

REVIEW PAPER

Advanced Concepts of the Propulsion System for the Futuristic Gun Ammunition

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ABSTRACT

This review paper reports various concepts of the gun propulsion system to meet the goal of the futuristic hypervelocity projectiles. The nonconventional concepts, such as liquid gun propellant, rail gun, coil gun, electrothermal gun, electrothermal chemical gun along with conventional energetic solid gun propellant have been discussed. Even though muzzle velocity around 2000 m/s has been claimed to be achieved using such nonconventional propulsion systems, it will take quite some time before such systems are in regular use in the battlefield. Hence, solid gun propellants containing novel energetic ingredients (binders, plasticisers, and oxidisers) would continue to be used in the near future and are expected to meet the requirements of the futuristic gun ammunition.

Keywords: Gun propellant, propulsion system, gun ammunition, high performance propellants, hypervelocity guns

1. INTRODUCTION

Since the conventional solid gun propellants have reached the saturation level in terms of energy output, a need exists for the development of high performance propellants for futuristic gun ammunition to propel hypervelocity projectiles'. Hypervelocity guns are the guns having muzzle velocity in excess of 2000 m/s. Modern tank guns have muzzle velocity in the range 1600–1800 m/s. With continuous improvements in armour technology, improved weapons with high muzzle velocity are under development and are expected to be deployed in the near future. In addition to armour defeating capability, high muzzle velocity endows the weapons with higher range, quicker response time and better accuracy. Also, hypervelocity projectiles are needed in modern aircraft

guns to defeat fast moving aircraft and for simulation studies on nuclear weapons^{2,3}.

A considerable progress has been made on solid propellants, especially the propellants, containing cyclic nitramine, such as RDX. However, the higher percentage of RDX used in gun propellant formulation leads to problems associated with gun erosion⁴. Hence, research and development activities were concentrated on the alternative concepts of the gun propulsion system, such as liquid gun propellant, rail gun, coil gun, electrothermal gun, electrothermal-chemical gun, etc. Liquid gun propellants possess certain advantages over the solid gun propellants in respect of lower flame temperature, muzzle flash, continuous zoning capability, good storage stability, insensitivity, better logistics, and lower cost. However, encountered

problems, such as gun design and ignition system along with combustion instability limit their application, and presently, no liquid gun propellant is in use. Electrically powered guns, though found to be attractive from the muzzle velocity point of view, storage of electrical energy is a major problem which has prevented its usage⁵. It is, therefore, the solid gun propellants, based on the novel energetic ingredients, being considered as an ultimate choice for the futuristic hypervelocity projectiles⁶. Solid gun propellants are preferred by the present ballisticians mainly due to the simple concept, lower cost, better thermal and chemical stability, and higher performance reliability. The present review gives a brief account of the gun propulsion system, such as liquid gun propellant, rail gun, coil gun, electrothermal gun, and electrothermal chemical gun. However, an emphasis has been made on the solid gun propellants based on the novel energetic ingredients as an ultimate choice for the futuristic gun ammunition.

2. LIQUID GUN PROPELLANTS

Interest in liquid propellants for guns has been generated after their use in rockets. Research has been carried out in the USA for their developments. Liquid propellants have been classified as monopropellants [isopropyl nitrate (IPN), hydroxyl ammonium nitrate (HAN), Me nitrate] and bipropellants [red fuming nitric acid (RFNA) + mono methyl hydrazine (MMHN), (liquid N_2 + liquid O_2)]. Similarly, bipropellants have been classified as hypergolic [red fuming nitric acid (RFNA) + unsymmetrical dimethyl hydrazine (UDMH)] and nonhypergolic [(liquid O_2 + liquid H_2) (H_2O_2 + NH_3)]. Considering the nature of gun systems, the use of cryogenic liquid propellants is out of question. Similarly, material constraints and stability have resulted in the rejection of potential candidates like RFNA and H_2O_2 . Main requirements placed on a potential candidate are high density, small variation of density with temperature, high specific heat and thermal conductivity and boiling point, less viscosity, thermal stability, etc. Ultimately, HAN, triethanol ammonium nitrate (TEAN) and water mixture has been selected as potential candidate for liquid gun propellant⁷.

