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Qualification Testing, Evaluation and Test Methods of Gas Generator for IEDs Application

B.A. Parate*, K.D. Deodhar, and V.K. Dixit

DRDO-Armament Research & Development Establishment, Pune - 411 021, India

*E-mail : baparate@gmail.com

ABSTRACT

In this work, the design qualification testing, evaluation and test methods of the gas generator using double base (DB) propellant having square flake shape is explained for an improvised explosive devices (IEDs) applications. Various kinds of the gas generators are used to save life of an aeronaut in the fastest way from the disable fighter aircraft. Due to their ruggedised design, compactness, safe transportation, repeatability in performance and quick operation, the gas generator are used. The gas generator is designed and developed keeping the functional, mechanical and structural requirements in mind. The gas generators are subjected to the various qualification tests, electrical characterisation followed by closed vessel (CV) firings at hot and cold temperatures. The gas generators after the successful qualification tests are validated through the ground trials i.e. dynamic firing of disruptor during the development phase. The damage caused due to impact of the projectile is assessed in terms of crater as acceptance criteria at stand-off distance of 0.5 m and 1m. The gas generator discussed in this research article is used to disrupt the suspected IEDs by creating a high-speed jet using water-jet disruptor. In conclusion, after the successful qualification testing, the gas generator for IEDs application meets all the specifications as per user's requirements.

Keywords: Closed vessel; Gas generator; Improvised explosive devices; Qualification testing and test methods

1. INTRODUCTION

The gas generators are largely used in an aerospace and aeronautics technology for actuating power units such as hydraulic turbines, alternators, ejection, dispensing, pressurising or inflating devices and auxiliary propulsion. Now days, the gas generators are being used in numerous applications which require a sudden and controlled generation of gases, varying from few micro or milli seconds to few minutes[1]. The gas generator under study comprises an electrical squib, the propellant or pyrotechnic compositions, which generally deliver the gas at a temperature more than 1200 K. The gas generator is initiated using the electrical squib. The qualification testing of the gas generator is of great importance to evaluate their performance characteristics for the confirmation of design, performance, safety, and susceptibility to known failure mechanisms. After the successful completion of the qualification testing as a acceptance criterion that the gas generators shall undergo for further trials. Test standards specify a common approach to conduct these qualification tests. For the gas generator qualification, test standards specify the various tests, number of gas generator, test procedures and the passing criteria. This research article provides an overview of approved standards to qualify the testing of the gas generators for IEDs application.

The gas generators for defence purpose consider high reliability and safety for various services. This will not suffice the service requirements. Therefore requisite additional requirements are absolute necessary. These requirements take into account the different disciplines of safety, reliability and maintainability. The gas generator is made of assemblies, sub-assemblies i.e. squib bridge assembly, and components such as the cartridge case, foil *etc*. Among them, the key component is the cartridge case. The concept of the case is of single chamber. The cartridge case is generally made up of brass, aluminium or steel materials. Brass and aluminium cartridge case materials are commonly used as non-corrosive and durable in nature. The cartridge case is generally called as the "bottle" that holds initiation means at the base centre, the pyrotechnic composition and the propellant. The squib makes flash, flame or spark initiating the whole explosive train when it is initiated by an electric current. The cartridge case not only supports everything but also forms a gas seal member to the wall of the cartridge where it is installed. High temperature and high pressure propellant gas are developed by the propellant when particular stimuli given to an explosive train. This results the case to expand. The expansion of cartridge case seals the chamber wall. This will prevent the escape of the propellant gas.

1.1 Description of the Gas Generator for IEDs Application

The gas generator used in a water-jet disruptor is made of brass material. The various components of the gas generator are end plug, case, propellant, separator, pyro composition, squib and lead wire. The other end of the gas generator is sealed

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using end plug and foil assembly having the threads. The gas generator has the squib at centre with lead wire for making an electrical connection. The end plug is made of brass material. The case has the mating threads for an easy assembly with the end plug, which is soldered with foil. The foil is made up of copper having 0.08 mm thickness. The gas generator is filled with the propellant and pyrotechnic composition and separated by a separator (a separator is made up of felt). DB propellant is used as the main filling in the gas generator for conduct of various experiments. Figure 1 depicts schematic of the gas generator showing its detail parts[2].

