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Ballistics of Main Seat Ejection Cartridges for Aircraft Application

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Abstract**—**This article outlines the ballistics of main seat ejection cartridges for aircraft application. The ballistics of main seat ejection cartridges plays a vital role during the ejection of the pilot in an emergency. The ballistic parameters such as maximum pressure, time to reach the maximum pressure, and time required to reach half the maximum pressure that responsible to the spinal injury of the pilot are assessed. Therefore, the evaluations of these parameters are very critical during various stages of development. Elaborate testing is carried out for main seat ejection cartridges on seat ejection tower (SET) at different operating temperatures considering physiological limits. As these trials are cumbersome in nature, a vented vessel (VV) testing facility is devised to lay down the performance parameters at hot and cold temperature conditions. Single base (SB) propellant having hepta-tubular configuration is selected as the main filling. Gun powder plays the role of a booster based on ballistic requirements. The evaluation methodology of various performance parameters of main seat ejection cartridges is explained in this paper. Physiological parameters such as maximum seat ejection velocity, acceleration, and rate of rising of acceleration are also experimentally determined on SET. All the parameters are observed well within physiological limits. This paper addresses the internal ballistic of main seat ejection cartridges, propellant selection, its calculation, and evaluation of various performance parameters for aircraft application.

Keywords**—**Ballistics of seat ejection, ejection seat, gas generator, gun propulsion, main seat ejection cartridges, maximum pressure, performance parameters, propellant, progressive burning and vented vessel.

I. Introduction

MAIN seat ejection cartridges are the essential part of all modern fighter aircraft in the inventory of user. They are widely used for the safe escape of the pilot from the endangered aircraft in a minimum possible time period [1]. Today's fighter aircraft are flying with the supersonic speed in the order of 2 to 3 Mach number or more speed [2]. With this high speed, the bailing out of the pilot from the aircraft under adverse situation is extremely critical. In order to rescue the pilot, a highly reliable and telescopic seat ejection seat provides a means and is essential for all recent fighter aircraft. The modern ejection seat has the ability to achieve sufficient height so as to clear the tail fin during the entire flight envelope for the full deployment of the main parachute before grounding. To prevent the damage to the spinal cord of the pilot, a controlled transfer of energy is highly needed. This will be possible by a proper selection of the propellant that transfers energy in the installment and controlled way considering the physiological limitations of pilot withstanding the maximum acceleration and the rate of rise of acceleration. The main seat ejection cartridges are responsible for imparting the maximum ejection velocity to bail out the pilot without any critical injury [3], [4]. The main objective of this paper is to determine the ballistic of main seat ejection cartridges in the VV, maximum acceleration and rate of rise of acceleration on the SET.

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II. Main Seat Ejection Cartridge Description

Engineering sketches of primary and secondary cartridges are shown in Fig 1. They form the part of the cartridge seat ejection (CSE) system along with the other cartridges. These cartridges are installed on the telescopic tube, which are located behind the seat. The primary cartridge is made up of a brass body and initiated using the firing pin of the firing mechanism. The primary cartridge consists of a case, washer foil assembly and sealing ring. The base of the case has a centrally located cap chamber at one end where the percussion cap is fitted. The cap is filled with highly sensitive material that produces the flash which ignites the adjacent booster. Two flash holes are provided in the cap chamber. The other end of the case has a step to accommodate the sealing ring and washer foil assembly. The hole in the washer is closed using copper foil. The main filling is SB propellant (33.5 ± 0.2 g) mixed with gun powder (1.3 ± 0.01 g) inside the cartridge case and gun powder (2 ± 0.01 g) in the vicinity of the cap acts as a booster.

The secondary cartridge consists of a cover and copper disc assembly, support and sealing ring. The cover and support are made up of brass. The disc is made up of copper. The sealing ring is made up of neoprene rubber. The other end of the cartridge has a step to accommodate the sealing ring. The hole in the cover is soldered with a copper foil. The main filling in this cartridge is SB propellant (39.6 ± 0.2 g) and gun powder inside the support (0.65 + 0.01 g) that acts as a booster.

