

Failure Study of Escape Aid Explosive Cartridge During Life Assessment Trials

Bhupesh Ambadas Parate^{1,*} 

¹.Armament Research and Development Establishment  – Air Pilot Plant Department – Pune – India.

*Correspondence author: baparate@gmail.com

ABSTRACT

The objective of research paper describes the failure study of escape-aid explosive (EAX) cartridges that failed during life assessment trials (LAT). The EAX cartridges serve as a critical component that is responsible for converting energetic materials into combustible gaseous products. The cartridges under study provide a delay between the trainer and trainee during the ejection of the seat in an adverse situation. Failure investigation plays an important role in the design and development cycle of EAX cartridges. The novelty in this research is that it attempts to carry out the failure study of the EAX cartridge during LAT. Failures of such devices lead to consequences involving missile launching, seat ejection, harness, bomb release, etc. This research paper focuses on the failure study of EAX cartridges for pilot seat ejection, methodologies for identifying root causes, and solutions for preventive and corrective actions to avoid the recurrence of such failures in the future. By applying a failure study in a systematic way, it is possible to identify the underlying causes of EAX cartridge failures and improve safety measures, reducing the risk of catastrophic failures during ejections. Failure investigation, when applied to the EAX cartridge in ejection seats, helps to identify failures that compromise the pilot's safety or cause malfunctions in complex systems. From the study, it was inferred that failure of EAX cartridge during life trial might be attributed to improper functioning of cap.

Keywords: EAX cartridge; Failure study; Seat ejection; Pilot safety.

INTRODUCTION

The escape-aid explosive (EAX) cartridges in seat ejection systems play a pivotal role in the safe and rapid ejection of pilots in an emergency situation. It is a critical component in military aircraft and certain high-performance civilian aircraft, designed for pilot safety during extreme conditions. The EAX cartridges are the heart of ejection seats as well as aircraft and helicopter applications. These are devices activated by the mechanical action a pin firing mechanism to initiate the explosive train. Ejection seats are an integral part of a pilot's safety system, designed to ensure quick and safe ejection from an aircraft in emergency scenarios. The ejection seats with the pilot utilize the EAX cartridge to propel the seat and pave an escape path to save the pilot's life. The EAX cartridges in these aircraft seats must function with high reliability under various environmental conditions, including extreme altitudes, temperatures, and pressures, etc.

Failures in EAX cartridges can result in delayed or ineffective ejections, which may lead to severe injuries or fatalities for the pilot. In this paper, one cartridge at cold (-26°C) condition could not fire in phase II: one cartridge in hot (45°C) condition and two cartridges at cold (-26°C) condition in which the time to maximum pressure (TP_{max}) in phase III was higher than the upper limit. The stipulated storage conditions of EAX require a temperature of $25^{\circ}\text{C} \pm 3^{\circ}\text{C}$ and relative humidity of $55 \pm 5\%$. All the cartridges were subjected to closed vessel (CV) firings. They convert the chemical energy of energetic materials into mechanical energy through a series of thermodynamic processes, including compression, combustion, and expansion. However, failures in EAX cartridges can

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result in significant operational disruptions and downtime. Therefore, ensuring the reliability and performance of EAX cartridges is crucial for maintaining aircraft safety and operational efficiency. Failures in these systems can severely impact aircraft performance and safety, leading to mission delays, unplanned maintenance, and potential crashes. Failure study is a structured method used to investigate and identify the probable causes of failures or malfunctions. It is a method to discover the root causes of problems or faults to find out the correct solutions. This process assumes that it is a much more successful method to avoid and respond to essential issues rather than just treating ad-hoc symptoms. This approach aims to prevent the recurrence of issues by addressing the root causes rather than just the symptoms. The aviation industry, with its stringent safety regulations, has adopted failure investigation as a critical tool in troubleshooting, maintenance, and continuous improvement of EAX cartridges. Failure investigation of EAX cartridges in aircraft applications is an essential process to ensure the safety, reliability, and operational readiness of the aircraft fleet. Failure in EAX cartridges can result from manufacturing defects, improper handling, environmental stresses, or aging. Failures in EAX cartridges can lead to catastrophic consequences, making the identification of root causes vital. This research paper presents a systematic approach to conduct failure investigation on EAX cartridges, identifies common failure modes, discusses methodologies employed in failure analysis, and proposes recommendations to mitigate recurring issues. The objective of this paper is to identify the probable causes of non-initiation of the cap, which is the first fire element of the explosive train, during life assessment trials (LAT). The failure is attributed to aging under accelerated LAT conditions. This study investigates the failure mechanisms of EAX cartridges during LAT, identifying key factors affecting their performance and proposing methodologies to enhance their dependability.

