGu. NGu forms a eutectic with its methylated derivative MeNGu melting at 128 °C [80]. Likewise, AN forms two eutectics with MeNGu melting at 117 and 118 °C [81]. Three formulations have been reported (Table 24 and Table 25).

AFX-453 has been developed at Eglin Air Force Base as melt-castable blast explosive in the 1980s for use with the Mk82 bombs [82]. AFX-453 is a modification of composition III given above in Table 18. There are two slightly different formulations reported in the literature (Table 26 and Table 27). AFX-453 has been reported to melt at 103 °C which demonstrates the beneficial effect of NGu on the binary eutectic system AN/MeNGu. The reported performance of AFX-453 is for an unknown density. Fig. 18 shows the variation of v_D with charge diameter of unconfined AFX-453.

Yet another eutectic melting at 104 °C named DEMN is formed by the quaternary composition given in Table 28 [85].

While the density of DEMN is too low to qualify for any application its mixtures with other high explosives such as additional NGu and RDX has been qualified as IMX-103(Table 29) [63].

3.2.1.4.5. NGu-CE-ECE. Tetryl and ethyltetryl in a mass ratio 70/30 form a eutectic melting at 85–88 °C [59]. This eutectic has been proposed as melt cast base for NGu by Schlüter and Hermann (Tables 30 and 31) [86].

3.2.2. Cure-castable formulations

Due to the low shock sensitivity of NGu, both hexogen and octogen have been applied as sensitizer in binary and ternary formulations with aluminium. Table 32 depicts the formulations while the performance is displayed in Table 33.

3.2.3. Pressable formulations

Several pressable formulations containing either NGu as the sole explosive component (AFX-902, X0228)[98–100] or in binary formulations with HMX (X0118, X0183) [102] as an additional explosive filler have been reported. These formulations are compared with formulations based entirely on 1,3,5-triamino-2,4,6-trinitrobenzene (TATB) (PBX9502), 1,1-diamino-2,2-dinitroethylene (FOX-7)(QRX080) [101] and octogen (HMX)(LX-14) (Tables 34, 35a and 35b).

Fried & Souers describe and rank AFX-902 as an "ideal explosive" comparable to LX-14 [121]. This is not surprising as the detonation pressure, Gurney energy and detonation velocity of AFX-902 reach 77.5%, 82.0% and 94.8% respectively of LX-14. Though both TATB and FOX-7 possess higher densities than NGu (+10; +8%) and have both higher detonation enthalpies than NGu (+13; +25%) the detonation velocity of AFX-902 is equivalent if not superior to both PBX-9502 and QRX080. The detonation pressure of AFX-902 is comparable to PBX-9502 and just 94% of QRX080. The Gurney Energy of AFX-902 is about the same as for PBX9502 and just 92% that of QRX080. The critical diameter for both AFX-902 and PBX-9502 appears to be in the same range. No data on FOX-7 based critical diameter is available.

The shock Hugoniot data for X0228 are depicted in Figs. 19 and 20.

3.2.3.1. Miscellaneous formulations. Gogyula et al. have reported about pressable binary formulations of NGu and Al in a mass ratio (85/15) [27,44]. Table 36 depicts the performance of various formulations containing different type aluminium powder against HMX/Al formulations as comparison.

Heat resistant explosive formulations based on NGu having high specific surface area (9000–16000 cm^2/g) are the subject of a

Table 18
Composition of NGu-based melt cast insensitive high explosives.

Component	CAS-no	NGA	NGA + AN	NGA/AN/RDX
TMD/(g·cm^{-3})		1.656	1.695	1.738
NGu/(wt.%)	556-88-7	17.50	7.00	4.20
Guanidinium nitrate/(wt.%)	506-93-4	22.50	9.00	5.40
Ammonium nitrate/(wt.%)	6484-52-2	60.0	84.0	50.4
Hexogen/(wt.%)	121-82-4	–	–	40.0

Table 19
Performance of NGA, NGA/AN and NGA/AN/RRDX [74].

	NGA TMD: 1.688 g/cm^3			NGA/AN TMD: 1.845 g/cm^3			NGA/AN/RDX		
	exp.	calc. at	calc. at	exp.	calc. at	calc. at	exp.	calc. at	calc. at
$\rho_{exp.}$/(g·cm^{-3}) (Δ)	–	–	TMD	1.60	1.60	TMD	1.66		TMD
v_D(exp.)/(m·s^{-1})	–	–	7932	Failed at 9.65 mm	6930	7336	7170	8319	8680
ϕ_{cr}/mm	–	–		diameter in steel					
p_{CJ}/GPa	–	–	22.13		15.91	18.42	25.00	25.30	28.67
T_{CJ}/K	–	–	2707					3376	3349
$E(V/V_0 = 9.0)$/(kJ·cm^{-3})	–	–	−5.56		−3.77	−4.07		−6.92	−7.40

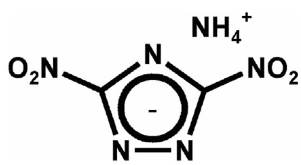

Fig. 16. Structure of ADNT.

Table 20
Composition of NGu-based melt cast insensitive high explosives.

Component	CAS-no	1	2
TMD/(g·cm^{-3})		1.749	1.751
NGu/(wt.%)	556-88-7	33.38	39.92
Ammonium 3,5-dinitro-1,2,4-triazolate/(wt.%)	67265-22-9	40.94	36.92
Ammonium nitrate/(wt.%)	6484-52-2	25.68	23.16

Table 21
Performance of NGA, NGA/AN and NGA/AN/RRDX [76].

	1 TMD: 1.749 g/cm^3			2 TMD: 1.751 g/cm^3		
	exp.	calc. at	calc. at	exp.	calc. at	calc. at
$\rho_{exp.}$/(g·cm^{-3}) (Δ)	1.655	1.655	TMD	1.654	1.654	TMD
v_D(exp.)/(m·s^{-1})	–	8105	8522	8160	8075	8500
p_{CJ}/GPa	26.1	24.18-	27.84	25.5	23.99	27.74
T_{CJ}/K	–	3199	3159		3161	3120
$E(V/V_0 = 9.0)$/(kJ·cm^{-3})	–	−6.23	−6.78		−6.17	−6.72

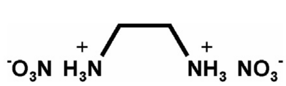

Fig. 17. Structure of EDDN.

formerly classified Soviet Union patent released 46 years after its submission (Table 37) [103].