Several designs for the combustion chamber of the gun system has been prepared. Bulk loading

gun systems were the first to appear. However, increasing incidences of combustion instability and erratic behaviour led to the regenerative loading gun system. Travelling charge gun system is the latest in the chamber design (Fig.1). In spite of the potential advantages of the liquid gun propellant, the concept has not been fully emerged. This is mainly due to lack of suitable gun barrel for the liquid propellant evaluation, investigation of the suitable ignition system, and means to resolve the combustion instability⁵.

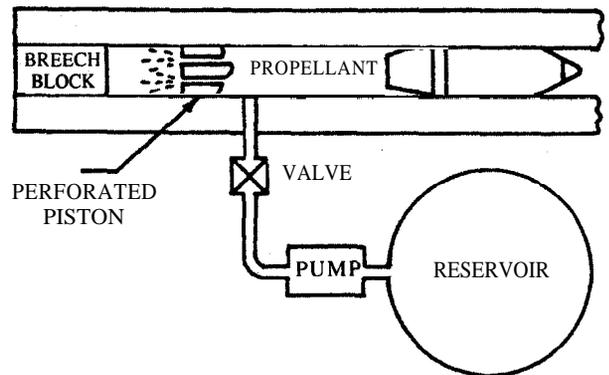


Figure 1. Travelling charge gun system

3. GUN SYSTEMS

3.1 Rail Gun

The inventor of the rail gun was Andres Louis-Octave Fauchon-Vileplee (a French scientist) who obtained three patents⁹ in 1920. Further development took place during 1944-45 when a German scientist, Hansler accelerated 10 g aluminium cylinder to 1210 m/s. Presently, 2.2 g masses have been accelerated to velocities 10 km/s using 5 m rail gun⁹.

Basically, a rail gun¹⁰ consists of two parallel rails; the projectile glides between these. When a current source is connected to the rails, the current flows from one rail to the projectile, through a conducting armature at the base of the projectile and to the other rail and back to the other direction through the armature and thus accelerates the projectile. The current creates a magnetic field that acts with the Lorenz force on the current flowing through the armature and thus accelerates the projectile⁹.

The principle of the rail gun¹⁰ is shown in Fig. 2. The short duration high ampere current C

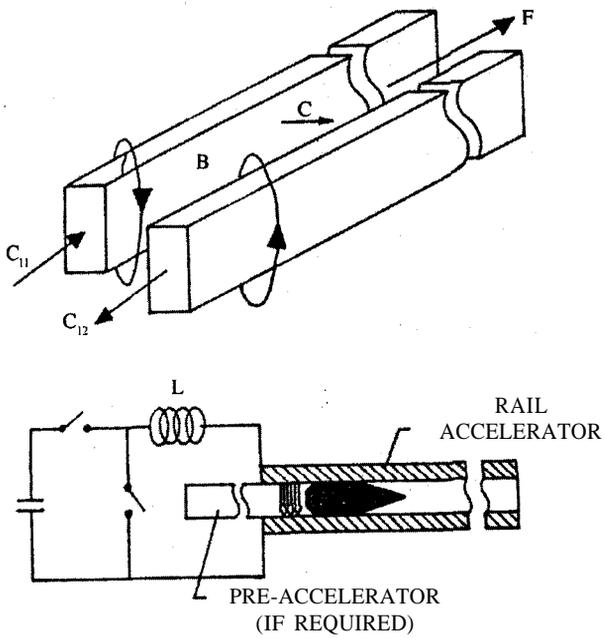


Figure 2. Schematic of rail gun

produces a magnetic field B which drives a plasma link, and thus, the projectile. The advantage of this propulsion concept is that it overcomes the projectile velocity limitations encountered in other gas or plasma-driven propulsion systems. However, there are some problems required to be resolved like arcing at the rails and at switch surfaces and self-contained power supply of the gun deliver currents in the mega ampere range. Efforts are being made to overcome the contact erosion and melting problems using self-activating crowbar switches and by carefully designing superconducting plasma armature. Also, research is in progress in the field of energy power supply and storage devices to reduce the overall volume and weight of the gun assembly. Only then does the weaponisation of this propulsion concept becomes feasible.