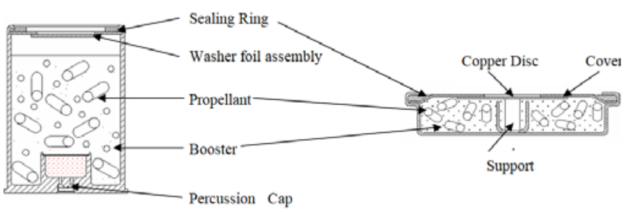

Fig. 1 Primary cartridge and Secondary cartridge

A. Use and Function of the Cartridges

The primary and secondary cartridges are main seat ejection cartridges. They are installed on the main gun in the aircraft cockpit. The main gun is propelled by energy derived after the burning of the propellant content inside them. During an emergency, these cartridges are used to operate the main ejection system when the pilot pulls the firing handle situated between his thighs. The whole system is fully automatic once initiated by the pilot. As the sear is withdrawn from the firing mechanism, the pin strikes the percussion cap, thereby generating the flash and primary cartridge initiates. The resultant flash passes through the flash holes and ignites a booster composition. This subsequently ignites the propellant. The pressure developed inside the cartridge causes the rupture of a copper foil and releases the gas pressure. The telescopic tube gets expanded. The ports of the intermediate tube are uncovered due to the expansion of the telescopic tube. This is the only means to rescue the pilot in an emergency from an endangered aircraft within the shortest possible time. The assembly of the main seat ejection cartridges (primary and secondary) on actual seat ejection gun is depicted in Fig. 2. The principle of the telescopic gun is used for the ejection of the pilot. The system comprises of the innermost tube, an intermediate tube and an external tube. This concept helps to avoid the requirement of a single tube considering the space constraint in the cockpit. The outermost tube is fitted to the aircraft structure. The various stages of the expansion of the telescopic tube with the total mass (pilot and seat) till the expansion of full system are illustrated in Fig. 3. The actual position of the telescopic tube in the steady-state in aircraft system is depicted at stage 1. The primary cartridge with a firing mechanism is fitted inside the innermost tube. The first primary cartridge is fired by the percussion firing mechanism. The expansion of the intermediate tube takes place due to high gas generation pressure and temperature by the propellant ignition inside the primary cartridge as indicated at stage 2. The mass is lifted upward and secondary cartridges are fired as these cartridges are exposed to high pressure and temperature because of port opening. This is shown at stage 3. At the end of the stroke, the pilot with an inner most tube is ejected out. This is shown at stage 4 [5]. During the seat ejection, the pilot will experience the force. Those forces are well within the physiological limitations. The idea behind the limitations is that the human body comprises of a heterogeneous man with solid, liquid and visco elastic components. Each system has the different response to accelerative force and different systems will fail under the different loading conditions.

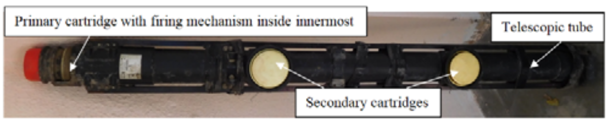

Fig. 2 Assembly of the primary and secondary cartridges inside the main gun

Hooper and Ellis have addressed the pilot protection and aviation safety to enhance the crashworthy performance of seats and restraint systems in the seat ejection during its testing. The authors discussed the design requirements of an aircraft seat [6].