4. Sensitiveness

4.1. Friction and impact sensitivity

NGu and the formulations based on it are mostly not very friction or impact sensitive, however, more sensitive components may trigger sensitivity as indicated below in Table 38.

4.2. Shock sensitivity

Nitroguanidine and the formulations based thereon are very insensitive to shock. Hence and due to the comparatively large critical diameter shock sensitivity of NGu-based formulations are typically assessed with NOL-LSGT [28], the ELSGT [105] and the SLSGT [106].

4.2.1. Critical energy

Shock initiation of a high explosive occurs when its unit surface area is subjected by a specific minimum energy while shock pressure, p, and shock duration, t, may vary. The energy fluence, E_{crit}, (J/cm^2) in a specific volume is therefore a characteristic figure to describe the sensitivity of an energetic material towards shock initiation [107].

$$E_{crit} = p \cdot u \cdot t$$

Lungenstraβ has determined E_{crit} for NGu and formulations based thereon as well as reference high explosives (see Table 39) [55].

For the hot-spot model Mader calculated adiabatic explosion times for shock initiation of high explosives with spherical holes [108,109]. Table 40 displays the variation of explosion time for different explosives and different temperatures (correlating with different shock sensitivity). Fig. 21 shows the influence of spot size and shock pressure on the initiation of NGu, TATB and HMX.

4.2.2. LSGT

The influence of charge density on the shock initiation pressure of both LBD and HBD-NGu in LSGT is depicted in Fig. 22 [28]. It

Table 22
Composition of NGu-based melt cast insensitive high explosives.

Component	CAS-no	NEAK	NEAK + NGu	NEA
TMD/(g·cm^{-3})		1.689	1.725	1.692
NGu/(wt.%)	556-88-7	8.0	49.1	30.0
Ethylenediammonium dinitrate/(wt.%)	20829-66-7	46.0	25.0	35.0
Potassium nitrate/(wt.%)	7757-79-1	7.00	3.75	
Ammonium nitrate/(wt.%)	6484-52-2	39.00	21.15	35.00
Microspheres/(wt.%)	–		1.0	

Table 23
Performance of NEAK [77–79].

	NEAK TMD: 1.6895 g/cm^3			NEAK + NGu TMD: 1.725 g/cm^3			NEA TMD: 1.692 g/cm^3		
	exp.	calc. at	calc. at	exp.	calc. at	calc. at	exp.	calc. at	calc. at
$\rho_{exp.}$/(g·cm^{-3}) (Δ)	1.64	1.64	TMD	1.59	1.59	TMD	???		TMD
v_D(exp.)/(m·s^{-1})	8020	7785	8013	7420	7550	8149	5670		8073
p_{CJ}/GPa		21.33	22.99		19.90	24.57			23.99
T_{CJ}/K		2819	2805		2837	2795			2835
$\sqrt{2E_G}$(~26 mm)/(m·s^{-1})	2510			–					
$E(V/V_0 = 9.0)$/(kJ·cm^{-3})		−5.57	−5.82		−5.27	−5.95			−6.03

Table 24
NGu-AN-MeNGu.

Component	CAS-no	I	II	III
TMD/(g·cm^{-3})		1.630	1.711	1.850
NGu/(wt.%)	556-88-7	11.30	64.52	53.39
Methylnitroguanidine/(wt.%)	4245-76-5	45.00	18.00	13.50
Ammonium nitrate/(wt.%)	6484-52-2	39.20	15.68	11.76
Aluminum/(wt.%)	7429-90-5	–	–	20.00
Sodium nitrate/(wt.%)	7631-99-4	4.50	1.80	1.35

reflects the common observation that porosity is a prerequisite for successful shock ignition.

LSGT-data on NGu-based formulations and reference materials are displayed in Table 41.

4.2.3. ELSGT

ELSGT data are displayed and compared in Table 42.

4.2.4. SLSGT

Data for the SLSGT have been reported in Ref. [65] and are compared with TNT and PBXN-109 (Table 43).

4.2.5. BICT Gap test

Results of the BICT Gap test [114,115] on pressed Nigutol-40 (having an unusual high porosity!) [54] and Guntol [60] have been published. However, both Nigutol and Guntol have critical diameters in the same ballpark as the test configuration ($\phi \sim 24$ mm) which is why these data are of questionable quality and hence will not be discussed here.

4.2.6. Run-to-detonation distance for shock to-detonation transition (SDT)

The run-to-detonation distance for neat NGu has been determined by Popolato et al. [116] and is depicted in Fig. 23.

The run-to-detonation distance for IMX-101 has been tested with different methods and is depicted in Fig. 24 for a charge density of $\rho = 1.56$ g/cm^3 [117].

The run-to- detonation distance of X0228 is depicted below in Fig. 25.

The law for X0228 reads

Table 26
Composition of AFX-453.

Component	CAS-no	a) 82,83	b) 84
TMD/(g·cm^{-3})		1.813	1.826
NGu (HBD)/(wt.%)	556-88-7	60.00	61.44
Aluminum/(wt.%)	7429-90-5	15.00	15.00
Methylnitroguanidine/(wt.%)	4245-76-5	13.00	11.70
Ammonium nitrate/(wt.%)	6484-52-2	11.50	10.19
Sodium nitrate/(wt.%)	7631-99-4	–	1.17
TDO/(wt.%)	61791-53-5	0.50	0.50

Table 27
Performance of AFX-453 [82–84].

	AFX-453 TMD: 1.813 g/cm^3		
	exp.	a calc. at	b calc. at
$\rho_{exp.}$/(g·cm^{-3}) (Δ)	??	TMD	TMD
v_D(exp.)/(m·s^{-1})	7600[a]	8027	8074
ϕ_{cr}/mm	69–77		
p_{CJ}/GPa		23.45	23.72
T_{CJ}/K		2527	2523
$\sqrt{2E_G}$(~26 mm)/(m·s^{-1})	2600		
$E(V/V_0 = 9.0)$/(kJ·cm^{-3})		−5.19	−5.20

[a] With a 177 mm diameter confined charge.