Some of the rail gun systems mentioned in the literature¹⁰ include:

- Augmented rail gun
- Stacked rail gun
- Transformer rail gun
- Storage transformer rail gun

- XRAM-gun
- Double-powered rail gun
- Superconducting augmented rail gun.

3.2 Coil Gun

The oldest form of electromagnetic guns built was the coil gun. The development of coil gun is reported to have started in 1845. The credit for the first patent on coil gun went to Prof Kristian Birkland of the University of Oslo. He accelerated 500 g projectile to a velocity of 50 m/s. German scientist Dr Jorachim Hansler continued the same work in 1944. A velocity of 4.9 km/s for projectile of mass 1.3 g was achieved by Soviet scientists⁵. The coil gun is shown in Fig. 3.

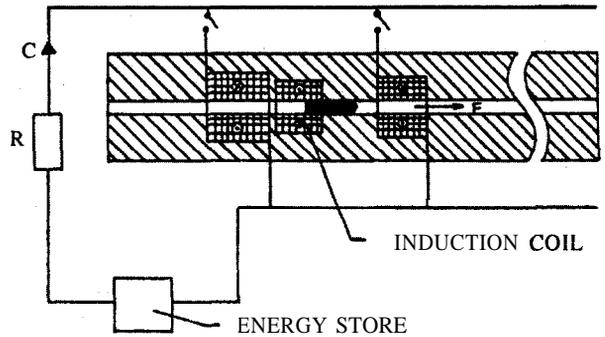


Figure 3. Schematic of electric coil gun

The gun consists of a barrel with a series of fixed accelerated coils. When these spools are electrified sequentially, a travelling magnetic field arises that induces a current in the projectile coil. As a consequence, the travelling magnetic field exerts the Lorentz force on the projectile coil current, thus accelerating the projectile⁵.

The main difference between the rail gun and the coil gun lies in the production of the current loops. In the coil gun, there are a number of loops that supply the same magnetic force to the projectile, whereas in the rail gun only a continuously changing current is produced. This makes the coil gun more efficient than the rail gun, but is also more complex. Moreover, the coil gun presents problems in high current switching. Therefore today's research is focussed on the rail gun¹⁰.

3.3 Electrothermal Gun

The third basic type of electrically powered gun is the electrothermal gun. The concept of an electrothermal gun using plasma rather than explosively released chemical energy from a combusting solid propellant charge was first considered in Germany in 1945. However, Yoler (General Electric Co.) claimed the first patent in 1956. Bioxom achieved a velocity of 2990 m/s for nylon spheres 13 mm in diameter". The electrothermal gun exists in several versions. In the simplest version, the gun consists of a conventional barrel with electrodes, leading to a plasma burner mounted on the breech-end of the weapon. A voltage across the plasma burner electrodes creates an arc that vapourises material poly-ethylene, placed between the electrodes. The vapourised material is superheated until it becomes a high pressure plasma which accelerates the projectile". The electrothermal gun is shown in Fig. 4. The electrothermal gun is expected to yield higher projectile velocities than the conventional guns. The projectile velocities of about 10 km/s have been projected for the future electrothermal guns¹⁰. However, the hot plasma may also increase erosion and shortens gun barrel life. The other problem associated with the present electrothermal gun is the enormous weight and size of the electrical power supply¹⁰.

3.4 Electrothermal Chemical Guns

The electrothermal chemical gun is an innovative hypervelocity propulsive system whose propulsive energy comes from an external energy source