III. Test Apparatus and Materials

The following materials and methods are used for the evaluation of performance parameters

(a) Main seat ejection cartridges (i.e., one primary and two secondary cartridges)
(b) VV
(c) Firing mechanism
(d) Gauge adaptor
(e) Data acquisition system (DAS)
(f) Conditioning chamber for subjecting the cartridges at hot and cold temperature

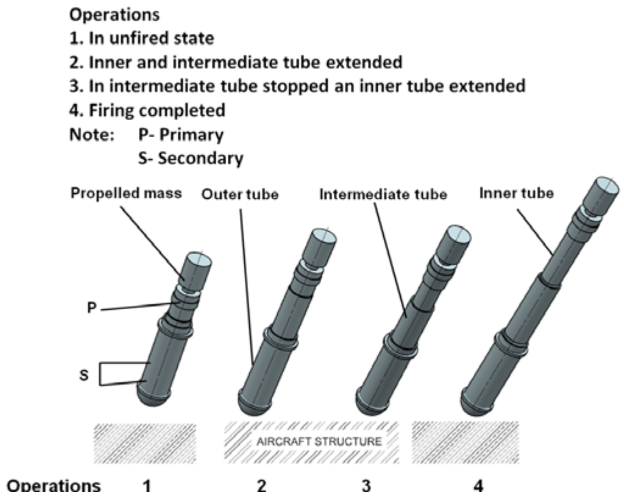

Fig. 3 Various stages of the telescopic expansion of the main gun

A. Propellant Selection

Hepta-perforated configurations have more significance for gun propulsions, as they give progressive burning profile comfortably. In seat ejection guns, the part of the entire energy is imparted to the seat-man combination in the beginning and the rest of the propellant energy of combustion gases for expansion of the telescopic tube. The gas energy generated by the primary cartridge has to execute two activities simultaneously (i) increase the pressure to provide acceleration within physiological limits and (ii) fill the empty space created due to the movement of an innermost tube with gas to maintain and sustain the high pressure. This definitely needs a propellant configuration, where the amount of gas generation continues to rise. High gas evolution is possible only when the burning surface area continues to rise. This needs a progressive burning profile. Since the gun propellants are manufactured by extrusion technique and their outer diameters are also very small (less than 10 mm), the progressive nature of burning can be attempted by this configuration alone.

Multi-perforated propellants configuration, which is mostly utilised in gas generating situations. It has more importance in the gun propellant technology. In this technology, inhibition is never applied and the propellants burn at all the exposed surfaces. The salient features of this configuration are enlisted below.

- This configuration has a very high progressivity ratio that is reflected in pressure-time.
- This configuration is used in cartridge actuated devices (CAD), impulse cartridges, ejector release cartridges (ERU) and seat ejection devices.
- This configuration is suitable for small devices and accordingly, dimensions are limited. Use in bigger devices will lead to very high-pressure rise.
- This propellant has smaller web availability and burning time is generally very short.
- This configuration has very high volumetric loading (90-95 %) and chamber volume is sufficiently filled with the propellant.
- Manufacturing of this configuration requires perforations, which are created by either mandrel or drilling.
- The production rate of this configuration is slow.
- The ignition system design for this configuration becomes critical as the propellant gases are distributed even though many perforations. Since perforations are invariably not interconnected, the flame spread in each of the perforation takes place independently.
- The web between any two nearest holes and between any outer holes and periphery is the same. This gives a sudden end of progressivity.
- This gives progressivity in uninhibited conditions.

A typical hepta-tubular propellant configuration during combustion inside the cartridge is shown in Fig. 4. Fig. 4 (a) shows 7 holes configuration. It depicts initial configuration, which contains one central perforation and six perforations on the pitch circle. During combustion, the outer diameter of the propellant shrinks and the holes diameter expands. The directions of combustion of different burning surfaces are illustrated in Fig. 4 (b). All six holes are equidistant from each other and also with the central hole. The outer diameter shrinks and meets the external six holes at the same time when the central hole touches the external six holes as shown in Fig. 4 (b). This is the first web transition. The simultaneity of convergence of all the burning surfaces restricts various dimensions. Only two cross-sectional parameters, namely (i) outer grain diameter (radius, R) and the hole diameter (radius, r) are needed and the pitch circle diameter of the external six holes from these two variables. The propellant is consumed in length direction also. Till the first transition, the propellant is a single piece, but after this propellant is divided in unconnected 12 pieces: six inner slivers and six outer slivers. Inner slivers are consumed first and this is denoted as second web transition. After the second web transition, only outer slivers remain as illustrated in Fig. 4 (c) at the third web transition, the entire propellant is consumed [7]. So, for hepta-perforated propellant grain, 3 web transition are defined - first the beginning of sliver formation, second is consumption of the outer sliver (convex triangle), the third is the consumption of the outer sliver (convex-concave triangle). This configuration is characterised by two diameters- one is grain diameter (D) and or hole diameter (d). Outer radius ($R=D/2$), hole radii ($r = d/2$), propellant density (ρ) and length (L). The various web transitions of the propellant grain can be estimated as:

- Initial propellant weight = $\rho\ \Pi\ L\ [R^2\text{-}7\ r^2]$ = 0.3 g (For single multi-perforated grain)
- Initial burning surface area = $2\ \Pi\ (R+7r)\ L$ = 306.65 mm^2

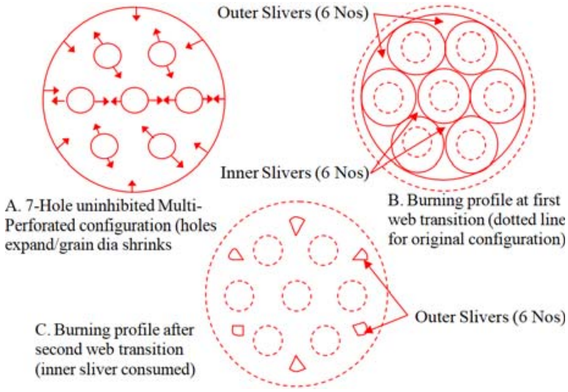

Fig. 4 Burning of hepta-perforated SB Propellant

$$First\ web\ transition,\ w_1 = \frac{(R\ -3r\ )}{4}$$

$$Second\ web\ transition,\ w_2 = \frac{(R-r\ )}{(2\sqrt{3})+r}$$

$$Third\ web\ transition,\ w_3 = \frac{(R^2-r^2)+(r+w_1)[4r+4w_1-2R\sqrt{3}]}{2(R+r)-2(r+w_1)\sqrt{3}}$$

For illustration numerical analysis of actual propellant dimensions R = 2.25 mm, r = 0.23 mm, L = 12.65 mm, ρ = 1.56 g/cc, w_1 = 0.39 mm, w_2 = 0.546 mm, w_3 = 0.610 mm, initial propellant weight 0.3 g, Initial burning surface area is 306.65 mm^2.

Before 0.39 mm web is consumed, all the holes are completely circular.

The basic chemical composition and physical properties of a SB propellant that is used for the VV firings are indicated in Table I.

TABLE I
BASIC CHEMICAL COMPOSITION AND PHYSICAL PROPERTIES OF SB PROPELLANT [8]

Chemical Composition			Dimensions of the propellant grain		
NC (13.1 to 13.25% N_2 content)	:	86 ± 1%	OD	:	4.5 mm (Nominal)
			Web	:	0.96 ± 0.05 mm
Di-Nitrotolune	:	10 ± 0.1%	Length	:	12.65 mm (Nominal)
Di-butyl Phathalate	:	3 ± 0.5%	Density	:	1.56 g/cc
Di-phenylamine	:	1 ± 0.15%	Shape	:	Hepta-tubular

Figs. 5 (a) and (b) illustrate the photo of a SB propellant and the gun powder utilized in the filling of main seat ejection cartridges. The gun powder is used as a booster in the filling of primary and secondary cartridges.