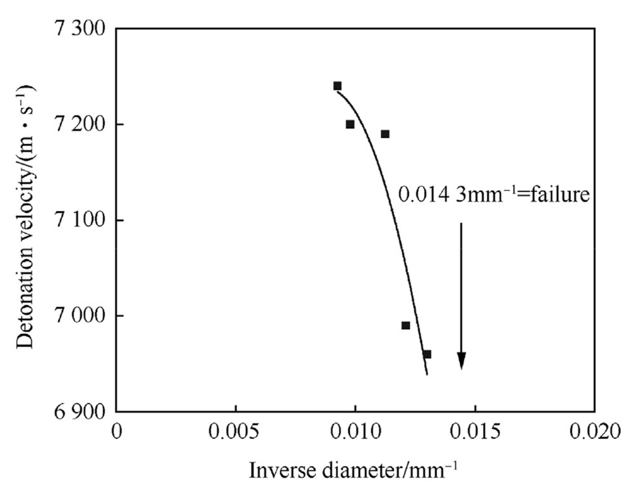

Fig. 18. Inverse diameter detonation velocity relationship for unconfined AFX-453 charges at unknown density.

Table 25
Performance of NGu-AN-MeNGu [81].

	I TMD: 1.630 g/cm^3			II TMD: 1.711 g/cm^3			III TMD: 1.850 g/cm^3		
	exp.	calc. at	calc. at	exp.	calc. at	calc. at	exp.	calc	calc. at
$\rho_{exp.}$/(g·cm^{-3}) (Δ)	1.52	1.52	TMD	1.63	1.63	TMD	1.72	1.72	TMD
v_D(exp.)/(m·s^{-1})	7400	7189	7664	7600	7688	8039	7400	7356	8020
p_{CJ}/GPa		17.62	21.07		21.30	24.25		18.23	22.95
T_{CJ}/K		2827	2797		2819	2790		2445	2438
$E(V/V_0 = 9.0)$/(kJ·cm^{-3})		−4.95	−5.49		−5.46	−5.86		−4.35	−4.91

Table 28
Composition DEMN and IMX-103 [86].

Component	CAS-no	DEMN	IMX-103
TMD/($g \cdot cm^{-3}$)		1.571	1.666
NGu (HBD)/(wt.%)	556-88-7	6.3	48.15
MeNGu/(wt.%)	4245-76-5	25.4	12.70
EDDN/(wt.%)	20829-66-7	33.4	16.70
Diethylenetriammonium trinitrate/(wt.%)	6143-55-1	34.9	17.45
RDX/(wt.%)			5.00

Table 29
Performance of DEMN and IMX-103 [63,85]

	TMD: 1.571 g/cm^3			TMD: 1.666 g/cm^3		
	exp.	calc. at	calc. at	exp.	calc. at	calc. at
$\rho_{exp.}$/($g \cdot cm^{-3}$) (Δ)	1.53	1.53	TMD	1.61	1.61	TMD
v_D(exp.)/($m \cdot s^{-1}$)		7020	7181	7500	7511	7741
ϕ_{cr}/mm	>75					
p_{CJ}/GPa		17.44	18.61		20.58	22.51
T_{CJ}/K		2836	2826		2894	2876
$E(V/V_0 = 9.0)$/($kJ \cdot cm^{-3}$)		−5.08	−5.28		−5.53	−5.82

Table 30
Composition NGu-Tetryl-Tetryl-E.

Component	CAS-no	
TMD/($g \cdot cm^{-3}$)		1.763
NGu (HBD)/(wt.%)	556-88-7	90
Tetranitromethylaniline/(wt.%)	479-45-8	7
Tetranitroethylaniline/(wt.%)	6052-13-7	3

Table 31
Performance of NGu-Tetryl-Tetryl-E [86].

	TMD: 1.763 g/cm^3		
	exp.	a calc. at	b calc. at
$\rho_{exp.}$/($g \cdot cm^{-3}$) (Δ)	1.709	1.709	TMD
v_D(exp.)/($m \cdot s^{-1}$)	8400	8009	8232
ϕ_{cr}/mm	≪ 32		
p_{CJ}/GPa		24.48	26.65
T_{CJ}/K		2927	2905
$E(V/V_0 = 9.0)$/($kJ \cdot cm^{-3}$)		−5.99	−6.27

*) with a 177 mm diameter confined charge.

$$\lg(p) = 1.42 - 0.19 \lg(x)$$

4.3. Projectile impact

Lee has calculated the critical projectile impact velocity versus projectile diameter relationship for bare X0228 from pop plot data. The results and comparative data for more sensitive high explosives Comp B and TNT are depicted in Fig. 26 [118,119]. Though “initiations” for both X0228 and TNT can be expected in the full range of projectile diameters it must be remembered that stable detonations will probably only develop when the projectile diameter is in the same range as the critical diameter of the corresponding explosive which is about 15–20 mm for both X0228 and TNT.

5. Insensitive munitions tests of NGu based formulations

Insensitive Munitions Tests as defined in AOP-39 serve the evaluation of the response of a particular store or a test vehicle towards threats typically encountered in the life cycle of an ammunition [6]. Table 44 displays those tests and the underlying scenario and the desired response of an article to be considered insensitive.

The corresponding responses are depicted in Table 45. The IM Signature Color code requires green if the response is met, yellow if the response is not more than one type higher, red if the response is more than one type higher and white if a test has not been conducted.

The IMX-101, AFX-770 and AFX-900 have been tested in full scale ammunitions (Table 46 and Table 47) and are compared against baseline vulnerable high explosive and blast formulations Comp B, TNT and H-6.

6. EI(D)S – Extremely Insensitive (Detonable) substances

Explosives that pass the full-scale UN-Test series 7 for formulations 7(a)~7(f) and the article 7(g)~7(k) are designated Extremely Insensitive (Detonating) Substances EIS (formerly EIDS). The corresponding articles (munitions containing those explosives) then are categorized as Hazard Division 1.6 [123]. Qualified EIS containing NGu are the aforementioned formulations AFX-760, AFX-770, AFX-920, and AFX-930 [124].

7. Summary

Swiss chemist Alfred Stettbacher – considered an authority in the field of explosives in his time – in 1936 tried to detonate 2.5 g Nitroguanidine stemmed in a rifle (8 × 57) cartridge with a common (lead azide, mercury fulminate, PETN) cap on a mild steel

Table 32
Composition of various NGu-nitramine formulations.

