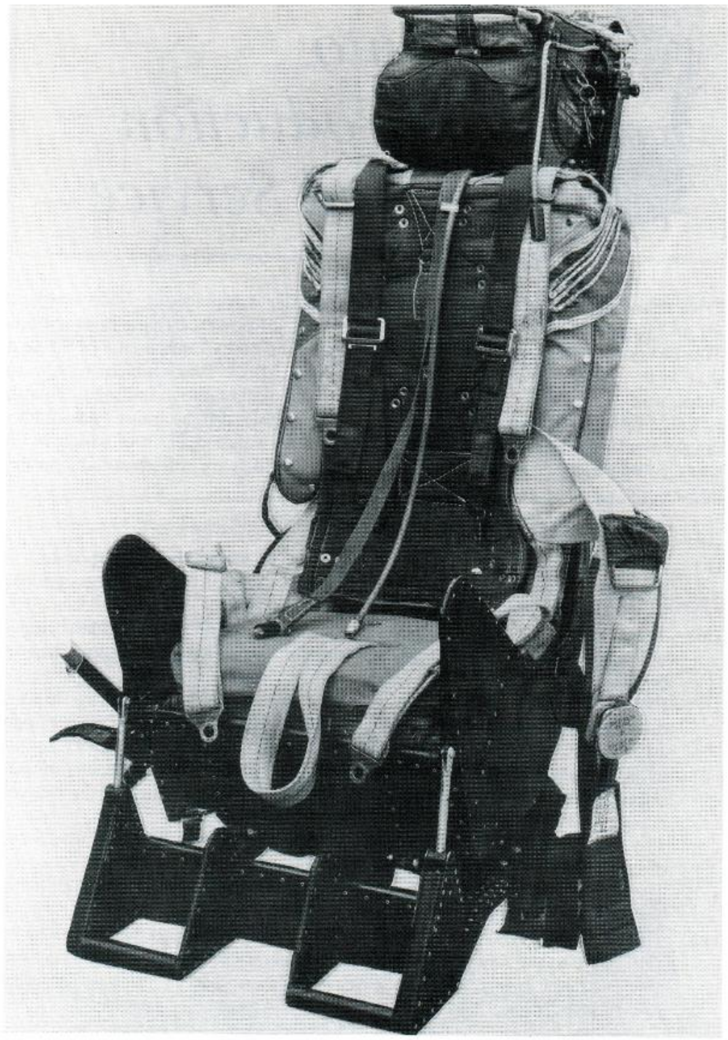
Ejection Seats

History and engineering



Sayyam Khurana

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1 Introduction

Ejection seats allow the pilots to escape from an aircraft that has become operational due to any reason. This can be usually due to technical failures, pilot errors or enemy fire. Over 10000 lives have been saved due to ejection seats.

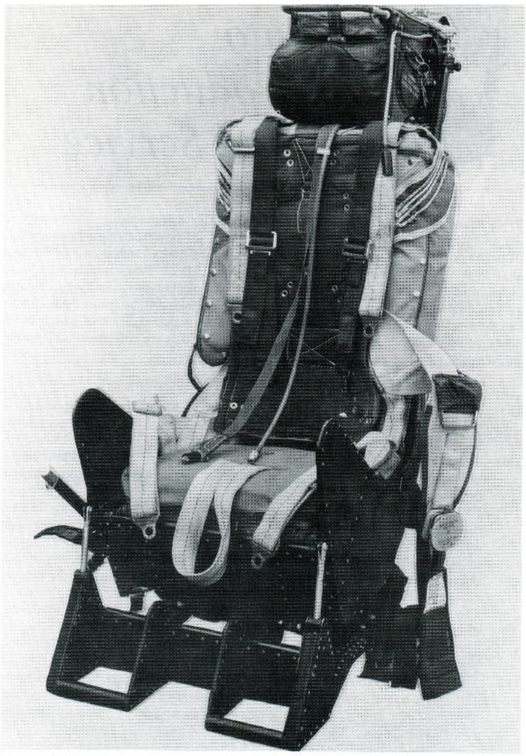


Figure 1: Martin Baker MK1 Ejection Seat

When a pilot is ejected using an ejection seat, they face three key shock loads i.e., Ejection Shock, Wind Blast and Parachute Deployment Shock. Higher ejection speeds are desirable for deployment at high aircraft velocities and low-altitude ejections, whereas ejection speed is proportional to the shock loads.