1.2 Function of the Gas Generator

The squib is a crucial part of the gas generator as a means of initiation. It comprises a high resistance wire (bridge wire) surrounded by a heat sensitive pyrotechnic composition. It is made of a highly sensitive energetic material such as lead styphnate (12 to 15 mg) pasted on a nichrome bridge wire, a moulded plug made of nylon material, and lead wires to make an electrical connection. When an electrical energy is supplied to the squib, it becomes red hot by 'Ohmic' or 'Joule' heating. The squib ignites the adjacent pyrotechnic composition, which in turn initiates the propellant. The propellant generates the hot combustion gas, which leads to the development of a high pressure in the confined space quickly. This high pressure ruptures a copper foil, which creates a plume of water through the barrel of a water-jet disruptor weapon. Based on the suitable applications, the gas generators have to satisfy a series of exhaustive qualification test requirements. Propellant selection is based on end use, high calorific value, high density, high force constant and longer life. Each gas generator has its own specific requirements with respect to safety, reliability and application[3]. The propellant must be carefully matched to its performance requirements, strength and its useful life. The real novelty of this work in respect of optimisation of propellant composition, booster composition, geometry and achievements are the propellant finalisation of quantity and formation of suitable explosive train. The propellant quantity has been finalised the energy required and availability of space. The propellant optimisation charge is evaluated by conducting the closed vessel tests at different temperature. This is static test for evaluating the peak pressure which is sufficient to the damage at the target end. This work is further validated and supported by conducting the actual experimental work.

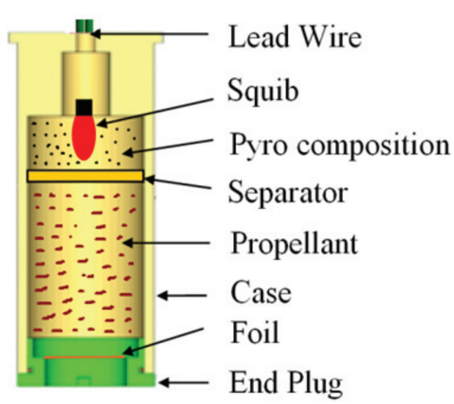


Figure 1. Schematic of the gas generator.

2. FORMULATION OF THE PROBLEM

A DB propellant is used as energetic material in the gas generator selected for qualification testing and the performance assessment on wooden / steel targets. This also includes realisation of the performance parameters through CV and an electrical characterisation of the gas generators. The experimental trials are conducted at a stand-off distance of 0.5 m and 1 m. All the trials show promising results and crater generated on the targets. There are no standard available to compare the performance of the gas generator for IEDs application. This helps to qualify the gas generator through the different process explained below with an interesting facts and experiences.

3. MATERIALS AND METHODS

The propellant should be selected with known characteristics and should be compatible with the case material. Based on the above requirements, DB propellant type is selected which consist of nitro-cellulose, nitroglycerine and other additives. The basic physical properties and chemical composition of square flake DB propellant that is used for conducting various experiments is given at Tables 1 and 2.

Table 1. Physical properties of square flake DB propellant[4]

Propellant shape	Square flake
Density	1.65 g / cc
Web	0.15 ± 0.02
Length	1 mm
Form factor	0.30
Calorimetric value	5045 J/g

Table 2. Chemical composition of square flake DB propellant[4].

Nitrocellulose (NC)	57.5± 0.2 %
Nitroglycerine (NG)	39.55 ± 0.1 %
Carbamite	1.70 ± 0.1 %
Mineral Jelly	0.40 %
Graphite	0.25 %
Volatile matter	0.30 %
Ash content	0.30 %

The images of square flake DB propellant with scanning electron microscope (SEM) used to determine internal ballistic parameters are depicted in Fig. 2 respectively.

4. TEST STANDARD FOR DESIGN QUALIFICATION TESTS (DQT)

The qualification testing is a part of verification activity undertaken during the development phase by the designer on many designs to ensure the gas generators are fit to produce an essential performance characteristic considering the end use. The qualification testing is often involves a rigorous set of tests such as drop, vibration, shock, leak test, electrical tests (AFC / NFC), resistance checks, environmental and other regulatory standards. The test procedures of the gas generator are predominantly worked out as per standard design practice followed at par with international standard. In order to prove the acceptability of the gas generator, they are subjected to the following tests as per joint service guide (JSG 0102)[5].

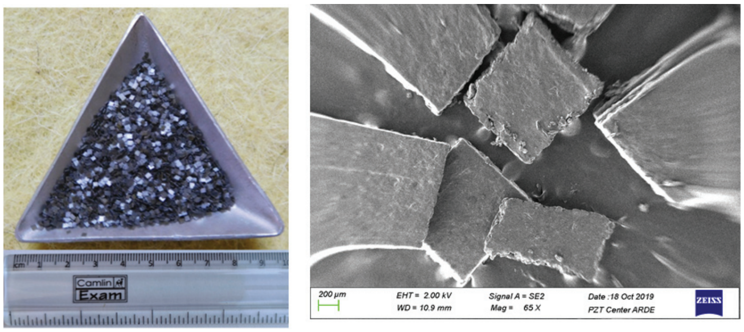


Figure 2. Square flake DB propellant (left) and SEM image (right).