LITERATURE REVIEW

Various kinds of literature have been reported for failure study/defect investigation pertaining to ammunition used in defense applications. Sharma *et al.* (2019) reported the failure investigation of the cartridge case. They investigated the microstructure of cartridge cases at different locations and correlated it with hardness. Further, the study revealed that the cartridge case had failed due to stress corrosion cracking. Cai *et al.* (2020) carried out theoretical and numerical investigations on the headspace of cartridge cases considering axial deformation and movement. Anggamawarti *et al.* (2020) studied the quality analysis of 5.56 mm ammunition defects using the Taguchi method. Gamage *et al.* (2017) explained the acceptance of Taguchi's quality philosophy and practice by lean practitioners in apparel manufacturing. Aiasi and Kazemi (2018) highlighted important concepts for solving problems related to the quality in a research information system by considering a case study. Chan *et al.* (2011) investigated the root cause of rubber seal failure used in primary packaging by ozone chamber testing and suggested the solutions for the problem. Bogusz and Wolszakiewicz (2020) reported the cause of malfunctioning of an EAX cartridge that filled with double base propellant. Parate and Sonawane (2023) has carried out defect analysis of a cartridge re-cocking defect. The author further studied the root cause analysis of gas generator for seat application (2025)

The EAX cartridges are employed in emergency ejection and escape systems, particularly in military and aerospace applications. These cartridges function by generating a controlled explosive force to activate escape mechanisms. Over time, environmental exposure, aging, and operational stresses may degrade their performance. Understanding the failure modes through LAT is essential for ensuring their reliability and safety.

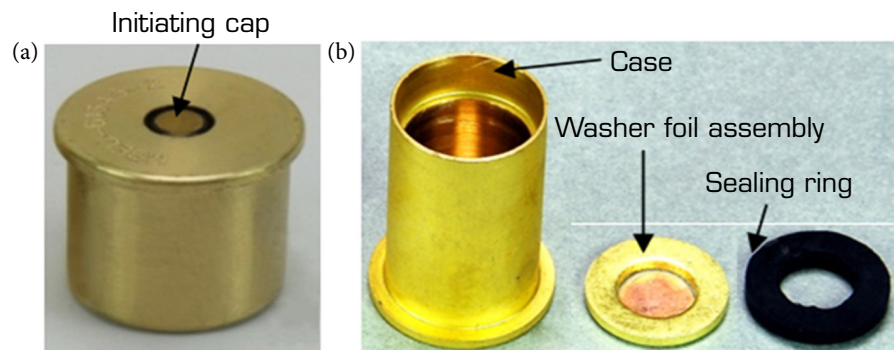
Overview of EAX cartridge

The EAX cartridges are critical components in various aerospace, defense, and industrial applications where precise and reliable actuation is essential. They operate based on the principle of converting chemical energy into thermal energy by burning energetic material. The design and materials used significantly influence their performance and reliability. Despite their reliability, EAX cartridges can fail under certain conditions, leading to potentially catastrophic outcomes. They are used for seat ejection applications in an emergency. The EAX cartridge is filled with a cap, double base propellant, and pyrotechnic composition. The EAX cartridge in this study is one cartridge of the CSE set used in the Hawk aircraft. The cartridge case is designed to accommodate the propellant and booster. The cartridge is filled with double base propellant and pyro composition, i.e., ME424. The cartridge consists of a case, washer foil assembly, and sealing washer. The cartridge case is made up of brass. The composition of brass is copper/zinc with a ratio of 57/38 and other ingredients with alloy elements such as Pb, Fe, Sb, Ni, Al, Sn, and As.