Designation	AFX760 CPX305 [87]	AFX770 [88]	AFX900 [89]	KS71 [90]	MBB1 [91]	AFX920 [84]	AFX930 [92]	MBB1 [91]	B-2244 [93,94]	HX-76 [95]	HX-310 [95]	ATEX [96,97]
TMD/($g \cdot cm^{-3}$)	1.654	1.631	1.803		1.639	1.584	1.614	1.639	1.540	1.557	1.581	1.492
NGu/(wt.%)	35	12	17	X	15	33(HBD)	37	15	69	55	10	60
RDX/(wt.%)	30	27	22	X	55	22(19% 4 µm, 3% 1 µm)	32	55	15	30		20
HMX/(wt.%)											47	
NTO/(wt.%)											25	
EDD/(wt.%)						15						
Al/(wt.%)	20	16	45		15	14	15	15				
HTPB/(wt.%)	15	18	16	X	15	16	16	15	16	15	18	20
AP/(wt.%)		27										

Table 33a
Performance of various NGu-nitramine formulations.

Designation	AFX-760 CPX-305 [87] TMD = 1.654 g/cm^3			AFX-770 [88] TMD = 1.631 g/cm^3			AFX-900 [89] TMD = 1.803 g/cm^3	AFX-920 TMD = 1.586 g/cm^3		AFX-930 [92] TMD = 1.614 g/cm^3		MBB-1 TMD 1.639 g/cm^3		
	exp.	calc.at	calc.at	exp.	calc.at	calc.at	calc. at	exp.	calc. at	exp.	calc. at	exp.	calc.at	calc.at
$\rho_{exp.}$/(g·cm^{-3}) (Δ)	1.65	1.65	TMD	1.618	1.618	TMD	TMD	?	TMD	?	TMD	1.50	1.50	TMD
v_D(exp.)/(m·s^{-1})	7000	7262	7282	6050	6705	6756	7353		7078	6700	7204	6592	6508	7081
ϕ_{cr}/mm	42–47			38*										
p_{CJ}/GPa		18.43	18.56		16.57	16.90	17.45		17.29		18.25		14.91	18.58
T_{CJ}/K		2224	3334		3559	3557	3057		3089		3234		3618	3601
$\sqrt{2E_G}$(~26 mm)/(m·s^{-1})								2180				2670		
$E(V/V_0 = 9.0)$/(kJ·cm^{-3})		−5.63	−5.65		−5.71	−5.77	−4.25		−5.22		−5.52		−5.33	−6.07

* Confined.

Table 33b
Performance of various NGu-nitramine formulations.

Designation	KS71 [90] TMD = ?	HX-76 [95] TMD = 1.557 g/cm^3		HX-310 [95] TMD = 1.581 g/cm^3			B-2244 [93,94] TMD = 1.540 g/cm^3	ATEX [96,97] TMD = 1.492 g/cm^3	
	exp.	exp.	calc. at	exp.	calc	calc.at	calc. at	exp.	calc. at
$\rho_{exp.}$/(g·cm^{-3}) (Δ)	1.48	?	TMD	1.57	1.57	TMD	1.53	?	TMD
v_D(exp.)/(m·s^{-1})	6800	7420	7225	7750	6849	6888	7200	7350	7015
ϕ_{cr}/mm		40		<10				<28 (confined) <110 unconfined	
p_{CJ}/GPa			18.71		17.84	18.15	17.82		16.55
T_{CJ}/K			2898		3225	3222	2663		2645
$\sqrt{2E_G}$(~26 mm)/(m·s^{-1})									
$E(V/V_0 = 9.0)$/(kJ·cm^{-3})			−5.25		−5.42	−5.48	−4.82		−4.61

Table 34
Composition of various NGu-nitramine formulations.

Designation	AFX-902	X0228	X0118 [78]	X0183 [78]	PBX9502 [98,99]	QRX080 [101]	LX-14 [59]
TMD/$(g \cdot cm^{-3})$			1.760	1.876			1.854
NGu/wt.%)	95.0	95.0	64.9	26.4			
HMX/(wt.%)			29.7	65.7			95.5
TATB/(wt.%)					95		
FOX-7/(wt.%)						95	
Kel-F®/(wt.%)				7.9	5.0		
Viton® A/(wt.%)	5						
Hytemp®/(wt.%)						5	
Estane ®/(wt.%)		5	5.4				4.5

*melt cast formulation after Ref. [].

Table 35a
Comparison of NGu based Explosives AFX-902 and X0228 with PBX9502 (TATB) and QRX080 (FOX-7).

	AFX-902 [98,99] TMD:1.774 g/cm^3			X0228 [4,100] TMD: 1.7268 g/cm^3			PBX-9502 [98,99] TMD: 1.941 g/cm^3			QRX080 [101] TMD: 1.844 g/cm^3		
	exp.	calc. at	calc. at	exp.	calc. at.	calc. at	exp.	calc. at.	calc. at	exp.	calc. at.	calc. at
$\rho/(g \cdot cm^{-3})$	1.742	1.742	TMD	1.704	1.704	TMD	1.894	1.894	TMD	1.760	1.760	TMD
$v_D/(m \cdot s^{-1})$	8344	8067	8201	8280	7903	8000	7589	7775	7928	8230	8149	8468
p_{CJ}/GPa	29.0	24.9	26.1	26.8	23.4	24.3	28.5	27.3	29.3	29.8	27.2	30.8
T_{CJ}/K	–	2720	2706	–	2690	2682		3195	3178	–	3445	3409
ϕ_{cr}/mm	<12	–	–	?			>9	–	–	?	–	–
$\sqrt{2E_G}$ $(19 \sim 26\ mm)/(m \cdot s^{-1})$	35	–	–	–			2411			2644		
$E(V/V_0 = 9.0)$ $(kJ \cdot cm^{-3})$	–	−5.82	−5.96		−5.57	−5.68	–	−6.66	−6.92	–	−6.99	−7.53
$k/(W \cdot m^{-1} \cdot K^{-1})$				0.453[a]			0.553[d]					
$c_p/(J \cdot g^{-1} \cdot K^{-1})$				1.328[b]			1.133[$)]					

[a] At $\rho = 1.694\ g/cm^3$
[b] At 37 °C and $\rho = 1.686\ g/cm^3$.
[c] At $\rho = 1.9\ g/cm^3$ and 37 °C.
[d] At $\rho = 1.893\ g/cm^3$.

Table 35b
Comparison of NGu based Explosives AFX-902 and X0228 with PBX9502 (TATB) and QRX080 (FOX-7).

