Development and Qualification Testing of Pyro-cartridge for Signal Cartridge Applications

Bhupesh A. Parate
Armament Research & Development Establishment (ARDE)
Dr. Homi Bhabha Road, Armament Post, Pashan, Pune - 411 021(Maharashtra), India

Phone: +91-20-2593 2501, Fax :+91-20-25865102, email: baparate@gmail.com
ORCID, B A Parate, http://orcid.org/0000-0002-1455-0826

Abstract: *This research work describes the development and qualification aspects of a pyro-cartridge device for signalling cartridge applications in an emergency, as required by military aircraft. Rapid and effective burning of illuminating composition plays a crucial role in military applications. For initiation of illuminating cartridge, a pyro-cartridge is used. A pyro-cartridge consists of energetic materials (EM), such as lead styphnate, and releases the energy by rapid a chemical reaction process. It releases the energy instantaneously so that striker from pyro-cartridge can then initiate the signalling cartridge. This signalling cartridge provides pre-coded signals with four different colours (Red, Green, Yellow and White) fitted in the dispenser of an aircraft system. The most important part of this work is to develop a pyro-cartridge and qualify its testing to ignite the composition of signalling cartridges through various design qualification tests, such as drop test and sealing test. The functional tests of signal cartridges using pyro-cartridge at hot and cold temperature is observed successfully. The electrical parameters such as all fire current, no fire current, ignition delay, determination of energy and power of squib are also covered in this research article.*

Keywords: *All fire current; bridge wire; Bruceton staircase; cartridge; ignition delay; no fire current; pyro-qualification; signalling cartridge; squib; testing*

INTRODUCTION

Pyro-cartridges are one shot devices or pyrotechnic devices. They comprises an integral part of explosive train that are widely used as initiating element in various applications such as power cartridges, aerospace, weapons, armament, civil blasting equipment. It helps to perform a variety of roles, such as initiating components in explosive trains, gas generators and sources of heat or mechanical energy to perform other munition system functions[1]. It comprises high resistance wire (bridge wire) surrounded by a heat sensitive pyrotechnic composition[2]. It is made of a highly sensitive energetic material such as lead styphnate pasted on a nichrome bridge wire, a moulded plug made of nylon material and lead wires to make an electrical connection. Operation of pyro-cartridge is based on ignition of highly sensitive energetic material; its shock wave generation is converted into useful work. In this paper, pyro-cartridges used to initiate signalling cartridge from an aircraft during emergencies or warfare missions. This article will outline development, function and qualification testing of a pyro-cartridge.

Article Details	Article No:- 0119
Manuscript Received:- 27/04/2020	Final Revisions:- 31/05/2020
Publication Date:- 31/05/2020	Archive Reference:- 1924