The cartridge has a cap chamber at one end where a percussion cap is fitted. Two flash holes are provided in the cap chamber. At the other end, the washer foil assembly is placed over the step provided in the case. When the cartridge is suitably initiated using a mechanical striker, it initiates the explosive train and burns the propellant.

Figure 1 shows the EAX cartridge used in seat ejection applications. Figure 1a and b depict the photo and components of the EAX cartridge, respectively. The EAX cartridge consists of the following components:

- Case: a body that holds the booster, propellant, and means of initiation.
- Washer foil assembly: soldered with copper foil to release the products of combustion after rupturing of the foil following the burning of the propellant.
- Sealing ring: made up of neoprene rubber for sealing and to avoid ingress of moisture.
- Cap: aids in initiating the explosive train. It is made up of brass material, the same as the cartridge case material.



Source: Technical specification.

Figure 1. The EAX cartridge used in seat ejection application. (a) photo of EAX cartridge; (b) components of EAX cartridge.

Function of EAX cartridge and its components

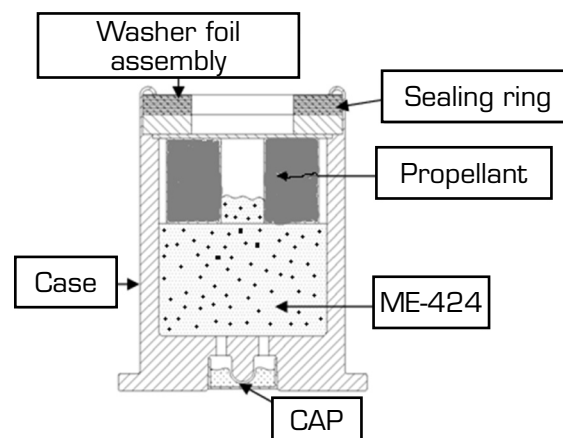
Presently the cartridge has been assigned a limited life of 2 years, which includes 1 year of installed life.

Function of the cartridge

Introduces a nominal delay of 0.35 seconds into the command firing system.

Ensures the rear seat is ejected before the front seat operates when the command system is selected "ON."

The engineering sketch of the EAX cartridge with internal components is depicted in Fig. 2. The aircraft part where the EAX

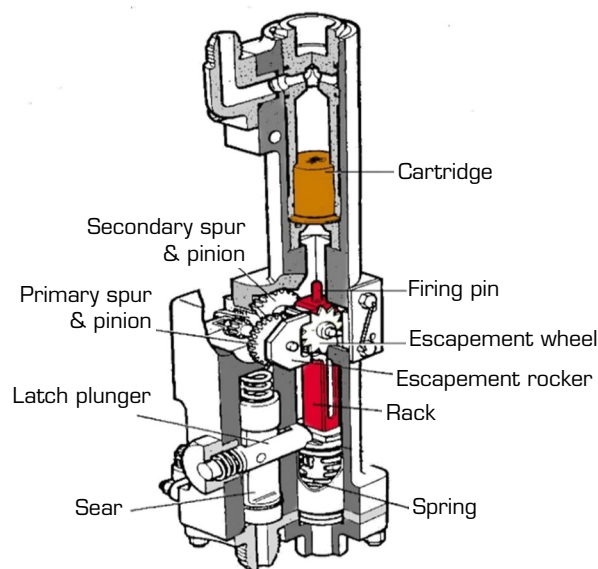


Source: Technical specification.

Figure 2. Engineering sketch of EAX cartridge.

cartridge is assembled into the actual aircraft seat is shown in Fig. 3. An ejection seat is designed to provide a pilot with a rapid means of escape from an aircraft in distress, such as during an emergency landing, engine failure, or damage to the aircraft. The seat ejection system comprises several key components, including:

- Ejection seat: the seat itself, designed to support the pilot and provide safety during the ejection process.
- EAX cartridge: it generates combustible gases to force the ejection seat from the aircraft.
- Cushion and restraint systems: to ensure the pilot remains securely seated during the ejection, cushioning and harness restraints are used.
- Survival equipment: parachutes and other survival tools that are deployed once the seat has been ejected from the aircraft.
- Rocket packs: they are fitted below the seat to provide additional thrust so as to clear the tail fin of the parent aircraft.