	X0118 [102] TMD: 1.760 g/cm^3			X0183 [102] TMD: 1.876 g/cm^3			LX-14 [59] TMD: 1.854 g/cm^3		
	exp.	calc. at	calc. at	exp.	calc. at.	calc. at	exp.	calc. at.	calc. at
$\rho/(g \cdot cm^{-3})$	1.712	1.712	TMD	1.815	1.815	TMD	1.823	1.823	TMD
$v_D/(m \cdot s^{-1})$	8380	8004	8195	8625	8463	8695	8800	8764	8875
p_{CJ}/GPa	30.1	25.07	27.02	34.6	30.30	32.98	37.40	33.96	35.43
T_{CJ}/K		3099	3080		3651	3618		4003	3985
ϕ_{cr}/mm									
$\sqrt{2E_G}$ $(m \cdot s^{-1})$							2970		
$E(V/V_0 = 9.0)$ $kJ \cdot cm^{-3})$		−6.35	−6.62		−7.98	−8.38		−8.81	−9.04
$k/(W \cdot m^{-1} \cdot K^{-1})$									
$c_p/(J \cdot g^{-1} \cdot K^{-1})$									

plate. However, the result of his attempt was only a small dent in the steel plate. Stettbacher with his experimental setup overlooked the low shock sensitivity of NGu and the large critical diameter of it. However, this one single failed experiment led him to drew an ill conclusion "(…). Zufolge seiner beträchtlichen Sauerstoffunterbilanz von 30,75% bei gleichzeitig 53,85% Stickstoffgehalt ist dieser Nitrokörper kein Sprengstoff. Seine Wirkung ist selbst bei kräftiger Zündung gering. (…)" which translates into "(…) Due to its considerable oxygen deficiency of 30.75% (sic!) combined with a high nitrogen content of 53.85% this nitro compound is no high explosive. Its performance even with fiercest initiation is feable (…)" [125].

In a popular review on insensitive high explosives in 1997 it was erroneously stated "NGu (…) does not meet the criterion of at least 75% HMX performance in detonation pressure and cylinder wall energy (…)" [126]. The authors of said review must have picked wrong numbers from the literature. In addition, they overlooked the then recent work by Fried & Souers (1996) – the developers of Cheetah –which assessed AFX-902 (95 wt% NGu) to perform like an ideal high explosive with the detonation pressure, Gurney energy and detonation velocity of it reaching 77.5%, 82.0% and 94.8% respectively of LX-14 based on 95% HMX [121].

Table 48 displays a synoptic ranking of NGu experimental performance with FOX-12, TATB, NGu, FOX-7 and HMX and percentage of NGu performance. Green is NGu baseline performance, yellow is inferior and blue is superior.

In summary highly dense nitroguanidine clearly outperforms *N*-guanylurea dinitramide (GuDN or FOX-12) and 1,3,5-triamino-2,4,6-trinitroethylene (TATB) with regards to Gurney Energy, detonation pressure and velocity (See Table 48) it is a close match in performance with 1,1-diamino-2,2-dinitroethylene (FOX-7)(**8**) with which it is structurally related [1] and reaches even up to HMX delivering up to 78% detonation pressure, 82% Gurney Energy and 95% detonation velocity.

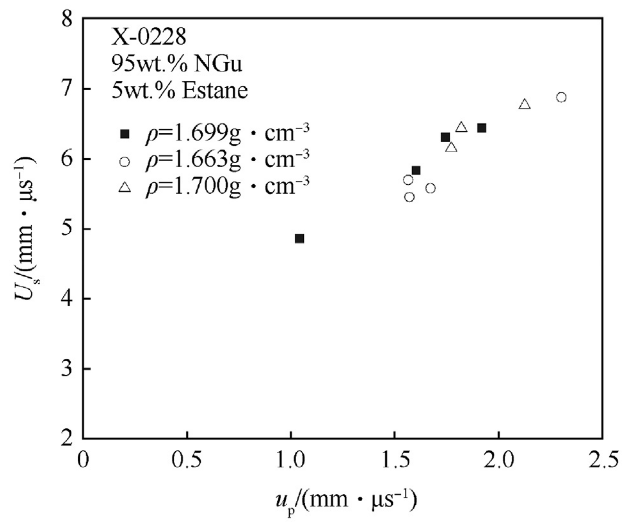

Fig. 19. $Us - u_p$ plane for X0228 at $\rho = 1.63$ g/cm^3.

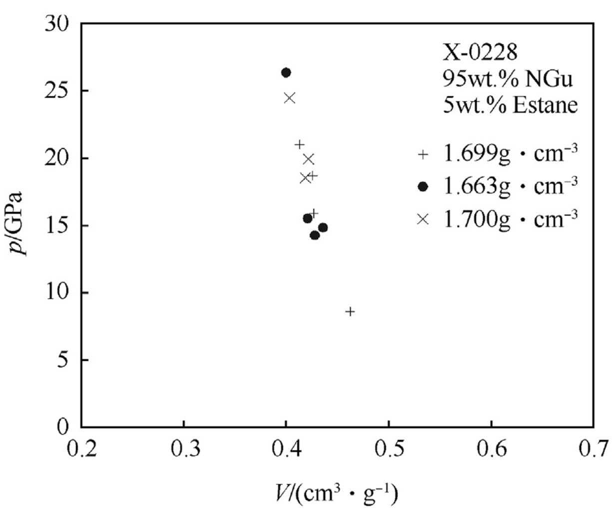

Fig. 20. $p - v$ plane for X0228 at various densities.

Table 36
Performance of NGu-Al and HMX-Al (85/15) as reference.

	Calc. NGu/Al	Al ϕ/ 15 µm	Al ϕ/ 100 nm	Al *fl*/ 1 µm × 20 µm x 50 µm	HMX/Al 100 nm	Calc HMX/Al TMD
$\rho_{exp.}$/(g·cm^{-3}) (Δ)	1.785	1.743	1.785	1.720	1.84	1.84
v_D(exp.)/(m·s^{-1})	8319	7940	7780	8130	8030	8457
ϕ_{cr}/mm		≪ 40	≪ 40	≪ 40		
p_{CJ}/GPa	25.58	26.0	27.5	26.5	30.0	30.05
T_{CJ}/K	3227	–	2550	2362	3350	4466
$E(V/V_0 = 9.0)$/(kJ·cm^{-3})	−6.51					−8.74
v_w/(m·s^{-1})	1882	1820	1840	1850	2180	2094

On top NGu and its formulations are the least sensitive dealt with regards to shock sensitivity.