Fig. 5 (a) Photo of a SB propellant

Fig. 5 (b) Photo of gun powder

IV. Experimental Test Set Up

The experimental set up comprises of main seat ejection cartridges, the VV, the firing mechanism, pressure sensor, charge amplifier and a scope corder. The static testing of the main seat cartridges is carried out in the VV. The functional trials of the seat ejection cartridges are carried out in a specially designed and fabricated VV to ascertain the performance parameters. This is test equipment, which is used to simulate the actual volume available in the aircraft system in which the cartridges are fitted to simulate the motion of telescopic expansion of the gun. This vessel simulates the volume changes occurring in the ejection gun due to the movement of the piston (inner tube). It is one of the methodology/technique from which energy created by a power cartridge is measured in terms of the maximum pressure (P_{max}), time to maximum pressure (TP_{max}) and time to half the maximum pressure ($T½P_{max}$) [9], [10]. The basic VV design is based on these three parameters. The cartridges are fired in the VV after subjecting at hot and cold temperatures. The complete experimental set up is shown in Fig. 6 (a). The engineering sketch of the VV is shown in Fig. 6 (b). The VV has an internal diameter of 100 mm, length: 859 mm and the internal vent diameter is 3 mm. One of the results in hot and cold temperatures is illustrated in Fig. 6 (c). Time to reach TP_{max}, time to half maximum pressure ($T½P_{max}$) and maximum pressure (P_{max}) are obtained from these profiles using DAS. The main seat ejection cartridges are fired in the VV at the hot and cold temperatures. A pressure sensor is screwed into the body in a radial direction perpendicular to the VV body. It converts the pressure into an electrical signal. This signal is being small and is further amplified by a charge amplifier. The charge mode pressure sensor, charge amplifier and scope corder are connected by a low noise cable. The pressure sensor is selected to have a fast response, small size, durability, hermetically sealed construction, measurement range 15000 psi, sensitivity 0.39 pC/psi and a rise time of ≤ 1 μ s. The performance parameters are taken from Table II. Hot and cold temperatures are indicated in red and blue colour. This signifies the chemical reaction rate. The final pressure of the gases at the exit of a vent is above the atmospheric pressure. The end plug is removed to clean the vessel after each firing of the cartridges.