5. DESIGN QUALIFICATION TESTS (DQT)

After completion of the gas generator design and structural analysis, specific tests are highly needed to prove the design. Hence, to qualify the design aspects of the gas generator, the following tests are conducted as per JSG 0102. These tests are described in the following paragraphs.

5.1 Drop Test

During the installation, transport or repair, the gas generators have a risk of being dropped and chances of accidental initiation. Under this test, the gas generators are dropped from a height of 1.5 m. This helps to ensure the safety of the gas generator during handling and transportation. The test facility for dropping at height 1.2 m is shown in Fig. 3 (a). A similar test is carried out at 12 m height using paradrop facility. The gas generators are dropped in vertical and horizontal orientations. Drop testing ensures the product stays in its original condition from manufacturing to implementation. The test facility is shown in Fig. 3 (b). The image of gas generators after this test is shown in Fig. 3 (c). The gas generator not functioned after this test.

5.2 Sealing Test

It is conducted to confirm the hermetical sealing of all the joints at half atmosphere. The gas generators are immersed in clean water filled in the desiccator. The pressure inside desiccator is reduced to 380 mm of Hg (half atmosphere) using a vacuum pump. Pressure is adjusted to half atmosphere using pressure gauge as shown in the adjoining Fig. 4. The emergence of water bubbles indicates that gas generator have leakages. None of the gas generator should leak at the end of this test. At the end of the test, no single gas generator observed as a leakage. This ensures the hermetical sealing of the gas generator at all possible joints. This is wet vacuum method of testing to ensure the sealing of all joints.

5.3 Vibration Test

The vibration test is performed to examine the response of a specimen under test (SUT) to a defined vibration environment level. The gas generators are undergone to the vibration tests using vibration fixture. A sinusoidal vibration with frequency range from 5 to 70 Hz and 12 mm peak-to-peak displacement is applied for 2 and ½ hrs. It is then followed by the random vibration with 0.03 g^2/Hz uniform spectral density (USD) in the frequency range from 70 to 2000 Hz for ½ hours

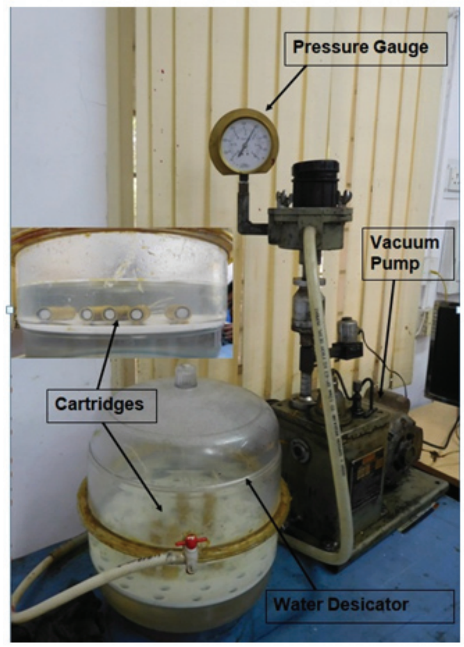


Figure 4. Test facility for sealing test.

(a) (b) (c)

Figure 3. Drop testing of gas generator: (a) Paradrop facility 1.5 m, (b) Paradrop facility 12 m, and (c) Gas generator after drop test.

on both the axes. The gas generators are successfully qualified the vibrations tests and withstood these forces. The vibration machine test set up and vibration fixture with gas generator is shown in Fig. 5. The random and sinusoidal vibration profiles are illustrated in Figs. 6 and 7 respectively. Fig. 7 shows acceleration *vs.* sinusoidal profile. The green lines represented in the Fig. 6 and 7 are the set values as per the test template and the profile should be followed. Orange lines shows the alarm level which is normally set to ± 5 to 10% of the set test template. Red lines indicate the abort level and are normally set to ± 10 to 20% of the set test template. In the Fig. 6, the *Y* axis represent power spectral density or acceleration spectral density which takes into consideration the combination of the random amplitude's and their frequencies.

5.4 Shock Test

The shock test is usually carried out to accurately determine the weakness of test specimen. It further helps to evaluate the protective package. The data evaluated during this test helps to understand whether the product is capable to withstand its "real world" environment. The detail of this test is given below.