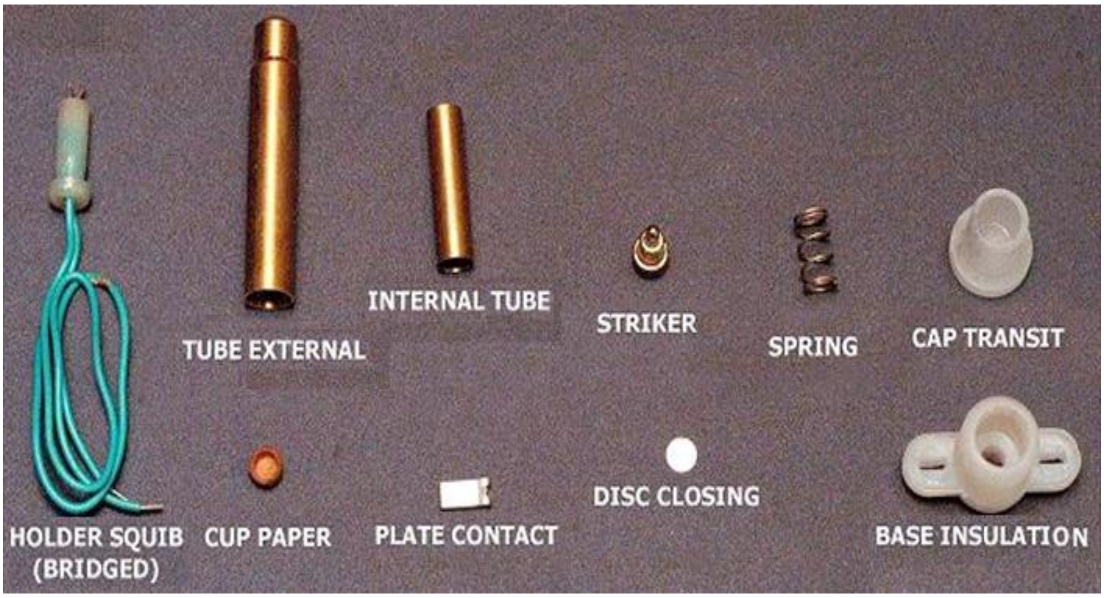

Figure 1 - The various components required for assembly of pyro-cartridge

DESCRIPTION OF PYRO-CARTRIDGE

Pyro-cartridge is used to fire signal cartridges for signalling purpose by the pilot in an emergency in case of radio communication failure. The empty assembly of pyro-cartridge consists of squib, internal tube, external tube, striker, spring, disc closing, cup paper, base insulation, cap transit and contact plates. Squib is assembled in internal tube with paper cup and internal tube is then turned over. Spring, striker and internal tube assembly are inserted into external tube and turned over to form the external tube assembly. The complete assembly is fixed to the base insulation and the lead wires of the squib are fixed to the contact plates. The internal tube and external tube are made up of brass material. Base insulation and base at the squib are made from nylon material. Disc closing is made from aluminium. Contact plates are made from copper and coated with silver plating. Spring and striker are made from steel. Cap transit is made from plastic material. Cup paper is made from ammunition paper. The squib is made from nichrome wire having diameter 0.041 mm. The resistance range of pyro-cartridge is 1.5 to 2.5 Ω. The various components required for assembly of pyro-cartridge is illustrated in Figure 1.

The main filling of the pyro-cartridge is lead styphnate (Chemical formula $C_6HN_3O_8Pb$) with mass from 12 to 15 mg. It has high shock and friction sensitivity with an autoignition temperature of 3300C. This is derived from styphnic acid. Lead styphante is used in detonators and primers. The schematic construction detail of pyro-cartridge is shown in Figure 2. With the passage of an electric current through the contact plate a lead styphnate bulb gets ignited due to Ohmic or Joule heating effect. Due to small volume of the cartridge, a shock wave is produced. The shock energy is just sufficient to puncture the closing disc and release the striker which is held under compression. The striker ejects and hits the primer of signalling cartridges. This is helpful when radio communication of the aircraft fails, as signal cartridges are fired by the pilot for signalling purposes. The signal cartridges are fitted with a percussion type primer, which is initiated by

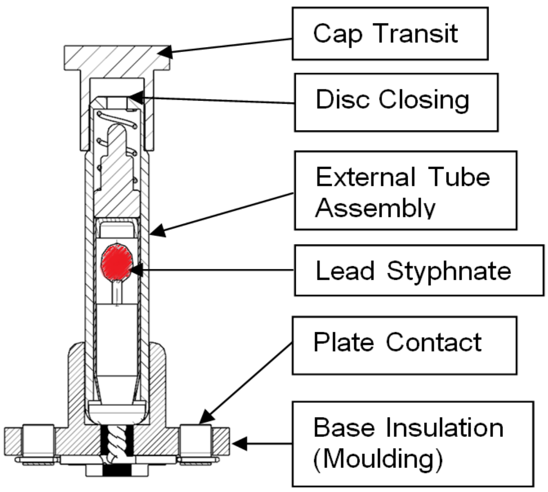

Figure 2 - The schematic construction detail of pyro-cartridge

firing the pyro-cartridge electrically using the aircraft's power supply.

GENERAL USES OF PYRO-CARTRIDGE

There is a requirement for energy to be delivered in a short period of time for operating various systems and sub-systems in an aircraft and missile. This is achieved using pyro-cartridge in gas generators. In general, the pyro-cartridge is an attractive option as it is light weight and will not add significant weight to the aircraft. Additionally, the pyro-cartridge plays a very important role in defence, space and aircraft applications. They are used in following ways[3]:

- To ignite the propulsion system for space applications
- To generate the gas to impart motion to a piston
- To apply pressurefor operating a system
- To provide thrust to release the externally carried store
- To acts as separator for externally carried store in fighter aircraft
- To stage separation in space applications

QUALIFICATION TESTING

Energy calculation of Squib

In an armament system, a pyro-cartridge essentially converts electrical energy into heat which further initiates the explosive train with its accompanying temperature rise. Pyro-cartridges are one shot devices widely used in applications gas generator, aerospace, weapons, armament, civil blasting equipment and other military systems for initiating the element in an explosive train. The first function of a pyro-cartridge is to provide adequate electrical current to cause ignition of the highly sensitive explosive i.e. lead styphnate. The electrical current accomplishes this ignition by heating the bulb of lead styphnate. Understanding of the initiation of explosives using a bridge wire in pyro-cartridges is important for engineers, designers, researchers and scientists.