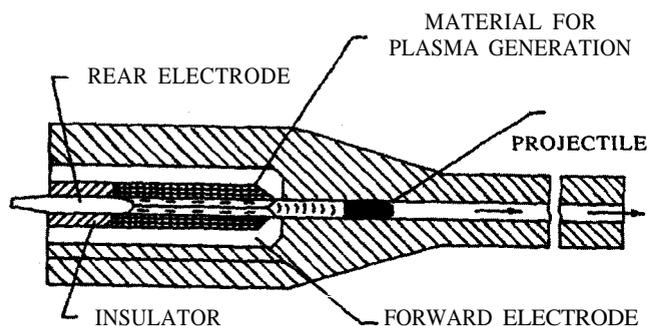


Figure 4. Schematic of electrothermal gun

(ie electrical energy input) as well as an internal energy source (ie chemical energy)¹. The electrical energy is discharged to the electrothermal chemical gun by a separate device called pulse-forming network (PFN). The chemical energy, on the other hand, is released through combustion of the working fluid (ie, liquid propellant) in the gun chamber. The electrothermal chemical gun provides several advantages over the conventional solid propellant and the liquid propellant guns. For example, the electrothermal chemical gun system can produce a higher muzzle velocity because the propulsive energy is not limited by the size of the combustion chamber and the amount of liquid propellant (ie, the ratio of the projectile mass to the propellant charge). As such, the muzzle velocity of an electrothermal chemical gun could exceed 2000 m/s. The electrothermal chemical gun also provides a better controllable operation, since the combustion rate of the liquid propellant can be regulated by the electrical energy input, thus preventing runaway combustion and abnormal pressurisation.

A typical electrothermal chemical gun system¹² consists of four major parts (Fig.5). These include the pulse-forming network, the plasma-generating cartridge, the gun barrel and projectile, and the working fluid (ie, liquid propellant). The primary function of the pulse-forming network is to store and discharge the electrical energy into the plasma-generating cartridge. The electrical energy is used to convert the wall material in the plasma-generating cartridge to high temperature plasma in the discharge process. The plasma fed into the gun chamber decomposes the working fluid, resulting in a pressure rise, and thus, the subsequent acceleration of the projectile takes place under the influence of the generated propulsive energy. Conceivably, by tailoring the pulse-forming network discharge process and selecting a suitable working fluid, it is possible to achieve a high muzzle velocity while maintaining a low breech pressure in the electrothermal chemical gun.

The electrothermal chemical gun was developed and subsequently improved by designers at the FMC and GT-Devices in the early 1980s. A muzzle velocity of 2750 m/s for a 30 mm gun was reported

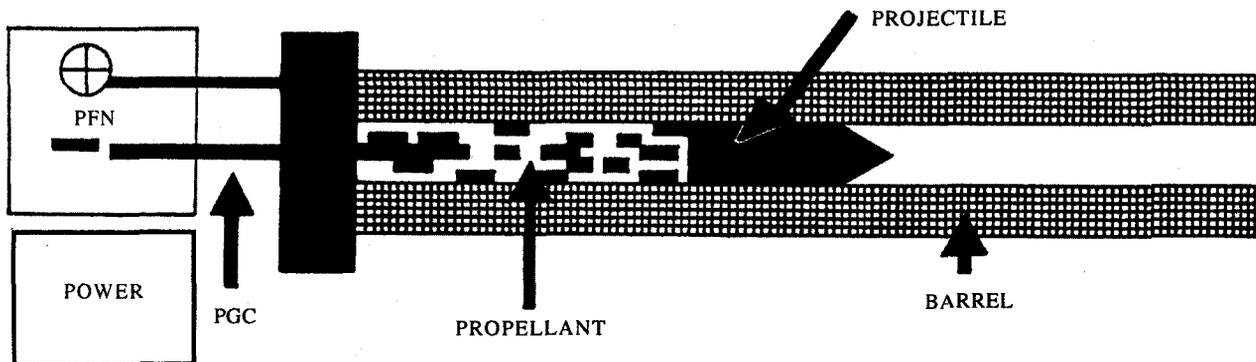


Figure 5. Schematic of electrothermal chemical gun

by researchers¹³, whereas a muzzle velocity of 2800 m/s for a projectile of 25 g was reported at GT-Devices¹⁴. Several studies have been conducted on the fundamental features of the electrothermal chemical gun, including the thermochemical properties of various working fluids, the pulse-forming network circuits and batteries, and **plasma/working fluid** interaction in the electrothermal chemical gun chamber. Theoretical models have also been developed. Oberle used a modified ballistic code to study the effects of electrical energy input and working fluids on gun performance¹⁵. Cook¹⁶, *et al* simulated the interior ballistic process of an electrothermal chemical gun by considering the motions of gas and liquid in the gun chamber as potential flows. Chen, *et al.* developed a comprehensive theoretical model to investigate the effects of the pulse-forming network discharge characteristics. In the present work, the model presented is further upgraded and employed to study the effects of electrical and chemical energy input on electrothermal chemical gun performance.