Ejection shock is the initial shock due to the cartridge fired catapult that pushes the pilot out of the plane. The seat is generally mounted on rails which guide the seat upwards. The seat cushion material plays a key role in ejection shock attenuation.

Wind Blast is the impact of high-speed wind on the pilots face upon exit from the plane. Face protection and windscreens are used to alleviate them.

Lastly, the parachute deployment shock is the loading on the pilot from the deployment of the drogue parachute. This can be attenuated largely by reefing the parachutes, but also by increasing the ejection velocity of the drogue.

2 History

It was the development of parachutes originally designed for balloon observation crews in WW1 and German pilots later that led to the development of ejection seats.

At first, ejecting meant climbing out of the cockpit and jumping off the wing. However, as aircraft speeds increased, this became increasingly improbable. In WW2 itself, the fighters reached speeds, where the slips stream pinned the pilots into their seats even after jettisoning of the cockpit. The success rate of jumping off a crippled aircraft at speeds up to 150 kt was 75%. This decreased to 25% at 200kt and barely 2% at 290kt.

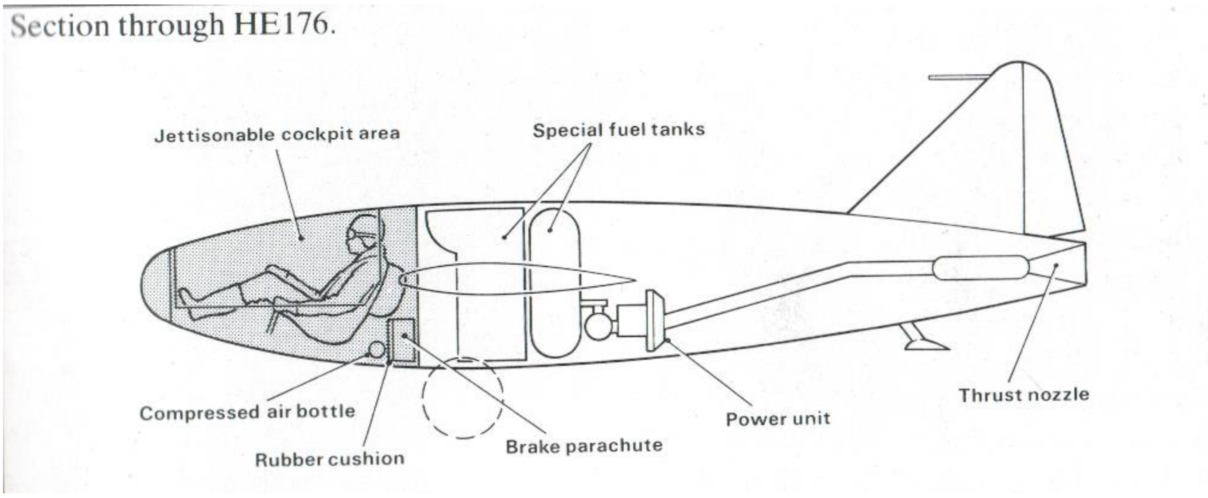
Fire was a common issue on planes going down due to combat. There were several instances of fire damaging the parachutes severely before escape.

The original ideas consisted of compressed springs under the seats that could push the pilots out. Early progress was largely made by the Germans and the Swedes which was picked up post-war by the British and the Americans. There are notes of British politician's concern that pilots won't be inclined to try to bring the plane back home if they had ejection seats.

2.1 Germany

Germans investigated a lot of different ideas in pre-war Germany with respect to crew escape. They settled on the idea of "Catapult seats". Junkers started working on forced ejection, when they wanted to test JU88 and were concerned of mechanical failure in the test aircraft. The seats were patented in 1941, however much information about them is not available. They were not installed on operational aircrafts.

As aircrafts got faster, the need for ejection seats became more apparent. He176 was the world's first "liquid fuel" rocket-propelled aircraft, and its design explored the ejection of complete cockpit assembly about 20 years before its use in ejection system of F-111. The locking mechanism used three bayonet fasteners on the fuselage longerons and was triggered using compressed gas. An illustration of the HE176 Pilot placement is shown below.