a) Energy for No Fire Current (NFC)

This is the maximum current that can be applied for sufficiently long duration with the probability of 'pyro-cartridge not firing' as 99.9%. It is determined by the 'Bruceton Staircase' method[4]. This method is commonly used to determine the sensitivity testing of ordnance, and is also called 'Up and Down'. It is applied at equal spaced tests levels that are selected before the start of experiment. The test is sequential in that the test level for a given shot is calculated by the outcome of the previous shot. Fifty samples are tested for NFC. In order to achieve fruitful results, it is very important to determine the test interval "d" as accurately as possible. If given a squib function, the subsequent squib is made at the next lower test level; if a squib does not function, the next squib is made at the next highest test level. If a given shot does not fire, the next shot is made at the increased test level. If the test interval "d" is too large, too few test levels will be used, and if the interval "d" is too small, too many test levels will be used. The interval value "d" should be between 0.33 times and 2.5 times the standard deviation[5,6]. The minimum number of test levels should be eight. There is a minimum of thirty test samples required to be fired so as to obtain reliable results. The Bruceton Staircase method provides information about the mean values. This testing is concentrated on the mean, little or no data is gathered in tails of distribution. The result is a tendency to underestimate the standard deviation. The weakness Bruceton Staircase method exists even in assuming that variate being investigated has a normal distribution.

NFC is an important as lower limit of the energy that, if inadvertently induced in a firing circuit, may prevent un-commanded initiation of the pyro-cartridge. Consider, that I is the current applied flowing through the squib, V is the potential difference across the two lead wire terminals and R is the bridge wire resistance of the squib. Initially the resistance of squib is measured by safety ohm meter. Accordingly the power supply voltage 24 V is adjusted. After adjusting voltage, electrical connections are made as shown in Figure 3. The

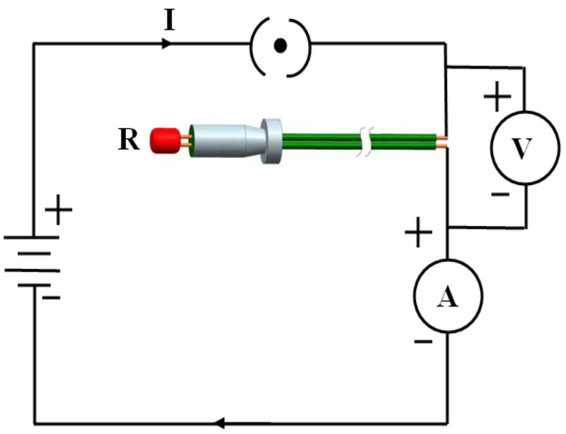

Figure 3 - Schematic electrical arrangement for squib testing

energy is received by the squib wire and converted into heat energy, and the temperature of a squib bridge increases.

The heat produced in the squib in time t will be as follows

The energy (E) required for initiation of squib

$= P \times t$ (Eqn. 1)
$= V \times I \times t$

According to Ohm's law, as

$V = I \times R$ (Eqn.2)

Substituting value of V in equation 2, the energy is expressed as

$E = I^2Rt$ (Eqn.3)

Using equation 1, Power for squib is determined as, $P = E/t$

P - Power in Watt (W)
I - Current in Ampere (A) [180 mA or 0.18 A]
R - Resistance in Ohm (2 Ω)
t- time (5 s)

Substituting the values in equation above equation 3, gives energy no fire current.

Energy in Joules (J) for no fire current = 0.18 × 0.18 × 2 × 5= 0.324 J

b) Energy for All Fire Current (AFC)

The minimum applied current in which 'probability of squib firing' is 99.9% will always ensure the firing of a pyro-cartridge. This is determined by Bruceton Staircase method as explained above. Fifty samples are tested for AFC and the AFC values evaluated experimentally for a pyro-cartridge is 600 mA. For a pyro-cartridge to function, there is certain value of firing current above which all pyro-cartridges should function without any failures. AFC is vital factor, as it contributes to delivering this energy to the system.

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 sec

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

Putting the values of I, R and t in equation above equation 3, gives all fire current.

Energy in Joules (J) for all fire current (J) = 0.6 × 0.6 × 2 × 0.01

=0.0072 J or 7.2 m J

This represents the minimum energy condition to fire the squib of a pyro-cartridge.