4. SOLID PROPELLANTS BASED ON NOVEL ENERGETIC INGREDIENTS

In view of the many problems associated with the advanced propulsion systems, *i.e.*, liquid gun propellants and electrically powered guns, the gun systems have not emerged fully on the scene **inspite** of their high energetic potential in terms of muzzle velocity. Hence, the attention of the ballisticians has currently been refocused on the solid gun propellants containing novel energetic ingredients, and active research is being carried out all-over the globe.

4.1 Next Generation Gun Propellants

Simmon⁶ explored the possibility of the next generation gun propellants based on the novel energetic ingredients. These new ingredients of current interest to the propulsion community and combinations thereof were examined to determine the limits of performance possible in terms of low gas molecular weight, flame temperature, and force constant. Polymers considered were nitrocellulose (NC), hydroxy-terminated poly-butadiene (HTPB), glycidyl azide polymer (GAP molecular **weight~2000**), 3-azido methyl 3-methyl oxetane (AMMO), 3, 3 bis azido methyl oxetane (BAMO), poly 3-nitro methoxy 3-methyl oxetane (NIMMO) and poly glycidyl nitrate (PGN), while plasticisers were glycidyl azide polymer (GAP, molecular **weight~300-500**), 1,3, diazido-3-nitrazapropane (DANP), 1, 5 diazido-3-nitrazapentane (DANPE) and alkyl nitrate ethyl nitramines (NENA). Solid oxidisers examined were cyclotrimethylene trinitramine (RDX), 2, 4, 6, 8, 10, 12 hexanitro 2,4,6,8,10,12 hexa azatetra cyclo (5,5 0,0, 5.9, 0, 3.11) dodecane (CL-20 or HNIW), 1,3,3 trinitroazetidine (TNAZ), ammonium dinitramide (ADN) and two triaminoguanidine salts, *ie*, triaminoguanidine nitrate (TAGN) and triaminoguanidine azide (TAGAZ), nitroguanidine (NQ) and three energetic diazido dinitramines, *ie*, 1, 6 diazido 2, 5 dinitrazahexane (DADNH), 1, 7 diazido 2, 4, 6 trinitrazaheptane (DATH) and 1, 9 diazido 2,4,6,8 tetranitrazanonane (DATN). Theoretical calculations made on⁷ examining more than 20 ingredients currently of interest to the propulsion community reveal that a force constant up to 1400 J/g would be within the reach (Tables land 2).

Table 1. Systems with force constant > 1400 J/g and flame temperature = 3500 K

System composition (percentage)	Force constant (J/g)	Flame Temp (K)	Gas (mol wt)
DANP(55 %) + Et-NENA (45 %)	1484	3546	19.87
DANP(65 %) + Pro-NENA (35 %)	1480	3503	19.68
DANP (30 %) + AND (30 %) + TAGAZ (40 %)	1477	3500	19.70
ADN (50 %) + DANPE (50 %)	1470	3500	19.80
TAGN (50 %) + DANP(50 %)	1464	3515	19.96
TAGN (15 %) + DADNH (85 %)	1463	3510	19.95
Et-NENA (15 %) + DADNH (85 %)	1452	3484	19.95
Et-NENA (42 %) + DADZP (58 %)	1443	3525	20.31
GAP (15 %) + Me-NENA (10 %) + DADNH (75 %)	1446	3489	20.06
TAAZ (40 %) + DANPE (60 %)	1439	3490	20.16
DATH (60 %) + DANPE (40 %)	1427	3497	20.38
RDX (55 %) + DANPE (45 %)	1425	3497	20.40
CL-20 (40 %) + DANPE (60 %)	1419	3525	20.67