A brake parachute was automatically released after separation to slow the cockpit. Tests conducted using the wooden cockpit from He111 showed a flaw where the parachute canopy failed to deploy and would get blown away against the cockpit. This was resolved by placing a rubber cushion behind the parachute connected to compressed air, much like a cold gas mortar system.

As the aviation industry moved to jet aircraft, Heinkel He280 incorporated a compressed gas-operated ejection seat. During the testing phase of He280 in 1942, the aircraft began to ice up at an altitude of about 8000 ft and test pilot Schenk had to use the ejection seat to land safely on the ground making him the first person in history to use ejection seats to save their life in an emergency. The design was later improved using guidance rails, cushioning and cartridge-operated ejection. This allowed for an ejection velocity of 32 ft/s with a peak of 14 g's. From late 1942, all high-speed fighter jets had some form of ejection seats.

Post-war analysis showed that in a lot of successful escapes, especially at high speeds, the pilots died or suffered critical injuries due to impact with the tail unit. This led to the requirement for the ejection seats to clear high fins. In aircrafts such as Dornier Do335, this also added the requirement to clear the rear propellers. One of the solutions for this problem was to blow off the fins and the rear propeller to reduce the required ejection velocity. Even after the modification, the seat installed on Do335 had a "Jolt" of 1250g/s, which is far beyond modern safety limits.

There were 5 steps in the Do 335 ejection sequence: "

1. Blow off the rear propeller.
2. Blow off the upper tail fin.
3. Arm the ejection seat.
4. Manually Jettison the Hood.
5. Squeeze the trigger on the armrest to fire the seat. "

2.2 Sweden (SAAB)

Main development in Sweden took place during 1939-1945. The first Swedish patent for ejection seats went to Saab in 1941. Saab directly chose the cartridge driven system over compressed gas, and their first seat went into production in 1943 to be fitted into the J21. Their first recorded operational use was in 1946 following a collision at 10000 ft between two aircrafts. Saab went to patent many design solutions for ejection seats such as restraints for arm, head and leg, rocket engine ignition, life vest inflation device. As their use became more prominent, ejection seats went through a period of continuous improvement and became more complex. The figure below displays the level of redundancies built into one of the Saab Ejection Seats

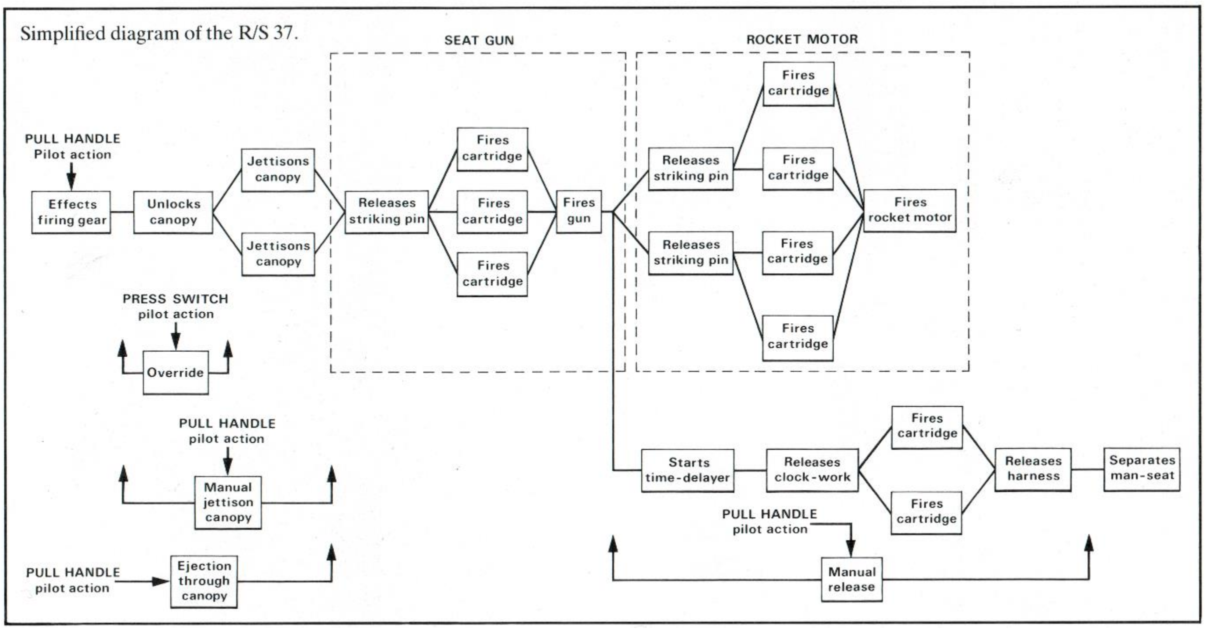


Figure 2: Logic Diagram of Ejection Seat Mechanisms

The deployment sequence of the Saab 35 Dracken Rocket Seat Ejection System on J35 & J37s used in 50s and 60s was: "