The firing current is one of the crucial characteristic of a pyro-cartridge, and provides information about safe handling during storage and transportation. This ensures that pyro-cartridge will function optimally, in order to achieve the designated task for the mission mode operation. The current vs. time parameters for the pyro-cartridge are plotted in Figure4. AFC region is shown in green colour, NFC is in white colour and uncertainty region with dotted for this pyro-cartridge. The uncertainty region is indicated with a dotted zone that lies between the all fire regions and the no fire region. From the graph, it is observed that as the current increases, the time required for functioning is reduced.

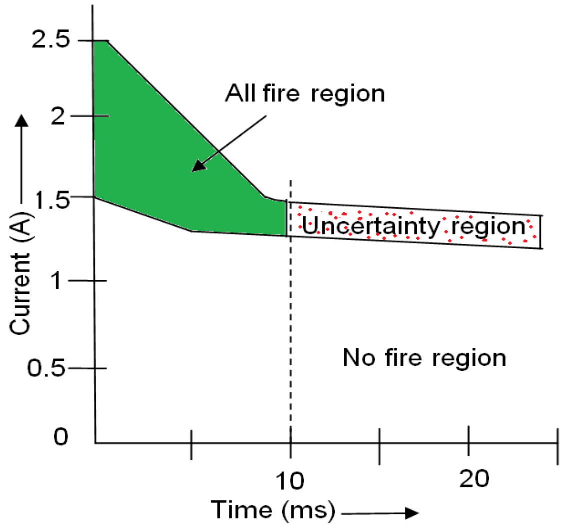

Figure 4 - AFC and NFC range of a pyro-cartridge

Furthermore, this helps the designer to select "all fire current" and "no fire current" levels when considering the requirements from the power source.

c) Hot Conditioning Test

Ten samples of pyro-cartridges are to be checked for resistance limits between 1.5 and 2.5 . These samples are then kept in an oven at 600C for 24 hours. Samples are subjected to functional test with minimum delay. This test is essential to confirm that there is no softening of the nylon material, disfiguring of the body of holder squib or melting of insulation leads. After conducting this test, it is inferred that pyro-cartridge can withstand the heat and thus has passed this test. All the pyro-cartridges performed satisfactorily in this test.

d) Charge Mass Test

Ten samples of pyro-cartridges are tested with a current of 2 A for the charge mass test. The fire fuse heads are weighted before and after firing. After the firing, the loose debris is brushed away and reweighed. The observed weight loss should be within 100 to 150 mg. This method is used to determine the correct charge mass of the pyro-cartridge during manufacturing as a part of the quality control process.

In addition to these tests, the pyro-cartridge also undergoes trials such as the drop test at height of 1.2 m, and sealing tests. All these tests help to simulate real-world behaviour in realistic environmental conditions using induced force [7]. The photo of the squib before and after firing is shown in Figs 5 (a) and (b) respectively.

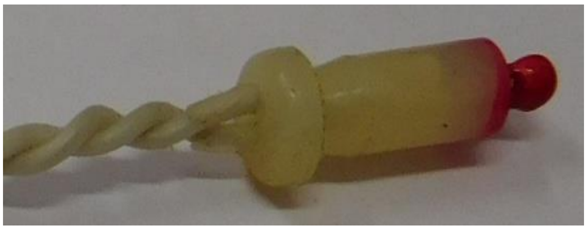

Figure 5a - Squib before firing

Figure 5b - Squib after firing

e) Drop Test

During installation, transport or repair, cartridges have a risk of being dropped. To ensure the safety of pyro-cartridges during handling and transportation, drop test are conducted in which pyro-cartridges are dropped from a para drop tower height of 1.2 m onto a steel plate. The test facility is illustrated in Figure 6. After conduct of this test, pyro-cartridges should not function. However, the same cartridges must function when fired in the dispenser system. This drop test is carried out to reveal any marked tendency for pyro-cartridges to be damaged or becoming non-functional when dropped. They are dropped in horizontal and vertical directions, with both squib up and down positions. Ten samples are subjected to the drop test. After the completion of the tests, the cartridges are disposed of appropriately. Drop testing ensures the product stays in its original condition from manufacturing to implementation. Certain advantageous of drop testing are listed below :

- Simulates how real-world drop shall affect the product
- Evaluates a product for its compliance with given standards
- Collects detailed data on the item's performance under drop test

f) Sealing Test

Sealing test is conducted to confirm the hermetical sealing of all joints at half atmosphere. The sealing apparatus is shown in Figure 7. Ten samples are subjected to the sealing test in which pyro-cartridges are immersed in a desiccator filled with clean water. Pressure is then reduced to 380 mm of Hg using a vacuum pump. Pressure is adjusted to half atmosphere using a pressure gauge as shown in the Figure 7 below. Emergence of water bubbles indicates leakage in the pyro-cartridges. No leakage was observed from the pyro-cartridges during this test. This ensures the hermetical sealing of pyro-cartridge at all possible joints.