Table 2. Systems with gas molecular weight ≤ 18

System composition (percentage)	Force constant (J/g)	Flame temperature (K)	Gas (mol wt)	Ratio of specific heat (γ)	WC
NC (30 %) + TAGAZ (70 %)	1066	2300	17.94	1.277	0.96
GAP (15 %) + TAGN (85 %)	1073	2325	18.01	1.278	1.74
ADN (30 %) + Bu-NENA(70 %)	1085	2349	18.00	1.276	1.31
TAGAZ (15 %) + TAGN (85 %)	1148	2485	18.01	1.271	2.50
TAGAZ (40 %) + Me-NENA (60 %)	1220	2646	18.02	1.275	1.33
DANPE (40 %) + TAGN (60 %)	1223	2655	18.05	1.277	1.28
Me-NENA (20 %) + ADN (22 %) + TAGAZ (58 %)	1273	2746	17.04	1.272	1.74
ADN (33 %) + TAGAZ (67 %)	1298	2707	17.02	1.270	2.34
DANP (25 %) + ADN (18 %) + TAGAZ (57 %)	1378	2987	18.01	1.275	1.26

4.2 Replacement of Non-energetic Plasticiser

Plasticisers are the key ingredients of the propellant which control the processing, plasticity, and mechanical properties of the propellant in addition to the desensitisation of the nitramine. Energetic plasticisers, in view of their higher heat of formation and density, enhance the energy of the propellant. The energetic plasticisers invariably contain functional groups, such as nitro, fluoronitro, fluoroamino, azido, etc. in addition to long carbon-carbon chain, and thus, these maintain the physicochemical properties of the propellant with high energetics. A number of energetic plasticisers have been synthesised and characterised recently. The promising candidates in the present context are GAP (molecular weight~500), DANPE, Bu-NENA and diazidodiester⁶.

4.3 Advanced Gun Propellants based on Glycidyl Azide Polymer

Kubota and Sonobe¹⁷ had studied the burning rate characteristics and chemical properties of GAP and recommended it as an energetic binder for high energy gun propellant formulations. They had formulated the compositions employing a copolymer of NC and GAP to provide low isochoric flame temperature and high force constant. It was also suggested that due to copolymerisation of NC-GAP, solid loading of crystalline oxidisers, i.e., RDX, HMX, TAGN and combinations thereof up to 70 per cent would be possible. Theoretical calculations reveal that force constant up to 1300 J/g with flame temperature less than 3000 °K are achievable. Experimental study indicates that the burning rate, pressure exponent, temperature sensitivity, and flame structure were dependent largely on the concentration of the crystalline additives. Therefore, the crystalline additive like RDX or HMX was always mixed with TAGN in an optimum ratio to obtain high force constant at relatively lower flame temperature in NC-GAP copolymerised propellant systems.

4.4 Ultra High Energy Gun Propellants

A series of ultra high energy azide containing gun propellants have been formulated in the USA,

wherein it is shown that propellants, having a force constant more than 1451 J/g at flame temperature less than 4000 K, is possible¹⁸. The propellant comprises 25-35 per cent NC-based binder and a combination of azide compounds of DADNH, DATH and DATN. The binder comprises NC, DANPE, and nitroisobutyl glycerol trinitrate (NIBGTN) in 1:1:1 ratio (Table 3).

4.5 High Energy Propellants based on Ammonium Azide

The high velocity gun propellants consisting of ammonium azide have also been suggested¹⁹. The propellant composition consists of an admixture of a hydrogen-rich material and a metal, which are capable of reacting exothermically. The ratio of the first material to the second material is selected, such that the exothermic reaction forms a solid phase and a gas phase containing substantial amount of hydrogen. Preferably the hydrogen-rich material comprises a material capable of providing nitrogen upon decomposition, such as ammonium azide and the metal comprises materials, such as boron, titanium, and titanium hydride, capable of reacting exothermically with the nitrogen generated by decomposition of the first material such that the solid phase comprises a solid nitride of the metal¹⁹.