1. Both handles located on the either side of the seat are pulled up. As well as starting the sequence, this action also releases the safety covers over the manual override handles.
2. A spring-loaded catch on the firing mechanism is pulled away.
3. Shoulder straps are retracted and locked by a ballistic rotary actuator.
4. The canopy locks are opened by means of electrically operated ballistic actuators.
5. The canopy raisers lift the canopy which is removed by the slipstream.
6. As the canopy departs it activates the ejection gun.
7. The legs are restrained.
8. Pipes for oxygen and G-suit are disconnected and the valve for the emergency oxygen supply is opened.
9. At speeds over 270 kt, the time delay for the harness release is switched over.
10. Start of time delay.
11. The parachute arming wire is locked to the seat.
12. The leg restraint cords start to loosen from their location points with the aircraft.
13. The rocket motor fires.
14. The seat stabiliser parachute gun is actuated by pressure from the seat gun and is fired.
15. The drogue gun pulls out the locking pin in the cover over the stabiliser and pulls out the auxiliary parachute which in turn extracts the stabiliser and retards the seat.
16. The harness is released from the seat.
17. The leg restraint cords are released from the seat.
18. Separation between man and seat occurs.
19. The top of the parachute pack opens and a drogue containing an auxiliary parachute and stabiliser is pulled out.
20. The time delay in the main parachute is armed. (Release time is 0.5 sec at an altitude of 10000 ft and lower. Above this it is blocked by the barostat.)
21. The parachutes are immediately released from the stowage and the auxiliary is deployed. (If the descent time to 10,000 ft is shorter than the time it takes for the seat to turn into the correct position, then the auxiliary is not released but extracts the main parachute at once.)
22. The stabiliser drogue (or the auxiliary parachute below 10,000ft) is released from the attachment points in the harness.
23. The cover over the main parachute with the auxiliary is opened and the stabiliser starts to extract the main parachute.
24. The life raft cover is opened, and the raft is inflated when the crewman starts to free himself from the harness."

SAAB have now switched to Martin Baker seats for their newer aircrafts.

2.3 Britain

The development of ejection seats in Britain was done post war by the Martin-Baker company. Both Germans and British evaluated the maximum g's the pilot could sustain using test rigs.

When news of Martin-Baker's ejection seat testing spread, people were eager to see it and even experience it like a roller coaster ride. An Image from the early human testing is shown below.