Figure 5 - Para drop tower

Figure 7 - Sealing test apparatus

EXPERIMENTAL SETUP

The experimental setup includes dispenser unit with firing stand, pyro-cartridge, electrical cable and arrangement for supply of 24 V DC. Position the firing stand at the designated area in firing ranges and fit the dispenser unit-housing (casing) on the firing stand at an inclination of 700 to the ground as shown in Figure 8 (a). Ensure that the connector socket points downwards and the flange of housing point upwards and then tighten it with nuts at two ends. To ensure the stability of the firing stand, sand filled gunny bags or heavy stones are placed as a dead weight at the base of the firing stand. Pyro-cartridges with signalling cartridges are depicted in Figure 8 (b). Confirm the connection of 24 V DC power supply to the firing control unit (FCU). Pre-tested firing cable from the FCU is laid to firing stand and connects to both ends of the FCU. Four pyro-cartridges are loaded in all four chambers of dispenser unit and pyro-cartridge connects to the strips by rotating a knob. Load a set of four cartridges in the respective housings and close the folding hinges. Screw the dispenser unit centrally into the housing with the use of a screw driver in such a way that the top of the signal cartridges are visible from the open end as illustrated in Figure 8 (a). Connect the power supply

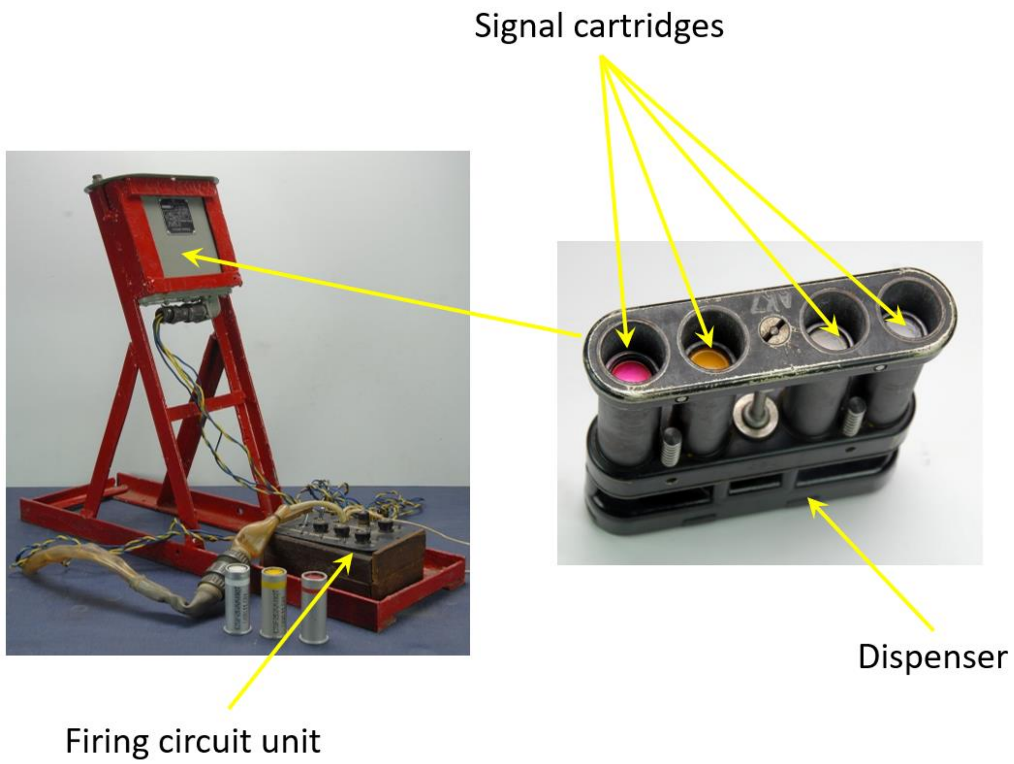

Figure 8 - An experimental set up for pyro-cartridge testing (a) Firing stand with dispenser