- The peak acceleration : 20 g
- Number of shocks : 12

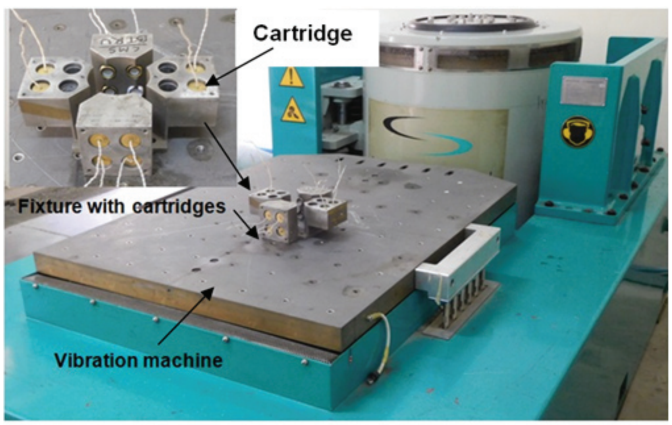


Figure 5. Vibration machine and Vibration fixture with gas generator.

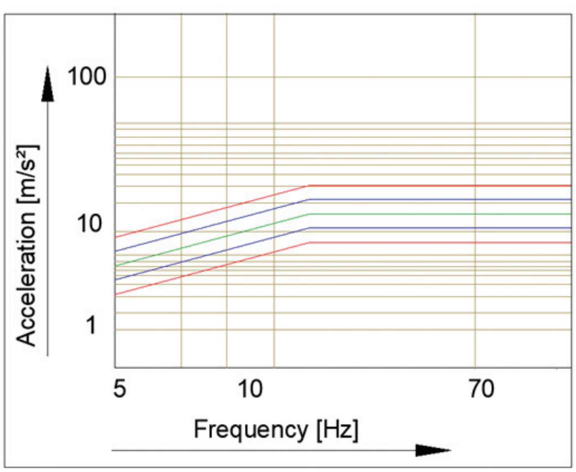


Figure 6. Sinusoidal vibration test.

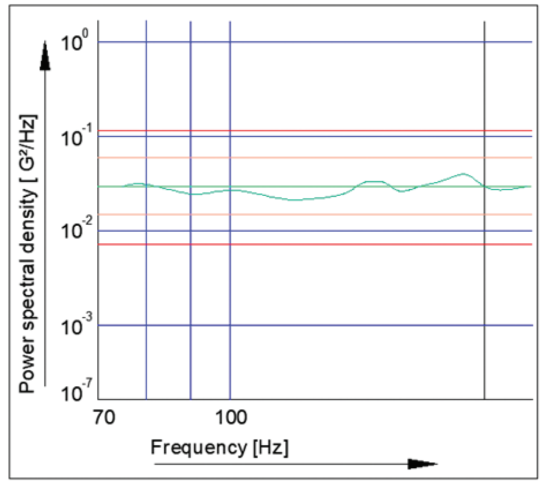


Figure 7. Random vibration test.

(6 shocks are in vertical axis and 6 shocks are in horizontal axis)

- Time : 11 ms
- Wave form : Terminal peak saw tooth

A shock test set-up, and load *vs.* time history are illustrated in the Figs. 8 and 9 respectively. At the end of above mentioned tests from 5.1 to 5.4, a CV firing is conducted at cold and hot conditions. The performance parameters *i.e.* P_{max} and TP_{max} realised in the CV of gas generators are within performance limits.

5.5 Energy Calculation of the Squib

In an armament system, an electro-explosive device (EED) is converting an electrical energy into the heat, which further initiates the explosive train with its accompanying temperature rise. The function of EED in the gas generator is to provide the adequate electrical current to cause the ignition of a highly sensitive explosive *i.e.* lead styphnate. An electrical current accomplishes ignition by heating the bulb of lead styphnate which produces enough heat to cause a booster to ignite. A

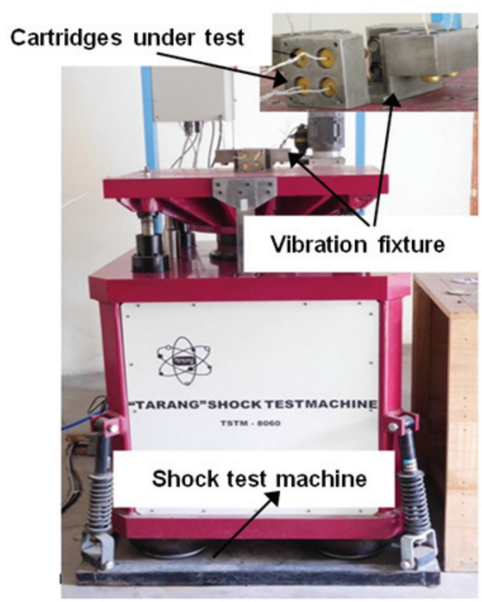


Figure 8. Shock test set-up.