Source: Elaborated by the author.

Figure 3. The EAX cartridge assembly.

Importance of EAX cartridges

The EAX cartridges for ejection seats function by providing the gaseous combustible products to propel the seat out of the aircraft. The rapid and reliable activation of the EAX cartridge is essential for the following reasons:

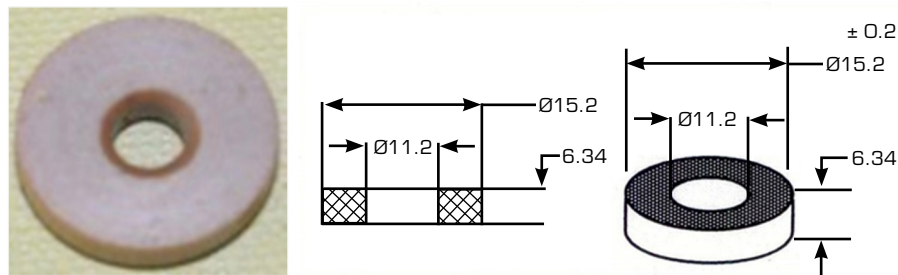
- Time sensitivity: in an emergency, the ejection must occur within milliseconds to avoid injury from the aircraft's EAX cartridge or altitude.
- Extreme conditions: the EAX cartridge must operate effectively across a wide range of temperatures, altitudes, and operational conditions.
- Pilot safety: a failure in the EAX cartridge can lead to a failed ejection, putting the pilot at risk of serious injury or death.

Due to the critical nature of their role, understanding the failure modes of the EAX cartridge in ejection systems is vital to enhance the reliability and safety of the entire seat ejection.

METHODOLOGY

The EAX cartridge in this study is made up of brass material and is coated with lacquer to prevent corrosion. Brass cartridge cases are manufactured either from bar stock by machining or by deep drawing of a round disc (called a "blank"). In this paper, the EAX cartridge case is manufactured using a machining process. The cartridge case has an integral anvil

at the center. Two flash holes are provided for the release of the flash. At the bottom of the case, the cap is located. The photos of the propellant with the engineering sketch of the propellant and pyrotechnic composition are shown in Figs. 4 and 5, respectively.



Source: Elaborated by the author.

Figure 4. Propellant photo and its engineering sketch.



Source: Elaborated by the author.

Figure 5. Photo of pyrotechnic composition.

The propellant should be selected with known characteristics. The propellant so selected should be compatible with the case material and non-hygroscopic in nature. Based on the above requirements, a double base propellant with a single perforation type is selected, which consists of nitrocellulose (NC), nitroglycerine (NG), and other additives. Pyrotechnic composition is selected as a booster in the explosive train. The chemical composition of the double base propellant, which was used for CV firings, is given in Table 1. The chemical composition of the pyrotechnic composition is given in Table 2.

Table 1. Chemical composition of double-base propellant.

Ingredients	Requirements	Unit
NC (2R)	57.0 ± 1.0	%
NG	32.0 ± 0.5	%
Carbamite	3.4 ± 0.3	%
Diethylphthalate (DEP)	3.04 ± 0.5	%
Monobasic lead salicylate (MBLS)	1.0 ± 0.1	Parts
Monobasic cupric salicylate (MBCS)	1.0 ± 0.1	Parts
Potassium nitrate (KNO_3)	1.0 ± 0.1	Parts
Carbon black (Printex-300)	1.4 ± 0.1	Parts
Candelilla wax	0.08	Parts
Zinc Stearate	0.08	Parts

Source: Taken from propellant specification.

Table 2. Chemical composition of pyrotechnic composition.

Ingredients	Requirements	Unit
Magnesium powder	38.0 ± 2.5	%
Potassium nitrate	51.0 ± 3	%
Hylak resin or phenol formaldehyde resin G PR 104	11 ± 1.5	%

Source: Taken from pyrotechnic specification.