cable to the FCU after ensuring the toggle switch is in 'OFF' position. Now put the toggle switch in 'ON' position. The firer now presses the corresponding firing button of the FCU for firing the cartridges with a pre-coded / numbered sequence from the dispenser unit. On firing, the star will be ejected from the signal cartridge and will produce light of its respective colour (fireball) on its trajectory. One of the red illuminations is indicated in Figure 8(c).The twenty four samples of each different pyro-cartridges are subjected to hot and cold temperatures in the environmental chambers using the established test methods. The functional trials of pyro-cartridges are performed after conditioning at hot (60oC) and cold (-40oC) temperature for six hours. The images of pyro-cartridges before and after the firings are depicted in Figs. 9 (a) and (b). Figure 9 (a) shows that the striker is intact with the assembly. Figure 9 (b) clearly indicates the protrusion of the striker from the pyro-cartridge assembly. This demonstrates the design and acceptance requirements of pyro-cartridge.

Figure 6 (b) - Pyro-cartridge with signal cartridge

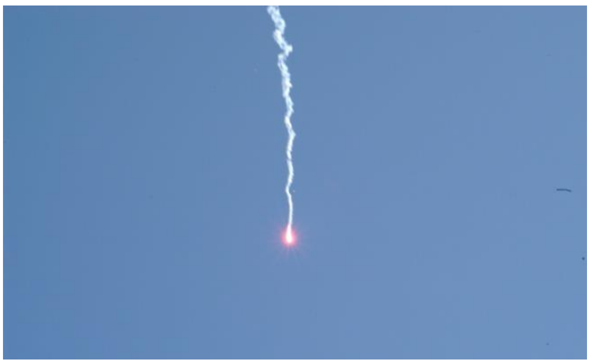

Figure 8(c) - Signal cartridge showing the colour

Figure 9 (a) - Pyro-cartridges before firing

Figure 9 (b) - Pyro-cartridges after firing

RESULTS AND DISCUSSIONS

After qualification tests, the pyro-cartridge are subjected to actual firing through a dispenser at hot (600C) and cold (-400C) conditioning. The different pyro-cartridges samples are conditioned at hot and cold temperatures for a minimum 6 hours. Twelve each of signal cartridge of the four different colours are fired using pyro-cartridge and dispenser (total 48 samples of signal cartridges). The pyro-cartridges are fired immediately with minimum time lag. Before the firing, there is no indentation on the primer of signal cartridges. After completion of firing trials, the signal cartridges show the striker mark. The photos of signal cartridges before and after firings are shown in Figures. 10 (a) and (b) respectively. All the signal cartridges show the proper illumination and clear indentation of the striker in all the cases. Thus development aspects of pyro-cartridges are proved. All the signal cartridges and pyro-cartridges are functioned satisfactorily.

Ignition delay measurements of pyro-cartridges are carried out by varying the voltage from 24 V DC. The ignition delay is measured using the flash detector. The various parameters such as power and energy are calculated. From the Table 1, it is observed that maximum power and energy occur at 24 V and minimum occur at 28 V. These trials are carried out