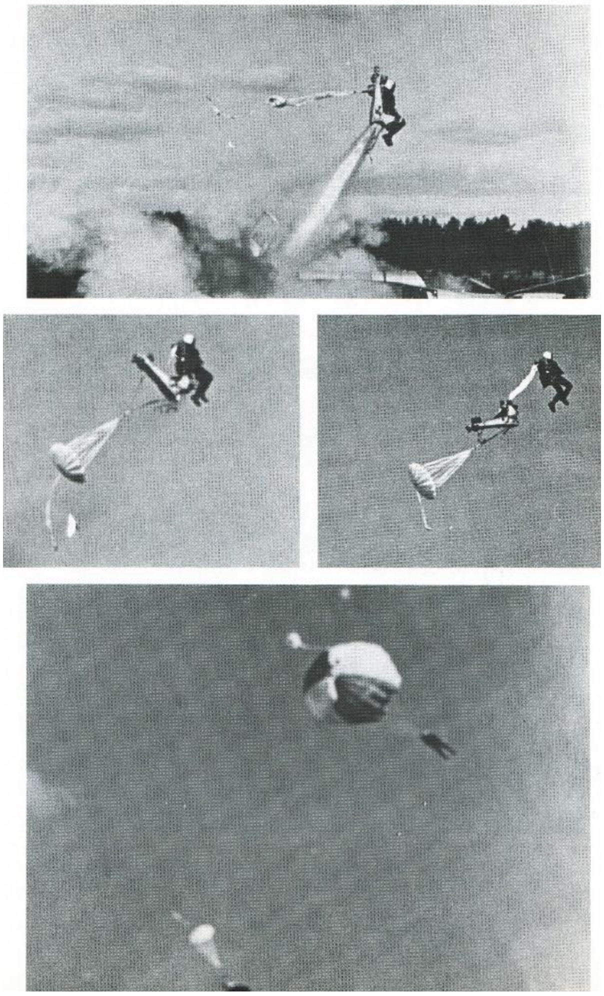


Figure 3 Human testing of the Martin Baker ejection seat

A journalist Charles Andrews was the first to try it for fun and was admitted in the hospital next day for a broken back (crushed spinal vertebrae). Investigation following this injury led to discovery of the importance of “Jolt”. The three key criteria for ejection seats that were identified were:

1. Peak acceleration of less than 21 g sustained for less than 1/10 s.
2. Max Jolt of 300g/s
3. Body posture such that the vertebrae are square to each other.

The figure blow shows the loading on the vertebra during ejection and also illustrates the importance of the alignment of the vertebra.

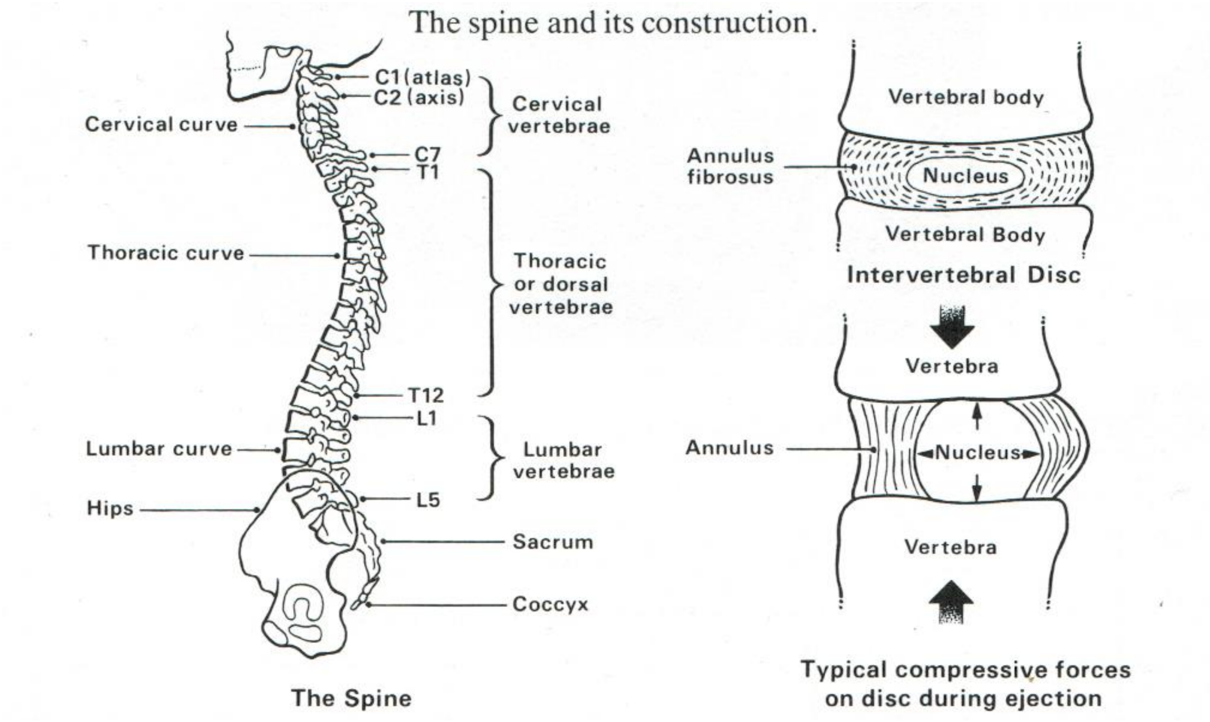
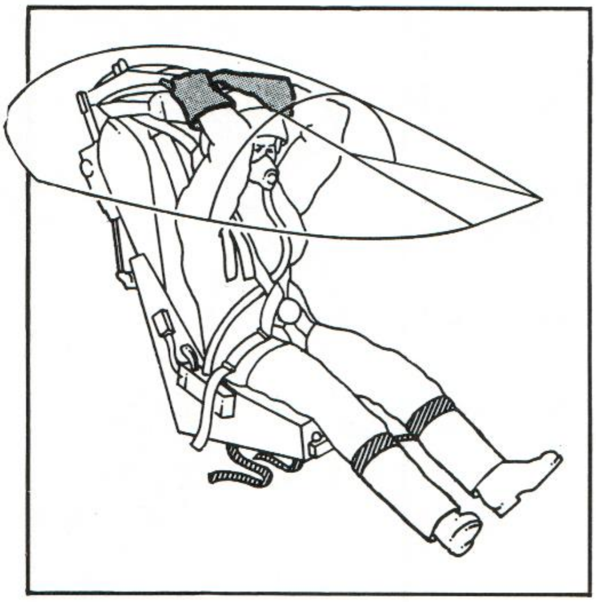
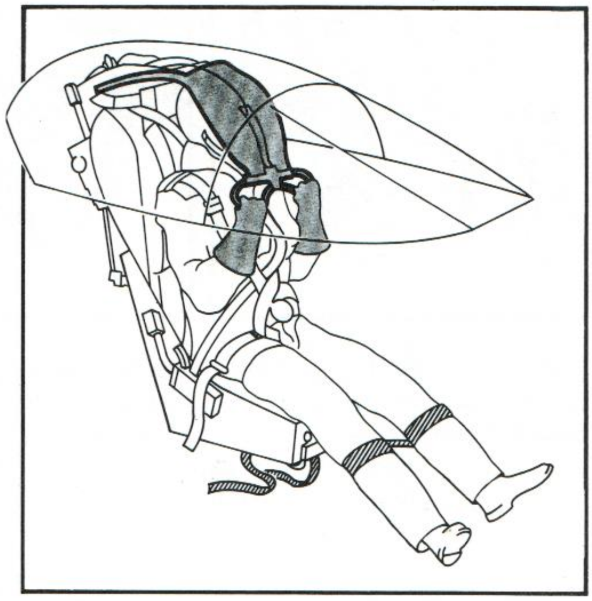