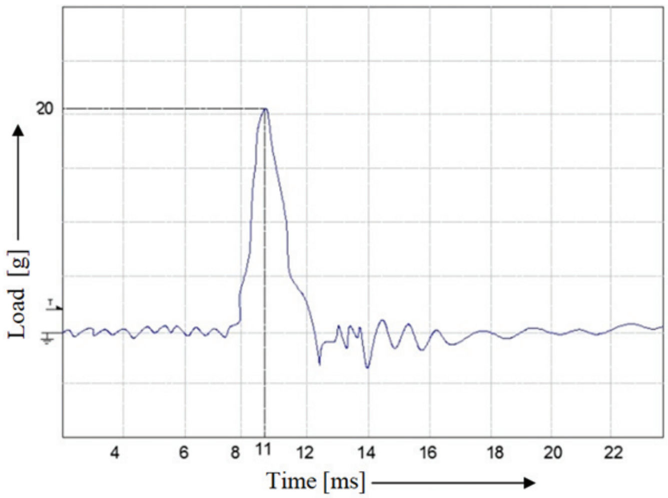


Figure 9. Load *vs.* time.

booster (gun powder) which is in immediate vicinity augments the ignition of the propellant further. The squib must be held firmly with the booster.

5.5.1 Energy for No fire Current (NFC)

It is the highest current that can be given to the gas generator for long duration with the probability of 'EED not firing' as 99.9%. NFC is estimated using Bruceton Staircase method[6]. This is an important as upper limit of the energy which can be induced in a firing circuit, may prevent un-commanded initiation of the EED. This method is popularly used to determine the sensitivity testing of ordnance and also called as 'Up and Down' approach. It is applied at an equal spaced test levels that are selected before the start of an experiment. The test is sequential in that test level for a given shot is calculated by the outcome of the previous shot. The energy is received by the squib wire and converted into heat energy; the temperature of the squib increases. The source of energy, the squib, gives in time t, the energy ($P \times t$) to the squib. If I is the current flowing continuously through the circuit, the heat produced in the squib in time t will be determined using energy formula, energy

$$(E) = P \times t = V \times I \times t \quad (1)$$

According to Ohm's law, as $V = I \times R$ (2)

$$E = I^2 R\, t \quad (3)$$

where

P-Power in Watt (W), I - Current in Ampere (A) [180 mA or 0.18 A], R - Resistance in Ohm (2Ω), t (time) - 5 s. Substituting the values in above equation 3, gives NFC.

Therefore, NFC = 0.18 × 0.18 × 2 × 5 = 0.324 J

5.5.2 Energy for All Fire Current (AFC)

The minimum applied current which has 'probability of the squib firing' 99.9% will always ensure the firing of EEDs. It is determined by Bruceton Staircase method as explained in the previous paragraph 5.5.1. The AFC value is evaluated experimentally for an EED is 600 mA. For the functioning of EEDs, it has a certain value of firing current above which all EEDs should function without any failures. This is a vital factor which contributes to deliver this energy over the specified life cycle. I - 600 mA or 0.6 A, R - 2 Ω (Average of 1.5 to 2.5 Ω). The average value is taken based on two extreme limits. t - 10 milli sec or 0.01 s

As the current is supplied, the bridge instantaneously fired in a milli second phenomenon.

Energy for AFC = 0.6 × 0.6 × 2 × 0.01

= 0.0072 J or 7.2 mJ

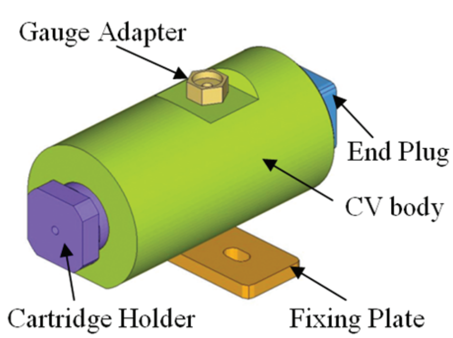
This represents a minimum energy condition to fire the squib.

The firing current is one of the crucial characteristic of the gas generator which gives the information about a safe handling during storage and transportation and high confidence of firing in the mission mode.