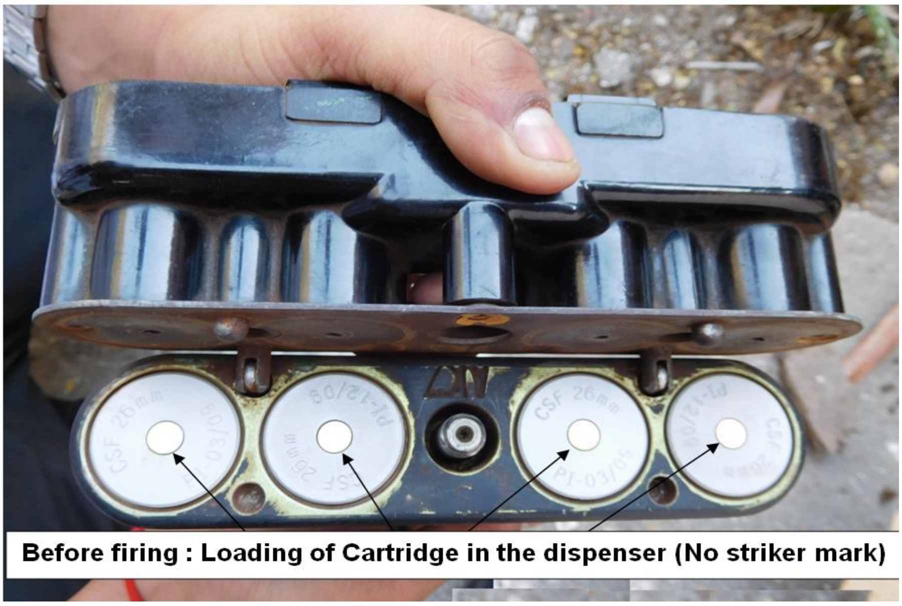

Figure 10 (a) - Signal Cartridges before firing by pyro-cartridge

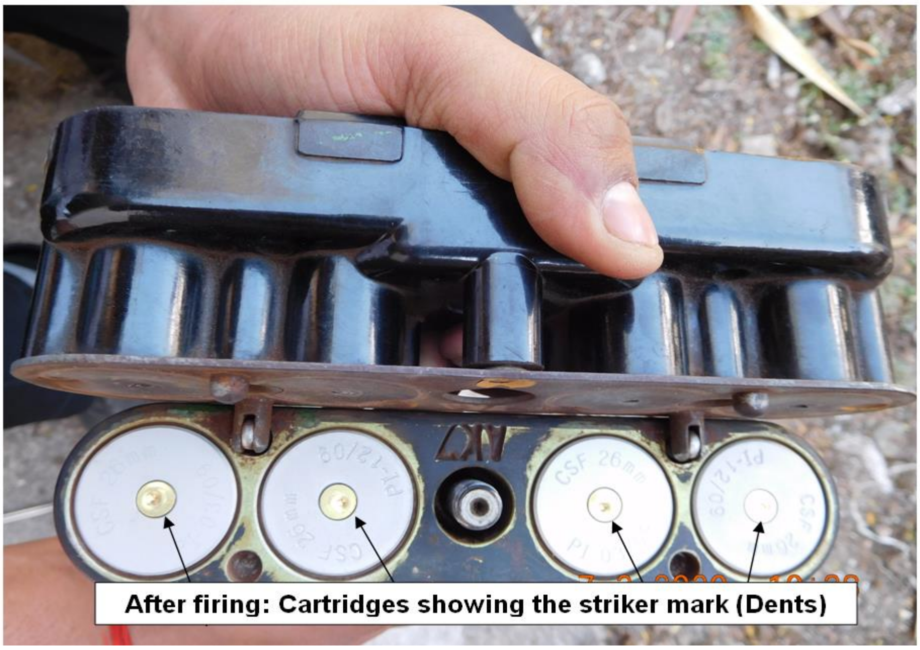

Figure 10 (b) -: Signal Cartridges after firing by pyro-cartridge

at an ambient temperature of 270C. Determination of the power and energy of a pyro-cartridge plays a very important role as electrical characterisation of an electrically initiated device[8,9].

As the power is supplied to the squib, the applied voltage V (Blue in color) and the actual supplied current I (Red in color) passing through the squib is monitored on an oscilloscope and measured. After a certain time, the rise of flash detector output signal is detected on the oscilloscope indicating the start time of squib ignition. The output signals are monitored with respect to time on the oscilloscope. In Figure 6, t1 is the time at which the current supply started, and t2 is the time at which the bridge wire of the squib breaks. The green line indicates flash detector output. The time difference between squib ignitions, i.e. the start time of the initial current and the time at which the bridge wire breaks, is measured as ignition delay. This value is considered to determine the actual energy of the squib. Two channels are used, one for current and other for

Table 1 - Measurement of ignition delay and determination of power and energy

Round	R (Ω)	I (A)	V (V)	Ignition delay (ms)	Energy (J)	Power(W) = *E/t*
1	2.07	2.48	24	0.69	8.784	12.731
2	2.11	2.05	24	0.74	6.561	8.867
3	1.92	2.18	24	0.66	6.022	9.124
4	1.92	2.18	24	0.7	6.387	9.124
5	2.12	1.72	28	0.53	3.324	6.271
6	1.62	1.53	28	0.66	2.502	3.792
7	2.11	1.7	28	0.59	3.597	6.097
8	2.12	1.85	28	0.582	4.222	7.255
9	2.1	1.52	30	0.52	2.522	4.851
10	1.73	1.57	30	0.797	3.398	4.264
11	2.2	1.75	30	0.517	3.483	6.737
12	2.17	1.63	30	0.527	3.038	5.765