Figure 4 Image of loading on the vertebra during ejection

To ensure the right posture and wind blast protection, Martin-Baker seats used a face blind for seat ejection trigger. The Illustrations below show the complete ejection sequence of the early Martin-Baker seats.



Preparing to eject.



Face screen pulled to commence ejection sequence.

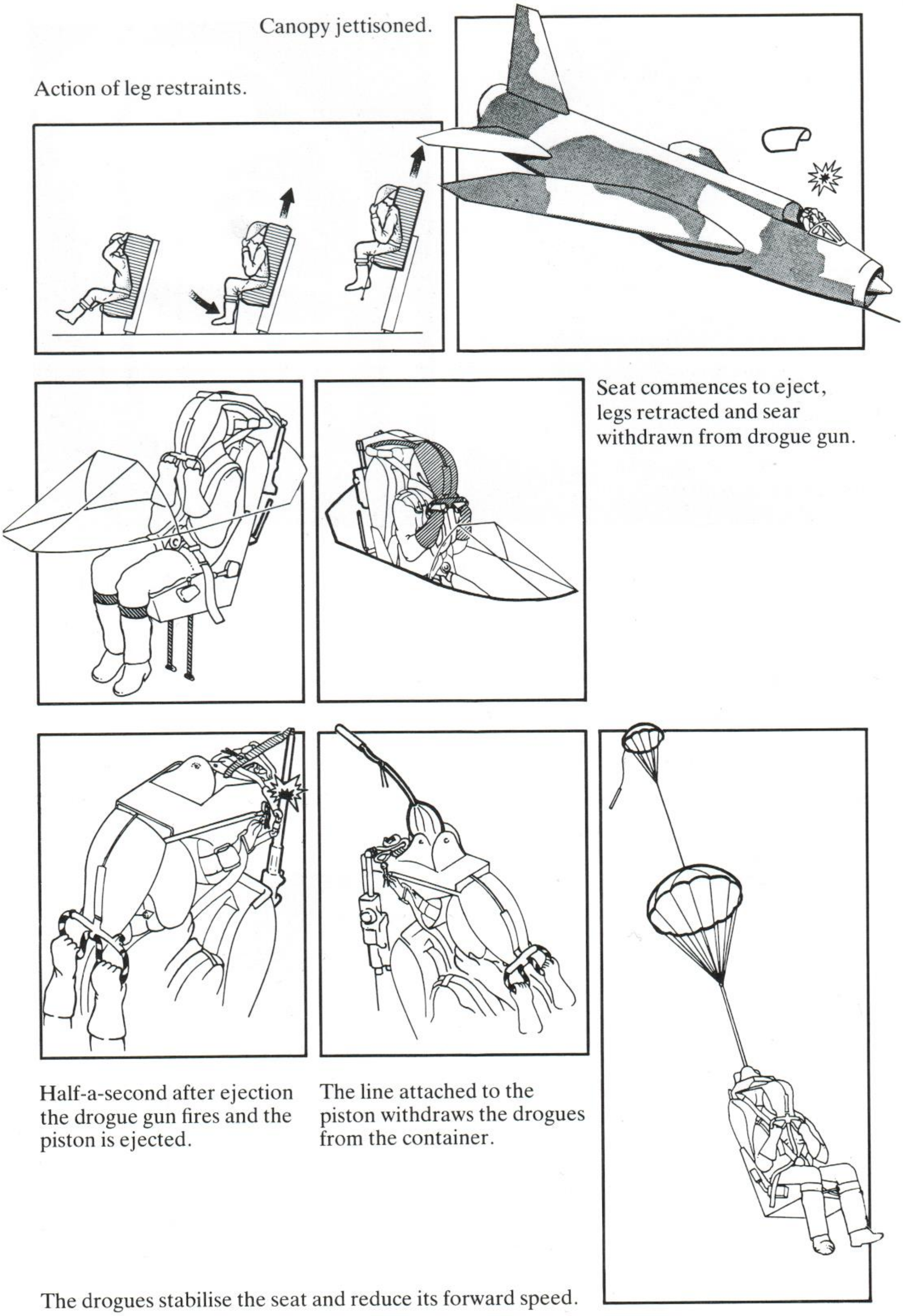
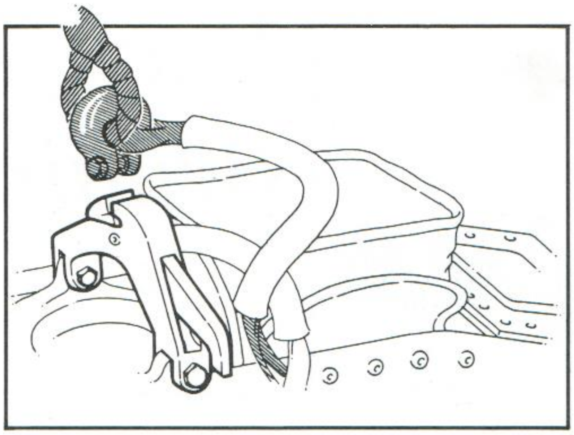
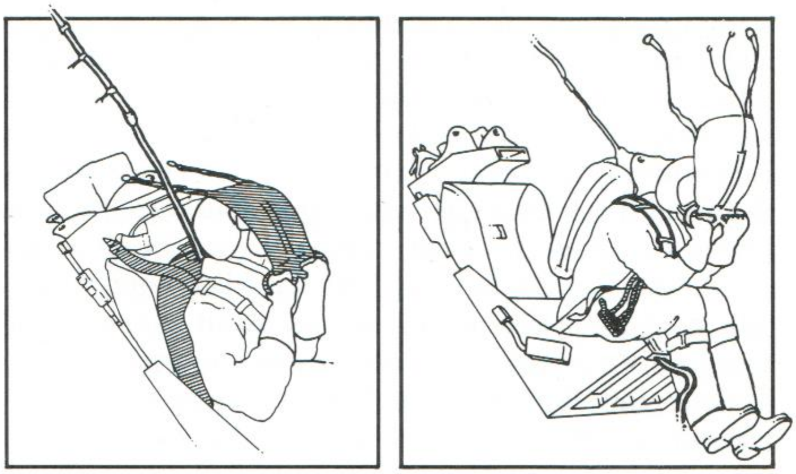


Figure 5 Sequence of the Martin-Baker ejection seat, part 1

When the seat is below 10,000ft and the speed has reduced sufficiently, the time release unit operates and the scissor shackle opens.