8. Outlook

While costly spherical high bulk density (SHBD-) NGu has been used in the past to achieve dense charges this review shows that dense charges can be obtained too by dissolving common LBD-NGu

Table 37
Composition, experimental and calculated performance of NGu-nitramine explosive formulations [103].

	RDX/NGu 80/20		HMX/NGu 80/20		HMX/NGu 40/60	
TMD/(g·cm^{-3})	1.799		1.876		1.822	
$\rho_{exp.}$/(g·cm^{-3}) (Δ)	1.720	1.720	1.770	1.770	1.705	1.705
v_D(exp.)/(m·s^{-1})	8200	8527	8500	8714	8100	8262
ϕ_{cr}/mm						
p_{CJ}/GPa		29.75		31.82		26.67
T_{CJ}/K		3951		3914		3364
$E(V/V_0 = 9.0)$/(kJ·cm^{-3})		−7.98		−8.30		−6.85

Table 38
50%-Friction, Impact, values of selected formulations.

Test method	Nigutol 60/40 [104]	IMX-101 [63]	ATEX [96,97]	AFX-453 [82,83]	AFX-770 [88]	NGu-Tetryl-Tetryl-E [81]
BAM-Impact/J	22.5					15.0
Rotter		>100			60–70	
ERL/cm		100	>320	>200		
BAM-Friction/N	–	240–252		>355	96	
250 lbf 8 ft s^{-1}			no fire			

Table 39
Critical Initiation energy for high explosives.

High Explosive	Density/(g·cm^{-3})	Impact Sensitivity/J	E_{crit}/(J·cm^{-2})
TATB (pressed)	1.80	>50	~500
TNT (cast)	1.59	15	320
Comp B (cast)	1.73	7.5	185
NGu (SHBD)	1.57	50	~455
Nigutol-60 (cast)	1.68	22.5	~390
Nigutol-92 (pressed[a])	1.70		~525

[a] And infiltrated after pressing at 90 °C with liquid TNT to fill the residual porosity.

Table 40
Adiabatic explosion times for different explosives after Ref. [108,109].

Explosive	Hot-Spot Temperature/K		
	700	1000	1300
NGu/µs	5504.00	124.00	18.47
TATB/µs	1290	6×10^{-3}	1×10^{-5}
HMX/µs	5.26	1×10^{-4}	5×10^{-7}
PETN/µs	0.08	7×10^{-6}	5×10^{-8}

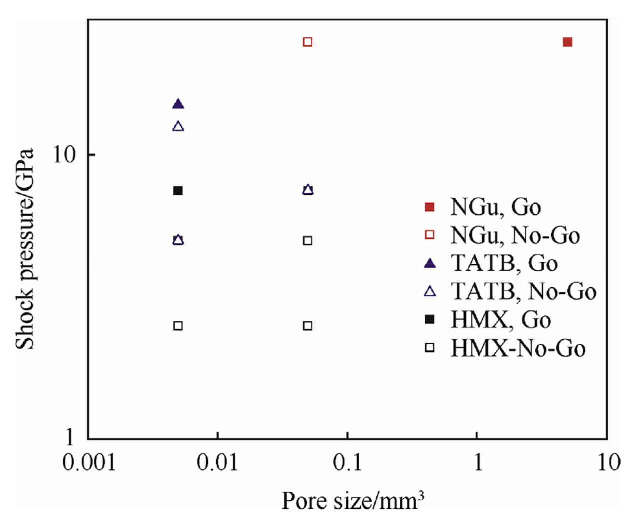

Fig. 21. Influence of Pore size and shock pressure on Initiation of NGu and other high explosives after Ref. [108,109].

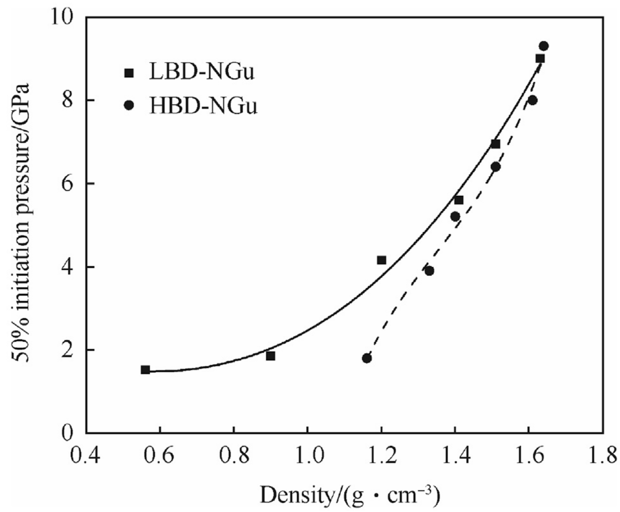

Fig. 22. Influence of Density of HBD and LBD on Shock initiation pressure after [28].

Table 43
SLSGT data for ALIMX-101 and two reference materials.

Formulation	Density/(g·cm^{-3})	Go/No-Go/GPa
ALIMX-101	1.81	5.87–5.49
TNT	1.58	0.75–0.64
PBXN-109	1.66	1.31

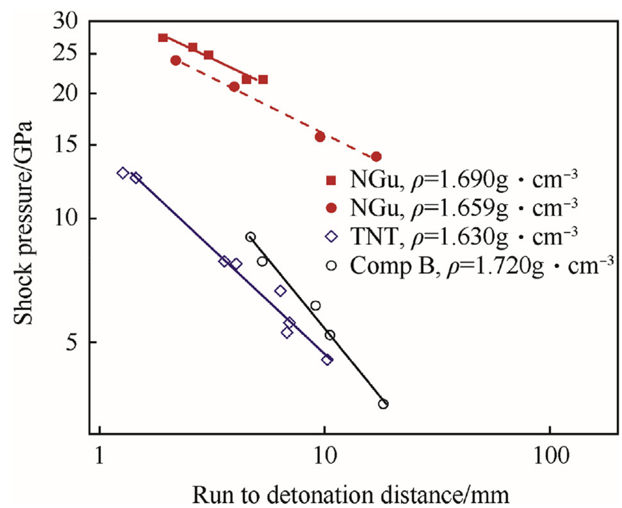

Fig. 23. Pop-plot for NGu, TNT and Comp B.

Table 41
LSGT data for NGu, its formulations and reference compositions.