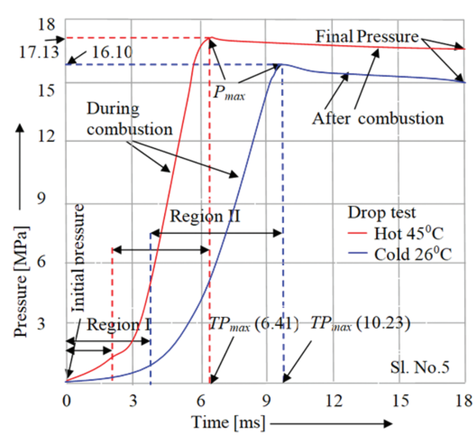
6 EXPERIMENTAL EVALUATION IN THE CV

6.1 Description of the CV

A CV is cylindrical in shape where the gas generator is loaded inside the cartridge holder. It consists of gauge adapter, fixing plate, CV body and end plug. The end plug is fitted to the gas generator of CV body. The cartridge holder is fitted at the other side. A gauge adapter with pressure sensor is fitted to the CV body. The vessel has been designed and fabricated for realisation of the performance parameters[7,8]. The CV assembly with various parts is shown in Figure 10 (a). Before the firing, the vessel is sealed from the threaded ends by positioning copper washers on the cartridge holder and end plug so that



(a)



(b)

Figure 10. (a) The CV assembly and (b). Pressure-time (*P-t*) profile.

gas liberated by the gas generator can not escape. A booster is ignited by the squib and generates the flash. The augmented flash by a booster ignites the main charge *i.e.* propellant. The propellant chemical energy is transformed into the heat energy. Pressure-time (*P-t*) profile generated after the firing of the gas generator is shown in Figure 10 (b).

6.2 Evaluation of Pressure - time (*P-t*) Parameters

Proof limits are experimentally assessed after conducting trials in the CV. The proof limits are generated by firing quantity 50 Nos. each at hot and cold conditions. The proof limits are laid on the basis of mean ± three times standard deviations. These are 12 MPa to 20 MPa P_{max} and 5 ms to 15 ms for TP_{max}. The pressure sensor is usually used to record the *P-t* parameters. The recorded *P-t* history is divided in two regions *i.e.* region *I* and *II*.

Region *I*: It is mainly due to booster combustion.

Region *II* : The region *II* is due to pressure start rise during the propellant combustion that is boosted by a booster. The end of the region is attained by the maximum pressure which leads to complete combustion of the propellant. One of *P-t* profile in hot and cold temperature conditions is illustrated at Fig. 10 (b). The pressure is rising and reaches to maximum value i.e. P_{max}. The final pressure is slightly less than P_{max}. The serial number 5 is selected from Table 3 for hot (**red** color) and cold (**blue** color) for drop test.

7. RESULT AND DISCUSSIONS

7.1 CV Trials

After the successful completion of qualification tests, the firing trials in the CV are carried out. *P-t* performance parameters are recorded. The test results are shown at Tables 3 to 6. All the parameters are consistent at hot and cold temperature conditions. All results are within proof limits. These are 12 MPa to 20 MPa for P_{max} and 5 ms to 15 ms for time to TP_{max}. These are acceptable limits are qualifying the gas generator for IEDs application.

After the conduct of all qualification it is observed that all the experimental values are within proof limits.

7.2 Dynamic Firing Trials

After realisation of the performance parameters of the gas generator in the CV, the dynamic firing trials with a water-jet disruptor are undertaken. The dynamic firing trials comprise of a water-jet disruptor, the gas generator, high-speed camera and targets. After design qualification testing, the gas generator is assembled with a water-jet disruptor. The experimental set-up for firing of a water-jet disruptor, interaction of a water-jet and the projectile is shown in Figs. 11(a) and (b). These images are captured using a high-speed photography. The trials are carried out at a stand-off distances of 0.5 m and 1 m on wood such as pine, teak, ply and steel targets. In the actual water-jet firings, the high speed of water jet with projectile impact on target due to high gas pressure generated by the gas generator causing the damage at the target end. The images of targets before (left) and after (right) impact during the dynamic firing trials of water-jet disruptor are illustrated in Fig. 12. The damage caused due to the impact of the projectile on various woods having same thickness is shown in Figs. 12(a), (b) and (c). In all the cases, the damage is assessed at a stand-off distance of 0.5 m and 1 m. The thickness of all wooden targets is 15 mm thick. The same phenomenon of the damage is noticed on steel plate having thickness of 0.5 mm at stand-off distances of 0.5 m. This is depicted at Figure 12 (d). This demonstrates the destruction capability of the gas generator using water-jet disruptor to cause the damage to these targets. In general the damage caused due to impact of the projectile on various targets is more than the projectile diameter.