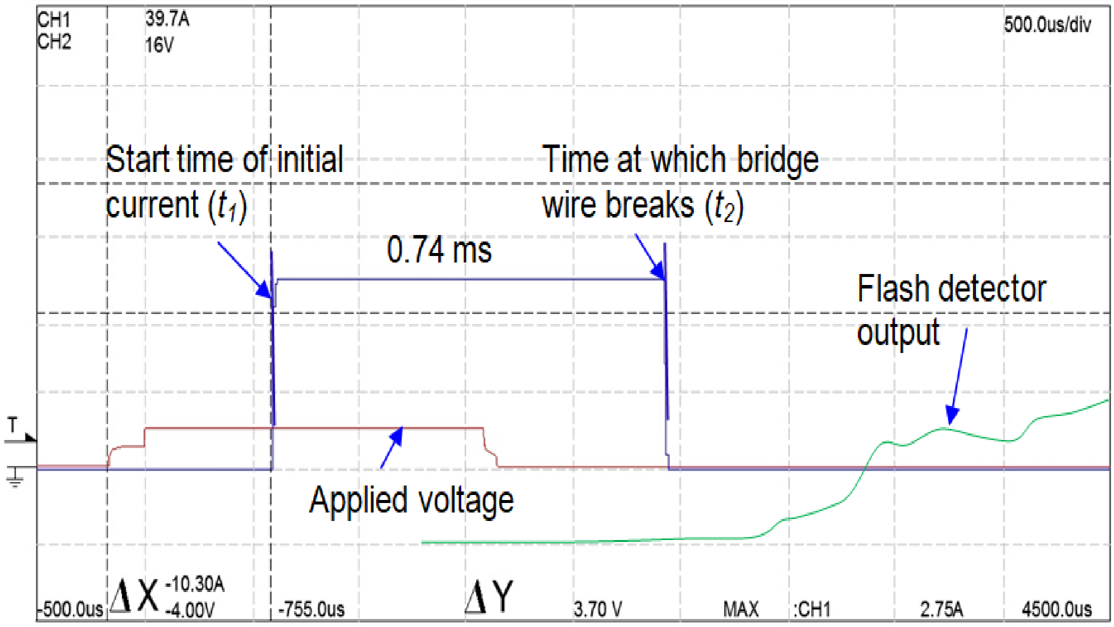

Figure 11 - Ignition delay profile for pyro-cartridge

voltage. One of the ignition delay profiles for round 2 of pyro-cartridge is depicted in Figure 11.

CONCLUSIONS

The experiment explained in this paper is used to determine the electrical energy required for this particular pyro-cartridge in order to initiate the signal cartridge. In this paper, development and qualification testing of pyro-cartridge is explained for military aircraft in an emergency. Calculations for the AFC and, NFC of pyro-cartridge using the Bruceton Staircase method and static trials in a dispenser are carried out. Pyro-cartridges are required to undergo various design qualification tests such as the drop test and the sealing test, and functioning trials on signal cartridges are concluded satisfactorily. During the development phase, all the components used in the assembly are tested and qualified before actual assembly of pyro-cartridge. The materials of construction (MOC) are qualified by conducting various relevant chemical and mechanical tests. As a part of the qualification and acceptance criterion of pyro-cartridges, the following number of samples as given in Table 2 are tested :

From the above deliberations, the following conclusions can be drawn :

- The minimum and maximum power of pyro-cartridge is 12.731 W and 3.92 W
- The minimum and maximum energy of pyro-cartridge is 2.502 J to 8.784 J
- The AFC and NFC of pyro-cartridge is 7.2 mJ and 0.324 J
- The minimum and maximum ignition delay of pyro-cartridge is 0.517 ms to 0.797 ms
- Functioning of the signal cartridge is tested and qualified by pyro-cartridge
- The pyro-cartridge withstand the drop test and sealing test
- A total of 200 samples are tested to prove the design ruggedness during development phase

The approach describe in this article helps to evaluate the minimum and maximum energy, power, and measurement of ignition delay required for ignition of a pyro-cartridge. From the above research activities, it is found that with change in ignition delay an electrical energy changes.

Table 2 - Qualification and acceptance criterion of pyro-cartridge

Number	Type of tests	Qty (Numbers)
1	NFC test of squib	50
2	AFC test of squib	50
3	Hot conditioning test of squib	10
4	Charge mass test of squib	10
5	Drop test of pyro-cartridge	10
6	Sealing test pyro-cartridge	10
7	Functional test of pyro-cartridge using dispenser	48
8	Ignition delay measurement of squib	12
Total samples tested		200

FUNDING

The author received no financial support for the research, authorship, and/or publication of this article.

ACKNOWLEDGMENT

It is with heart filled gratitude that corresponding author thank to Dr. V V Rao, Outstanding Scientist and Director ARDE for kind permission to publish this work.

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