Ignition system failure

The ignition system is responsible for igniting the pyrotechnic in the EAX cartridge. Failures in the ignition system can result from issues such as:

- Insufficient flash generation: failures happen if the flash is too weak to ignite the explosive train of the cap composition or booster composition.
- Faulty igniters: over time, igniters can wear out, fail to produce the necessary flash, or fail to ignite the pyrotechnic composition of the explosive train.
- Blunt firing pin: the blunt firing pin or spring force is not sufficient for proper indentation on the percussion cap.

Mechanical failures

Mechanical failure can occur due to the extreme forces and pressures exerted on EAX cartridges during filling and assembly, handling, activation, use of sub-standard tools, etc. Mechanical failures are typically caused by wear, fatigue, or improper material selection. Common mechanical failures include:

- Valve malfunctions: valves used to control the flow of combustion products can become stuck or fail, resulting in insufficient or delayed ejection.
- Leakages: cracks or failures in seals or the EAX cartridge body, hoses, or pressure chambers can lead to gas leakage, rendering the system ineffective.
- Corrosion: exposure to moisture, salt, and other environmental factors can lead to corrosion of metal components within the EAX cartridge, impacting its functionality.
- Vibration and shock: can lead to dislodged components or fractured encapsulation.
- Aging: over time, material fatigue can reduce mechanical integrity.

Thermal failures

Thermal failures arise when EAX cartridges are exposed to temperatures beyond their design tolerances. These can include:

- Overheating: prolonged exposure to high temperatures can degrade pyrotechnic material.
- Thermal cycling: repeated temperature fluctuations may cause mechanical stresses and cracks.

Environmental factors

- Moisture ingress: can degrade pyrotechnic materials or cause corrosion.
- Ingress of moisture for cap: it causes failure to initiate the composition.

Maintenance-related failures

Improper or insufficient maintenance of EAX cartridges can lead to component degradation or failure. These issues include:

- Storage: not maintaining the storage conditions as per laid down procedure.
- Packaging boxes: not using hermetically sealed packaging boxes.
- Improper assembly: faulty assembly practices can lead to misalignments, causing operational failures.

System integration and compatibility issues

In some cases, failure of EAX cartridges may not be the result of an isolated malfunction, but rather an issue with its integration into the larger ejection seat system. Compatibility issues with other components such as the seat harness, sensors, or emergency release mechanisms can cause EAX cartridges to perform incorrectly. Examples include:

- Improper system calibration: faulty calibration of sensors that monitor EAX cartridge pressure, temperature, or force can lead to delayed or inaccurate activation.
- Poor installation: if EAX cartridge is not correctly installed within the seat ejection system, it may not function as intended, even if the cartridge itself is in working order.

Tests conducted on EAX cartridges

A set of EAX cartridges was subjected to standardized life assessment tests. The methodology included:

Environmental conditioning (Intensified Standard Alternative Trials [ISAT] and Air Exposure [8U]): exposure to high humidity, extreme temperatures, and cyclic thermal stress.

- Vibration testing (17U): to assess the effect of induced forces during handling and transportation
- Functional testing: static firing tests in CV to evaluate performance parameters.
- Non-destructive inspection: X-ray imaging to detect internal defects of the cap.

The discussion on the closed vessel test of EAX cartridges is explained in the experimental set-up.

Acceptance test procedure (ATP)