Formulation	Density/(g·cm^{-3})	comments	Go/GPa	Ref.
NGu (neat)	1.64	?	9.00	[28]
NGu	1.59		7.31	[110]
NGu/Wax (95/5)	1.55		9.93	[110]
IMX-101	1.70		9.16	[111]
IMX-103	1.61		7.90	[63]
AFX-930	1.61		7.12	[106]
QRX080	?		4.64	[112]
Comp B	1.71		2.59	[59]
TATB	1.802		6.58	[59]
TNT	1.61	Cast	4.58	[59]
GUDN	1.66	Pressed	6.25	[39]
Guntol-50	1.652	cast	6.20	[39,132]

in molten energetic ionic liquids (see § 3.2.1.4). In view of the immense current international interest and research efforts in the field of new energetic ionic liquids for melt cast applications [127–131] and given the availability, good performance and extreme low sensitiveness of nitroguanidine, NGu is a natural

Table 42
ELSGT data for NGu, its formulations and reference compositions.

Formulation	Density/(g·cm^{-3})	NGu-type	Particle Sizes/μm	Go/No-Go/GPa	Ref.
Nigutol-50	1.663	HBD	NGu 105–210	3.44–3.32	[52,53]
	1.643		NGu 297–420	3.73–3.59	[52,53]
	1.638	SHBD	NGu 105–210	>4.21	[52,53]
	1.636		NGu 297–410	3.28–3.15	[52,53]
EAFB-2	1.590	HBD	NGu 210–297	3.89–3.75	[52,53]
	1.610	SHBD	NGu 210–297	3.89–3.75	[52,53]
CPX-305	1.650	?	?	3.12–3.00	[87]
AFX-770		?	RDX 2 μm, type 1	5.51	[88]
			6 μm type 1	5.63	[88]
			20 μm type 1	4.27	[88]
			20 μm type 2	4.63	[88]
HX-76		SHBD	?	3.85–3.61	[95]
HX-310		?	?	2.65–2.54	[95]
IMX-101	1.650	?	?	5.9	[113]
NGu	1.610	HBD		12.21	[105]
	1.630	LBD		12.89	[105]
	1.640	HBD		13.06	[105]
TNT	1.620	cast		9.25	[59]
PBXN-109	1.660			1.65	[59]
TATB	1.830			10.61	[59]

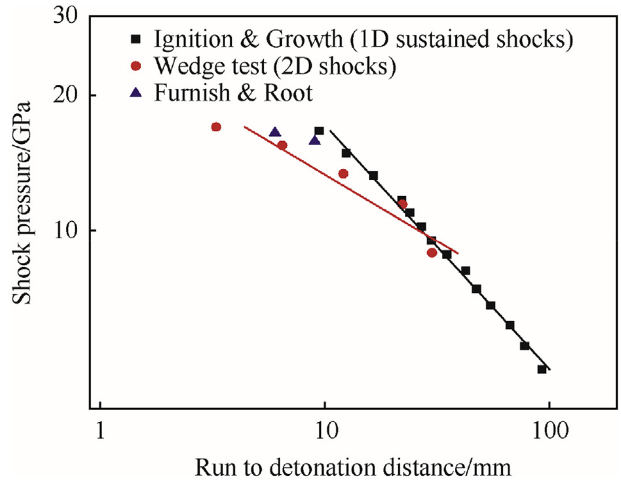

Fig. 24. Pop-plot for IMX-101 ($\rho = 1.56\ g/cm^3$).

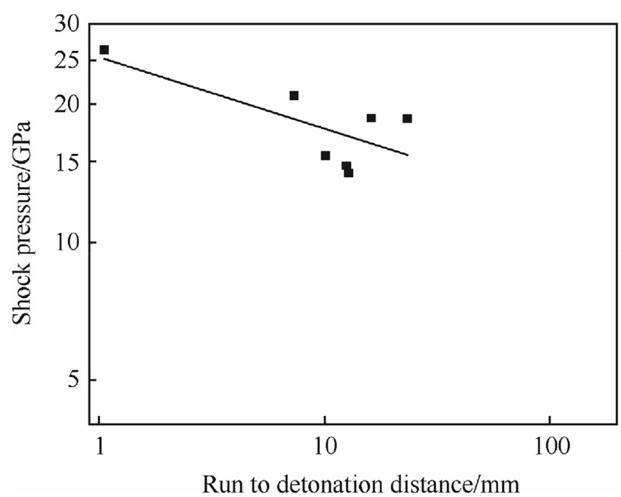

Fig. 25. Pop-plot for X0228 ($\rho = 1.699\ g/cm^3$).

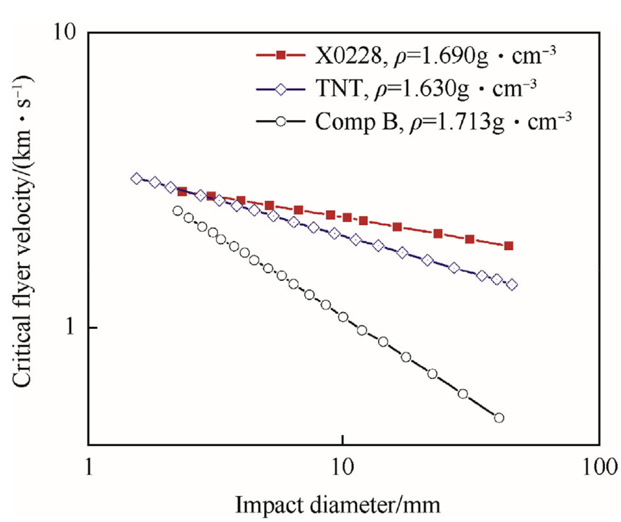

Fig. 26. Critical flyer velocity for bare X0228 compared to TNT and Comp B.

Table 44
Threat, definition and Minimum pass-requirement [120].