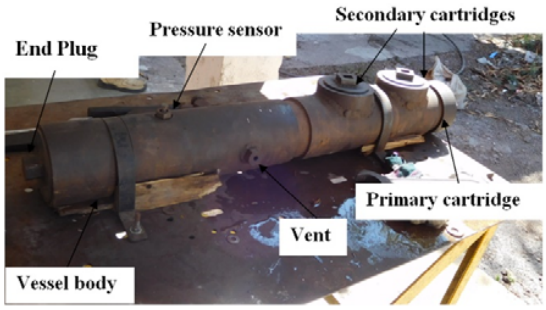

Fig. 6 (a) Experimental test set up for firing

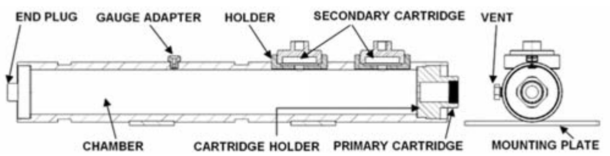

Fig. 6 (b) Engineering sketch of the VV

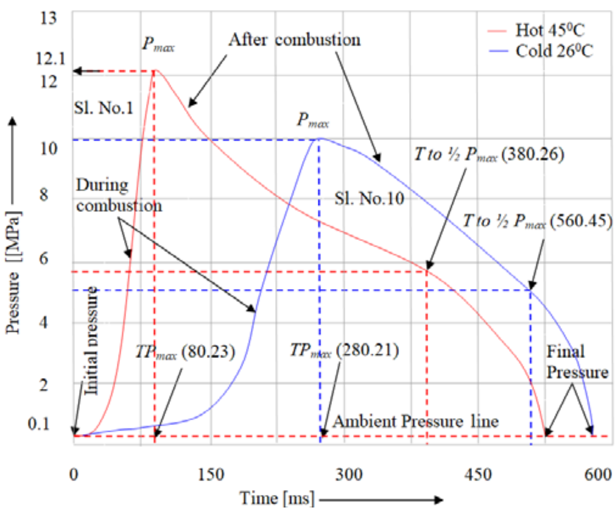

Fig. 6 (c) Pressure-time profiles generated in VV

V. Result and Discussion

A. Performance Parameter Evaluation in the VV

The performance evaluation parameters pertaining to the main seat cartridges using a SB propellant are generated in the VV [11] by firing 10 Nos. of cartridges each at the hot and cold temperatures are given in Table II. Statistics of parameters are determined and encapsulated below. Pressure-time profiles generated in VV for round No. 1 in red colour at hot temperature and round No. 20 in blue colour at cold temperature is shown at Fig. 6 (c).

TABLE II
PERFORMANCE PARAMETERS OF MAIN SEAT EJECTION CARTRIDGES

Hot (45^{0}C)				Cold (-26^{0}C)			
Sl. No.	P_{max} [MPa]	*Time to P_{max}* [ms]	*Time to ½ P_{max}* [ms]	Sl. No.	P_{max} [MPa]	*Time to P_{max}* [ms]	*Time to ½ P_{max}* [ms]
1	12.1	80.23	380.26	11	12.01	95.18	390.14
2	12	89.13	396.68	12	11.98	99.13	400.24
3	11.57	100.2	412.95	13	11.40	102.93	405.12
4	11.46	105.87	425.72	14	11.36	108.92	430.49
5	11.34	110.95	430.65	15	11.32	115.78	435.84
6	11.31	125.28	463.12	16	11.28	130.15	470.87
7	11.30	128.97	468.78	17	11.21	150.86	500.12
8	11.28	135.48	478.98	18	10.16	200.5	516.72
9	11.1	140.12	490.13	19	10.05	250.12	540.65
10	11.01	150.43	500.24	20	10	280.21	560.45
Min	11.01	80.23	380.26		10	95.18	390.14
Max	12.1	150.43	500.24		12.01	280.21	560.45

Fig. 7 (a) Photo of cartridges before the firing in VV

Fig. 7 (b) Photo of cartridges after the firing in VV

From Table II, it is observed that, in the hot temperatures the maximum pressure generated by this cartridge using a SB propellant varies from 11.01 to 12.1 MPa, whereas time to Pmax varies from 80.23 to 150.43 ms. Time to half Pmax varies from 380.26 to 500.24 ms.

In cold temperatures, the maximum pressure generated by this cartridge using SBP varies from 10 to 12.01 MPa, whereas time to *Pmax* varies from 95.18 to 280.21ms. Time to half Pmax varies from 390.14 to 560.45ms. The time in case of hot temperature is less than cold temperature and pressure is more in hot temperature than cold temperature. This is because the propellant has already gained some temperature during hot conditions as pressure is directly proportional to the temperature. Hence, the response time is less as compared to cold temperature. All the cartridges are placed in conditioning chambers for a minimum period of six hours and immediately fired in the VV with a minimum temperature loss and with the minimum delay.

After the conduct of each firing, the smooth extractions of the cartridges from the VV are noticed in all cases. No hard extraction and bulging of the cartridges are noticed. The images of cartridges before and after the firings are depicted in Figs. 7 (a) and (b) respectively. The cartridges after firing depicted at Fig. 7 (b) shows that copper foils are ruptured due to high pressure and temperature of combustible gases.