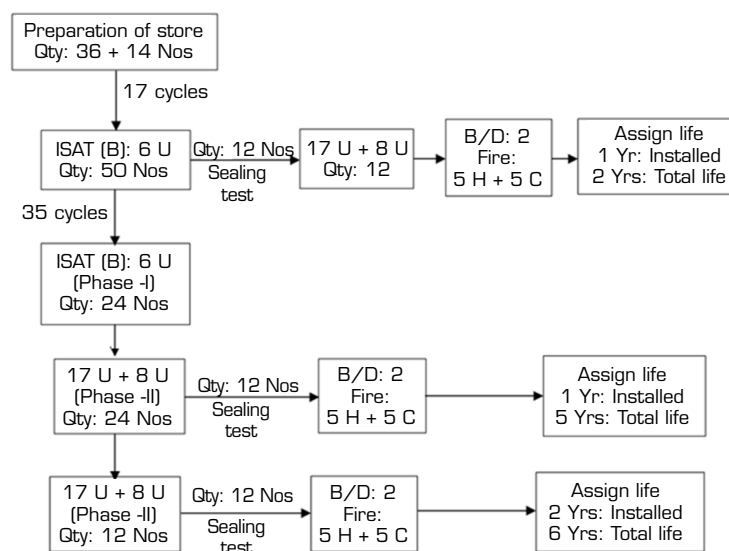
The ATP for an EAX cartridge case (or any specialized cartridge case used in aerospace, defense, or industrial applications) outlines the structured process to verify that each unit meets design and performance specifications before acceptance into service. Typically, for the acceptance of the case includes dimensional inspection with geometric features, visual inspection, and verification of surface coating thickness. ATP of cartridge case requires all tests to pass without deviation.

RESULTS AND DISCUSSIONS

To find the probable causes of failures, a systematic investigation was carried out that included firing trials of EAX cartridges and X-ray analysis of percussion caps. The following experiments were performed.

Experimental set-up for CV firing

EAX cartridges were subjected to CV testing in hot and cold temperatures for 6 hours as per the schedule given in Fig. 6. Before firing trials, the body of the CV was visually inspected for structural integrity, seals, and proper installation of pressure sensor (gauge)



Source: Technical specification.

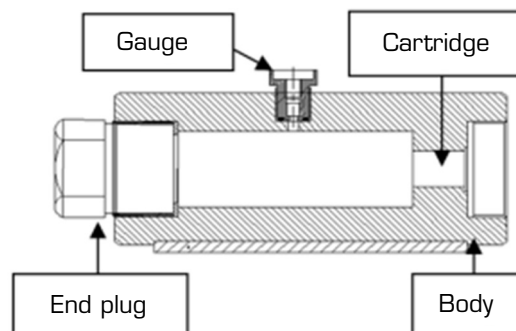
Figure 6. Flow chart for LAT.

and other instrumentation. Provision of an end plug is made for releasing gases after firing. EAX cartridges were checked for any visible damage or defects. The EAX cartridge was installed securely in the designated position inside the vessel using the firing mechanism with safety pin and lanyard. Proper alignment to minimize debris impact on the sensor was ensured. The CV was locked securely. All seals were intact and capable of withstanding expected pressures, which was verified. Pressure sensor and other monitoring devices as required were connected. The data acquisition system (DAS) for real-time monitoring was configured (Parate *et al.* 2021). Blast shields, fire suppression systems, and emergency shutoff mechanisms were ensured. A communication system was functional. A final review of all connections, instrumentation, and safety systems was performed. It was confirmed that all personnel took shelter in a safe area. The firing system was arranged, and readiness was confirmed through the control panel or operator interface. The lanyard that fires the EAX cartridge was pulled. Maximum pressure and the corresponding time to reach maximum pressure were recorded. The event was allowed to complete, and the vessel was allowed to stabilize. It was ensured that the vessel's pressure and temperature returned to safe levels before the next firing. Observations, data, and any anomalies encountered during the firing were recorded. Any residues or debris were removed from the vessel interior. The EAX cartridge was removed from the vessel and observed for any cracks. The engineering sketch of the CV and $P-t$ curve of the first reading in hot condition of Table 3 are shown in Figs. 7 and 8, respectively. The continuous pressure is obtained from DAS in which pressure is converted into voltage through charge amplifier to obtain $P-t$ curve using DAS.

Table 3. LAT phase II results.

Sl. no.	Hot (+ 45 °C)		Cold (-26 °C)	
	Pmax 55 to 90 kg/cm ²	TPmax 50 to 80 ms	Pmax 55 to 90 kg/cm ²	TPmax 50 to 80 ms
1	65.11	62.18	78.75	60.46
2	66.10	66.33	67.68	65.90
3	71.66	55.25	68.4	54.50
4	69.21	62.91	63.41	74.38
5	88.94	54.50	Not fired	Not fired

Source: Firing trial data results.