Threat Acronym	Pass-Requirement	Definition	Scenario
Fast Cookoff FCO	No response more severe than type V (burning)	Average temperature between 550 °C and 850 °C until all munitions reactions completed. 550 °C reached within 30 s from ignition	Magazine/store fire or aircraft/vehicle fuel fire
Slow Cookoff SCO	No response more severe than type V (burning)	Between 1 °C/h and 30 °C/h heating rate from ambient temperature	Fire in an adjacent magazine, store or vehicle
Bullet Impact BI	No response more severe than type V (burning)	From one to three 12.7 mm (armour piercing) round velocity between 400 −850 m/s	Small arms attack
Fragment Impact FI	No response more severe than type V (burning)	Steel fragment from 15 g with velocity up to 2600 m/s and 65 g with velocity up to 2200 m/s	Fragmenting munitions attack
Sympathetic reaction SR	No propagation of reaction more severe than type III (explosion)	Detonation of donor in appropriate configuration	Most severe reaction of same ammunition in magazine, store aircraft or vehicle
Shaped charge Jet impact SJC	No response more severe than type III (explosion)	Shaped charge calibre up to 85 mm	Shaped charge weapon attack

Table 45
Response descriptors for IM Tests i.a.w. STANAG 4439 [120].

Configuration	FCO	SCO	BI	FI	SR	SCJ
IMX-101 M795 Shell	V	V	IV	V	NR	III
Guntol-45						*III*
Comp B M107 Shell	*III*	*III*	*III*		*I*	*I*
TNT M795 shell	III	III	IV		I	I

Table 46
IM-Test Signature for 155 mm Artillery Shell [122].

Configuration	FCO	SCO	BI	FI	SR	SCJ
AFX-770 Mk82			V		NR	
AFX-900 Mk82					NR	
H-6 Mk82	*I*	*I*	*I*	*I*	*I*	

Table 47
IM-test signature for GP-bomb.

	FOX-12		TATB		NGu	FOX-7		HMX	
TMD (g cm-3)	1.76		1.935		1.77	1.934		1.906	
ρ exp (g cm-3)	1.666		1.894		1.742	1.76		1.823	
V_D (m s-1)	7870	*94.3 %*	7589	91.0 %	8344	8230	*98.6*	8800	105.5 %
P_{CJ} (GPa)	26.11	*90.0 %*	28.5	98.3 %	29.0	29.8	*102.8 %*	37.4	129.0 %
Ø cr (mm)	20><52		<9		<12	*?*			
2√E_G (m s-1)	2374	*97.4 %*	2411	99.0 %	2435	2644	*108.6 %*	2970	122.0 %

Table 48
Performance synopsis NGu -FOX-1-FOX-7-TATB-HMX.

	FOX-12		TATB		NGu	FOX-7		HMX	
TMD/$(g \cdot cm^{-3})$	1.760		1.935		1.770	1.934		1.906	
$\rho_{exp}/(g \cdot cm^{-3})$	1.666		1.894		1.742	1.760		1.823	
$v_D/(m \cdot s^{-1})$	7870	94.3%	7589	91.0%	8344	8230	98.6%	8800	105.5%
p_{CJ}/GPa	26.11	90.0%	28.50	98.3%	29.00	29.80	102.8%	37.40	129.0%
ϕ_{cr}/mm	20–52		<9		<12	?			
$\sqrt{2E_G}$ $(m \cdot s^{-1})$	2374	97.4%	2411	99.0%	2435	2644	108.6%	2970	122.0%

candidate for future highly dense, high performance low sensitivity melt cast formulations. Groven et al. have just observed that Resonant Acoustic Milling (RAM) of LBD-Nitroguanidine yields agglomerates of dense NGu-bundles resembling HBD-NGu [133].

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List of abbreviations

$\sqrt{2E_G}$	Gurney Energy, $m \cdot s^{-1}$
Øcr	critical diameter, mm
ρ	density, $g \cdot cm^{-3}$
$\Delta_f H$	enthalpy of formation, $kJ \cdot mol^{-1}$
$\Delta_{det} H$	enthalpy of detonation, $kJ \cdot mol^{-1}$
$\Delta_{vap} H$	enthalpy of vaporization, $kJ \cdot mol^{-1}$
μ_{dp}	particle diameter, mm
§	mass fraction, wt.%
Ω	Oxygen balance, wt.%
AN	Ammonium nitrate, NH_4NO_3
AOP	NATO-Allied Ordnance Publication
BI	Bullet Impact
CAS	Chemical Abstracts Service
CE	Tetryl, $C_7H_5N_5O_8$
dp	decomposition point, °C
EI(D)S	Extremely Insensitive (Detonating) Substance
ELSGT	Extra Large Scale Gap Test
FCO	Fast Cook Off
FI	Fragment Impact
FOX-7	1,1-Diamino-2,2-dinitroethylene, $C_2H_4N_4O_4$
FOX-12	GUDN
GP	General Purpose
GUDN	N-Guanylurea dinitramide, $C_2H_7N_7O_5$
HBD	high bulk density
HE	high explosive
HMX	Octogen, $C_4H_8N_8O_8$
IM	Insensitive Munitions
IMX	Insensitive Melt cast Explosive
LBD	low bulk density
LSGT	Large Scale Gap Test
LVD	low velocity detonation
Mk	Mark
mp	melting point, °C
m_r	molecular weight, $g \cdot mol^{-1}$
NATO	North Atlantic Treaty Organization
NGu	Nitroguanidine, $CH_4N_4O_2$
NOL	Naval Ordnance Laboratory
NTO	3-Nitro-1,2,4-triazolone, $C_2H_2N_4O_3$
P	Pressure, GPa
P_{CJ}	Chapman Jouguet pressure, GPa
PETN	Pentaerythritol tetranitrate, $C_5H_8N_4O_{12}$
RDX	Hexogen, $C_3H_6N_6O_6$
SCJ	Shaped Charge Jet Impact
SCO	Slow Cook Off
SR	Sympathetic Reaction
SHBD	Spherical High Bulk Density
SLSGT	Super Large Scale Gap Test
STANAGNATO	Standardization Agreement
TATB	1,3,5-Triamino-2,4,6-trinitrobenzene, $C_6H_6N_6O_6$
T_{CJ}	Chapman Jouguet temperature, K
TDO	N-Tallow-1,3-diaminopropane dioleate, CAS-No.[61791-53-5]
TMD	Theoretical maximum density, $g \cdot cm^{-3}$
TNT	2,4,6-Trinitrotoluene, $C_7H_5N_3O_6$
U_s	shock velocity, $m \cdot s^{-1}$
U_p	particle velocity, $m \cdot s^{-1}$
v	specific volume, $cm^3 \cdot g^{-1}$
VD	detonation velocity, $m \cdot s^{-1}$
V/V_0	9.0 Cylinder Energy at expansion ration 1:9, $kJ \cdot cm^{-3}$

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