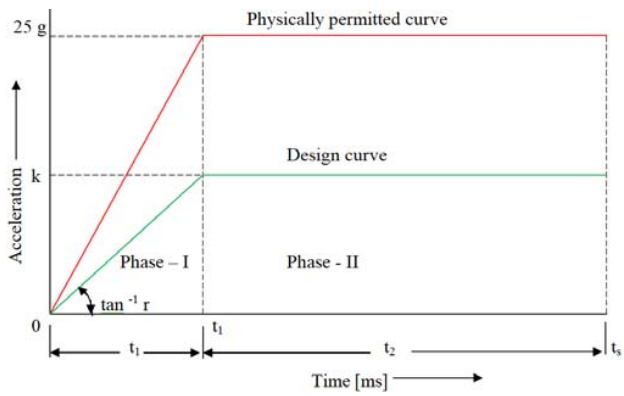

Fig. 8 Acceleration *vs.* time for physically permitted and the design curve

According to the institute of aerospace medicine (IAM), Bengluru the maximum acceleration and rate of rise of '*g*' should not be greater than 25 '*g*' and 300 *g/s*. Acceleration *vs*. time for physically permitted and design curve is shown in Fig. 8. The physically permitted curve is indicated in red colour while the design acceptable curve is indicated with a green colour. If these limits are more than design physiological limits, it will contribute to injury of the spinal cord of the pilot. From this figure, it is observed that the total time taken is divided into two phases. In phase -*I*, acceleration increase steadily and reaches to the maximum value in time t_1. In the phase-*II*, acceleration is kept constant up to a stroke time t_s.

Phase *I* is governed by the pressure generation by the primary cartridge and phase *II* is the sustenance of pressure by secondary cartridges after a certain time gap. An area under the acceleration - time profile indicates the velocity. The ejection velocity *V* is, expressed as

$$V = \int_0^{t_s} a(t) \tag{1}$$

t_s is the total time of operation

The acceleration *a(t)* gained during ejection is given by

$$\left.\begin{aligned} a(t) &= r\,t, \text{ for } 0 \le t \le t_1 \\ &= k, \quad \text{for } t_1 \le t \le t_s \end{aligned}\right\} \tag{2}$$

k and *r* are constants, representing sustenance and the rate of rise of acceleration.

Integrating (1) using (2) gives

$$V = r\int_0^{t_1} t\,dt + k\int_{t_1}^{t_s} dt = r\frac{t_1^{\,2}}{2} + k\,t_2 \tag{3}$$

where $t_2 = t_s - t_1$

Here, it is assumed that an ejection gun with a piston arrangement provides the required velocity to the seat - pilot combination.

We consider that L_1 and L_2 are the stroke lengths (the distance covered by the piston in the gun tube) during the first and second time phases respectively, they are given by

$$L_1 = r\int_0^{t_1}\int_0^{t_1} t\,dt$$

$$= r\frac{t_1^{\,3}}{6} \text{ and } L_2 = \int_{t_1}^{t_s}\int_0^{t_1} r\,t\,dt\,dt + k\int_{t_1}^{t_s}\int_{t_1}^{t_s} dt\,dt \tag{4}$$

$$= \frac{k^2\,t_2^{\,3}}{2r} + \frac{k\;t_2^{\,2}}{2} \tag{5}$$

Therefore, the total stroke length of the piston is given by

$$L_s = L_1 + L_2$$

Substituting for t_1 and t_2 from (4) and (5) in (3), the ejection velocity *V*, in terms of total stroke length, acceleration and the rate of rise of acceleration, is given by

$$V = \left[2k\,L_s - \left(\frac{k^4}{12\,r^2}\right)\right]^{\frac{1}{2}} \tag{6}$$

From (6), it is clear that, with the permissible values of *k* and *r*, higher velocity can be obtained only by increasing the stroke length L_s.