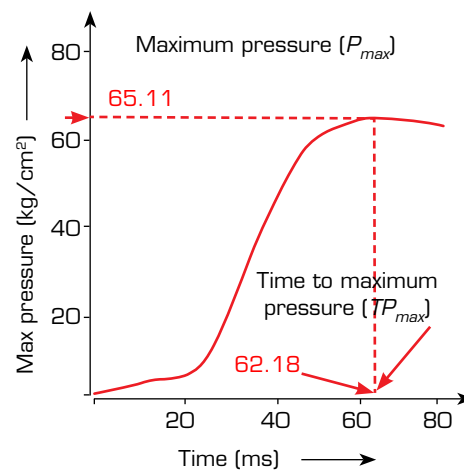


Source: Elaborated by author.

Figure 7. Engineering sketch of CV.

Life assessment trials

Fifth numbers were subjected to LAT as per the flow chart for the trial schedule given in Fig. 8. The EAX cartridges realized the performance parameters as per specified proof parameters and assigned total life of 2 years that includes 1 year installed life. During phase II trials, out of 10 cartridges, one cartridge in cold condition did not fire after completion of 35 cycles of ISAT (B), followed by one cycle 8U air exposure and vibration. The results are shown in Table 3. All the performance parameters were observed within specified proof limits. The propellant and pyrotechnic composition were observed intact. Proper indentation was noticed on the misfired cartridge. Hence, the cause of not firing of the cap was undertaken.



Source: Elaborated by author.

Figure 8. Pressure-time (P-t) curve.

LAT phase III trials (35 cycles of ISAT [B], followed by two cycles 8U air exposure and vibration); cartridges even after more degradation in comparison with phase II have all fired (5 nos. at +45 °C and 5 nos. at -26 °C). It indicates that the aging of the propellant may not be the cause of misfire. The results are shown in Table 4. The firing trials of EAX cartridges were conducted after completion of all trials in CV as per the experimental set-up.

Table 4. LAT phase III results.

Sl. no.	Hot (+45 °C)		Cold (-26 °C)	
	Pmax 55 to 90 kg/cm ²	TPmax 50 to 80 ms	Pmax 55 to 90 kg/cm ²	TPmax 50 to 80 ms
1	51.68	137.00	70.18	64.28
2	83.35	57.58	70.18	64.28
3	73.27	64.59	56.07	92.44
4	70.18	62.73	54.89	86.41
5	76.69	60.94	72.43	62.36

Source: Firing data trial results.

Observations after firing in phase II

Five out of five cartridges fired satisfactorily in hot conditions.

Four out of five cartridges fired satisfactorily in cold conditions.

Maximum pressure (P_{max}) and TP_{max} within limits.

Pyrotechnic composition was observed intact (booster destroyed subsequently).

Propellant of misfired cartridge was observed intact (removed from cartridge).

Indentation on all caps found satisfactory.

In hot condition, one case out of five cartridges had P_{max} lower than the lower limit. In case of firing at hot condition, TP_{max} in one case and in cold condition for two cases was higher than the upper limit.

Observations after firing in phase III

All 10 cartridges functioned.

P_{max} for one cartridge in hot condition is lower than the lower limit.

TP_{max} for one cartridge in hot condition is more than the upper limit.

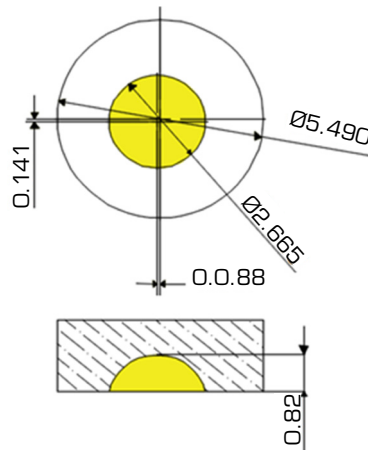


TP_{max} for two cartridges in cold condition is more than the upper limit.