4.6 High Energy Propellants based on Metallic Powder

Incorporation of aluminium powder into the conventional gun propellants was suggested to improve the ballistic properties of single-base and double-base propellants²⁰. The experimental investigations reveal that addition of aluminium in the conventional single-base and double-base propellants increases the force constant, and consequently, the muzzle velocity of a projectile. It decreases the molecular weight of the combustion gases and keeps the temperature within the safety limits of the gun. The optimum content of aluminium in the propellant composition was found to be not more than 5-8 per cent. With such a percentage of aluminium, it is expected that flame temperature will increase up to 3100-3300 K, the force constant will increase 15-20 per cent and muzzle velocity by 4-8 per cent. The increase in

Table 3. Ultra high energy azide containing gun propellant formulations

Formulation	Binder (percentage)	Weight (percentage)			Force constant (J/g)	Flame Temp (K)
		DADNH	DATH	DATN		
F-1	25.0	40.0	35.0	--	1487	3872
F-2	25.0	50.0	25.0	--	1452	3667
F-3	25.0	60.0	15.0	--	1494	3795
F-4	25.0	40.0	--	35.0	1498	3908
F-5	25.0	50.0	--	25.0	1496	3859
F-6	25.0	60.0	--	15.0	1498	3811
F-7	30.0	46.7	23.3	--	1479	3819
F-8	30.0	46.7	--	23.3	1485	3842
F-9	30.0	43.3	--	21.7	1478	3827
1:1:1 (NC (12.6 N%) / DANPE / NIGBTN)						
F-10 (JA-2)	NC (59.5) + NG (14.9) + DEGDN (24.8)					
F-11 (References)	25.0 (33 NC + 66 NG)	75 Wt % RDX	--	--	1396	4306

energy of the conventional propellants by incorporation of aluminium simultaneously leads to reduction in the molecular weight of the combustion gases due to deoxidation²⁰ of CO_2 to CO.

4.7 High Energy Propellants based on Energetic Oxetane Prepolymers

An attractive approach to high energy, low sensitivity propellants involve the use of energetic oxetane prepolymers as suggested by Wardle²¹, et al. A high energy binder based on random copolymer of 3,3 bis (azido methyl) oxetane and 3-azidomethyl3-methyloxetane (BAMOIAMMO) was used. Using activated monomer, polymerisation of energetic oxetanes consisting of BAMOIAMMO with HNIW (CL-20), RDX and combinations of the two have offered potentially attractive high energy TPE gun propellants. It is reported that gun propellant consisting of BAMOIAMMO with RDX gives force constant more than 1300 J/g, and with CL-20, more than 1400 J/g.

5. CONCLUSION

Even though the modern concepts of the gun propulsion system, such as liquid gun propellant and electrically operated guns are highly promising for propelling the futuristic hypervelocity projectiles, the same have not emerged on the global scene due to acute problems associated with these. In view of this, the solid gun propellants based on the novel energetic ingredients like CL-20, TAGAZ, ADN, BAMO, AMMO, GAP, Bu-NENA azidonitramines, etc. have been recommended to meet the objectives of the futuristic gun ammunition. Even though these novel ingredients are currently being used in experimental formulations, it is expected that these will form the basis for futuristic high energy propellants. Future research in advanced solid gun propellants will also take place using gun propellant formulations containing compounds like azide, nitramine, triaminoguanidine, and hydrazine, which will produce low molecular weight combustion gases. Such fundamental research is

essential for the development of futuristic hyper-velocity guns. Hence, muzzle velocity in the range 2000–2500 m/s is expected to be achieved using solid gun propellants without resorting to rather unconventional methods of the propulsion like liquid gun propellant and electrically operated guns.

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Dr Amarjit Singh obtained his **PhD** from the University of Pune. He is Group Director of Gun Propellant Division of the High Energy Materials Research Laboratory, Pune. He has more than 57 publications and 3 patents to his credit. He has participated in a number of national and international seminars and workshops. His major contributions in the area of high energy materials include establishment of indigenous technology for triple-base gun propellants with increased energy and piezometric efficiency, low vulnerability propellants for gun ammunition, energetic binders and plasticers for gun applications, pyrotechnic screening, and coloured smokes for MBT *Arjun*, Lakshya, etc.