B. Dynamic Testing of Cartridges on SET

This test is essential in order to ensure the performance of main seat ejection cartridges under simulated conditions. It is a unique facility available and extensively used to obtain parameters such as acceleration, rate of rise of acceleration and velocity during the firing of the main seat ejection cartridges. The test set up consists of 50 m long main tower consisting of guide rails on the supporting structure. The main tower provides a guided path to the seat of simulated weight. It is inclined with 20° angle with vertical that simulates the same position in the aircraft. Main tower is supported by two auxiliary towers. The ejection seat with an anthropomorphic dummy is mounted on the trolley that moves on guided rails when gun fires. On the firing of the cartridges, the seat is ejected up and is arrested by means of sprang and ratchet mechanism which ensures that the trolley gets locked to the structure when velocity becomes zero. The seat is lowered using winch-operated trolley. SET images, anthropomorphic dummy, acceleration - time profile and velocity - time profile are shown in Figs. 9 (a)-(d) respectively. The acceleration is found out by fixing an accelerator mounted to the hip of the dummy pilot. From the acceleration *vs*. time profile maximum '*g*' and rate of rise of '*g*' are determined. For velocity measurement, the equi-spaced coils are placed on the main tower. Experimentally the velocity is measured using pick-up coils (mounted on the structure) and a magnet on the trolley at known distance. The time interval between the two magnetic coils is determined. The ratio of distance and time indicates the velocity in m/s. The velocity is obtained by integrating acceleration - time profile using in built software. The maximum seat ejection velocity including pilot mass is experimentally determined as 20 m/s. This is the velocity by which seat clear the tail fin of fighter aircraft. All the performance parameters such as the maximum acceleration, the maximum velocity and rate of rise of acceleration are observed well within physiological limits. The firing of main seat ejection cartridge on SET is cumbersome, therefore time to reach TP_{max}, time to half maximum pressure ($T½P_{max}$) and maximum pressure (*Pmax*) are generated in the VV firing.

Fig. 9 (a) Photo of SET

Fig. 9 (b) Anthropomorphic dummy.

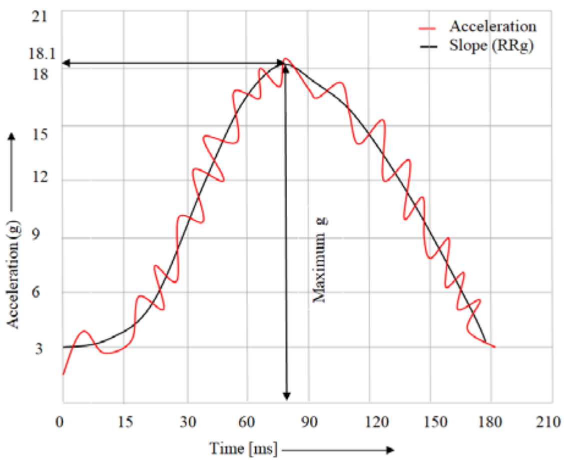

Fig. 9 (c) Acceleration - time profile

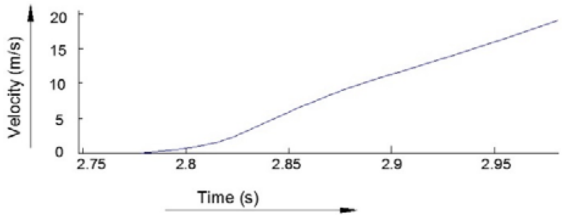

Fig. 9 (d) Velocity - time profile

VI. Conclusions

The ballistics of the main seat ejection cartridges are addressed in this research article. The main objective of this paper is to describe the evaluation methodology of various performance parameters of the main seat ejection cartridges used in the seat ejection using a VV for aircraft application. The physiological parameters are also experimentally evaluated by dynamic testing of the main seat ejection cartridges on the SET. All the performance parameters are observed well within physiological limits as laid by IAM. The following inferences are drawn from this research article.

- The maximum seat ejection velocity imparted to the seat - man combination should not be more than 25 m/s.
- The rate of rise of acceleration should not be more than 300 g.
- The maximum pressure generated by a SB propellant in the main seat ejection cartridges is in such way that it will achieve the required ejection velocity.
- Maximum velocity of seat ejection determined experimentally is 20 m/s.
- To determine performance parameters, the static trials are carried out in the VV.

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Authors' Contributions

B. A. Parate had the original idea for writing the manuscript and performed the experimental trials related to research activities. The author of this paper participated in the planning, execution and analysis of this study.

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Conflict of Interests

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