Indentation on all caps found satisfactory

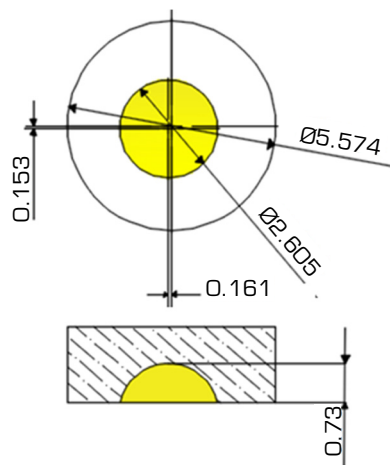
Indentation measurement

The indentation on caps was measured for fired and misfired cartridges. The same is illustrated in Figs. 9 and 10, respectively. The results are given in Table 5.



Source: Elaborated by author.

Figure 9. Fired cartridge.



Source: Elaborated by author.

Figure 10. Misfired cartridge.

Table 5. Indentation measurement on fired and misfired cartridges.

Parameter	Fired cartridge	Misfired cartridge
Indentation diameter	2.605	2.665
Indentation depth	0.73	0.82
Indentation offset (X)	0.161	0.088
Indentation offset (Y)	0.153	0.141
Cap diameter	5.574	5.490

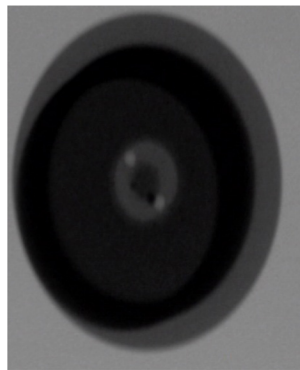
Source: Firing trial data results.

From the Table 5, it is clearly observed that there are no significant deviations in parameters for fired and misfired cartridges. Dimensional analysis reveals that the indentation of the firing pin on the misfired cartridge is at par or even better as compared to the fired cartridge. Hence, failure of the cartridge due to improper firing pin indentation is ruled out.

X-ray study of cap

X-rays of fired and misfired cartridges were carried out for comparative analysis in order to assess the cause of misfire. The X-ray images of fired and misfired cartridges are depicted in Figs. 11 and 12, respectively. X-rays were carried out fired, misfired and fresh cartridges. X-rays revealed that there is no density difference in the case of fired and misfired cartridges. The density of both these cartridges is less compared to the density of fresh cartridge cases with filled caps. From this study, it is revealed that filled cartridge density is more than that of the misfired cartridge. This may be due to less quantity or absence of explosive composition in the cap of the misfired cartridge. It was also noted that all cartridges fired during phase III trials, where the cartridges underwent more severe conditions compared to phase II trials.

Breakdown of the cap of both fired and misfired cartridges was carried out to ascertain the exact cause of failure. Caps of both fired and misfired cartridges were examined. It was concluded that the black debris as compared in the failed cartridge is less compared to the fired cartridge. This could be due to less quantity of explosive in the cap or improper initiation of explosive in the cap. This could have resulted in non-initiation of the further explosive chain.



Source: Digital X-ray report.

Figure 11. Fired cartridge.



Source: Digital X-ray report.

Figure 12. Misfired cartridge.

CONCLUSIONS

The study underscores the necessity of rigorous LAT for EAX cartridges to ensure their reliability in critical applications. By identifying predominant failure mechanisms and implementing robust maintenance strategies, the operational safety of these devices

can be significantly enhanced. Failure of EAX cartridge during life trials may be attributed to the following factors: all cartridges, even after more degradation in comparison with phase II, fired in phase III trials. This indicates that the ageing of cartridge is not the cause of misfire. Hence, the cause of misfire of one cartridge during phase II trials may be due to improper functioning of cap.

Recommendations

The committee suggested the following recommendations to avoid reoccurrence of these failures in future for future production lots:

- Failure of cartridge is due to faulty cap.
- Failure is not due to aging of explosive elements during accelerated LAT.

Scope for future study

The scope for future work includes carrying out charting methods related to ammunition failure. In a failure study (or reliability study), charting methods help visualize and analyze failure data to understand patterns, predict reliability, and identify potential issues.

CONFLICT OF INTEREST

Nothing to declare.

DATA AVAILABILITY STATEMENT

All data sets were generated or analyzed in the current study.

FUNDING

Not applicable.

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