Disruptor trials for a number of samples against each target are carried out. In few cases, the target structures are broken and in other cases, craters are made. This is observed at stand -off distance of 0.5m and 1m. It is depends on the variations in velocity of water and the force experienced by the targets

Table 3. Drop Test (1.5m)

Hot (+ 45ºC)		Cold (- 26ºC)	
P_{max} [MPa]	TP_{max} [ms]	P_{max} [MPa]	TP_{max} [ms]
17.02	5.87	14.87	7.87
16.87	5.98	15.13	6.87
16.41	7.98	16.00	9.12
16.56	7.43	15.23	10.76
17.13	6.41	16.10	10.23

Table 4. Sealing Test

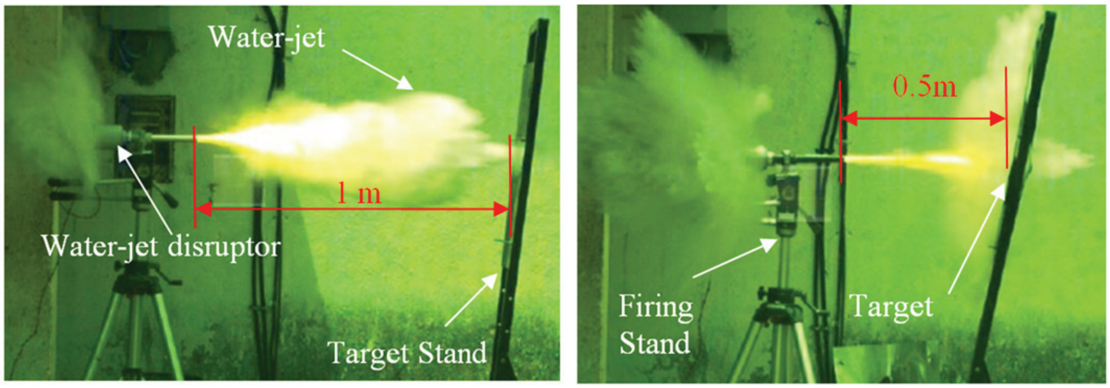
Hot (+ 45ºC)		Cold (- 26ºC)	
P_{max} [MPa]	TP_{max} [ms]	P_{max} [MPa]	TP_{max} [ms]
15.02	5.95	13.87	10.76
16.43	6.02	14.76	9.50
16.78	7.13	15.02	8.56
15.87	6.97	15.98	8.90
15.56	6.87	14.15	9.22

Table 5. Vibration Test

Hot (+ 45ºC)		Cold (- 26ºC)	
P_{max} [MPa]	TP_{max} [ms]	P_{max} [MPa]	TP_{max} [ms]
16.43	7.12	14.87	9.34
14.43	6.71	15.34	8.92
15.76	5.87	12.98	12.56
14.12	5.97	14.14	10.67
15.89	6.12	14.98	8.66

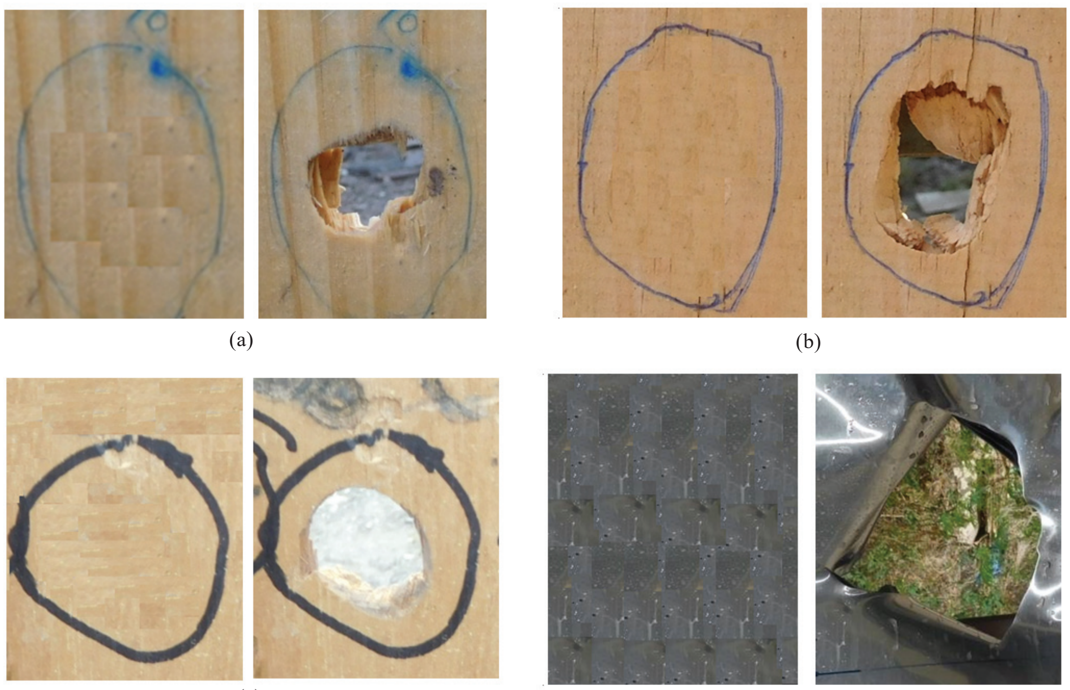
Table 6. Shock Test

Hot (+ 45ºC)		Cold (- 26ºC)	
P_{max} [MPa]	TP_{max} [ms]	P_{max} [MPa]	TP_{max} [ms]
16.15	6.90	15.45	7.01
15.41	5.67	14.98	7.98
16.78	5.88	13.56	11.89
15.34	6.90	15.65	9.80
14.78	7.17	15.89	9.55



(a) (b)

Figure 11 (a) Firing of a water-jet disruptor and (b) Interaction of a water-jet and the projectile.



(a) (b)

(c) (d)

Figure 12 (a). Pine wood (15 mm), (b) Teak wood (15 mm), (c) Ply wood (15 mm), and (d) Steel (0.5 mm).

during penetration of the projectile. In all the targets cases, the projectile defeats the different target structures. Craters created by the projectile due to the gas produced by the gas generator at various stand-off distances on various wooden targets are illustrated in Tables 7 and 8 respectively. The idea is to assess the damage in terms of craters on various targets as no standard are available as acceptance criteria for the disruptor applications.

8. CONCLUSIONS

From the foregoing deliberations, it is clear that to prove the gas generator testing in the development phase its qualification testing, realisation of the performance parameters in the CV, electrical characterisation including dynamic trials are highly needed. The gas generator passes through all the tests satisfactorily. The damage assessment of the gas generator due

Table 7. Test results of a disruptor firing at 0.5 m stand-off distance for DB propellant.

Round No.	Target Types (stand -off distance 0. 5 m)				
	Ply wood (15 mm thick)	Teak wood (15 mm thick)	Pine wood (15 mm thick)	Steel plate (0.5 mm thick)	Remark
1	19×20	Broken	16×20	20×25	
2	20×20	16×22	Broken	21×23	
3	Broken	17×21	16×21	20×24	Crater dimensions (mm)
4	20×22	Broken	Broken	22×25	
5	20×21	15×19	16×22	20×25	

Table 8. Test results of disruptor firings at 1 m stand-off distance for DB propellant.

Round No.	Target Types (stand -off distance 1 m)				Remark
	Ply wood (15 mm thick)	Teak wood (15 mm thick)	Pine wood (15 mm thick)	Steel plate (0.5 mm thick)	
1	20×21	18×19	16×20	22×26	Crater dimensions (mm)
2	19×20	20×21	20×18	22×24	
3	19×21	Broken	Broken	22×21	
4	19×20	18×21	16×21	24×26	
5	20×19	17×19	17×21	21×25	

to the projectile impact is considered as a measure of acceptance and test method for IEDs application.

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CONTRIBUTORS

Dr B.A. Parate, Scientist 'F', Joint Director is working at ARDE. He joined ARDE in March 1999. He has presented many papers in International / National journals, seminars and conferences. He obtained PhD in Mechanical Engg from DIAT, Pune in the year 2020. His doctoral research is based on 'Experimental and Analytical Analysis of Water-Jet Disruptor'. He has guided many students of BE and ME for completion of various projects.
Contribution in the current study, he did the literature survey, performed the experiments, data analysis and interpretation of results. He provided an idea for writing the first draft of the manuscript.

Mr K.D. Deodhar, Scientist 'F' is a post graduate in Mechanical Engg and heading the Division of Canopy Severance System and Power Cartridges for use in fighter aircraft required by Indian Air Force & Indian Navy.
Contribution in the current study, he organised the references of this research article.

Mr V.K. Dixit, Scientist 'H' is a graduate in Mechanical Engineering and working on various armament systems more than 33 years. He is the recipient of Scientist of the Year Award, towards his immense contribution in armament system. Presently, he is Associate Director at ARDE, Pune.
He was involved in fine tuning of results, writing and correcting the manuscript.