The pull of the drogues is transferred to the lifting lines and the face screen and parachute and the occupant is lifted out of the seat, allowing the seat to fall free.



The occupant makes a normal parachute descent.

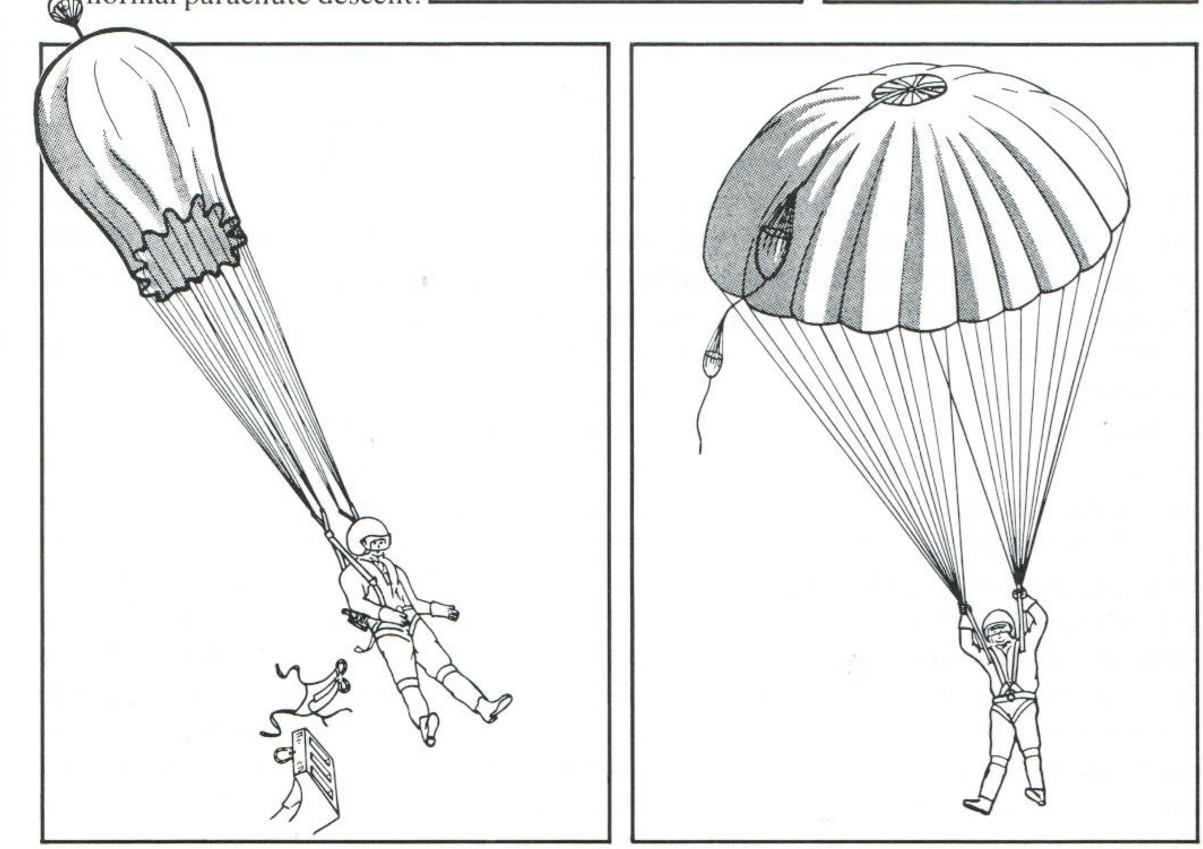


Figure 6 Sequence of the Martin-Baker ejection seat, part 2

2.4 America

Ejection seat development mostly took place post WW2 in United States and were built upon the foundation of German and Swedish designs.

Ejection seat manufacturers faced unique challenges as they had two customers, USAF, and Navy. USAF considered altitude under 1000 ft un-survivable, but navy wanted ejection seats capable at much lower altitudes. Stencil SIII seats were preferred by Navy as they were capable of ejection at 200 ft whereas Martin Baker and McDonnel-Douglas seats require at least 500 ft. Lower altitude ejection did lead to higher loads on the pilot and increased chance of injury. An illustration of Stencil SIII seat is shown below.

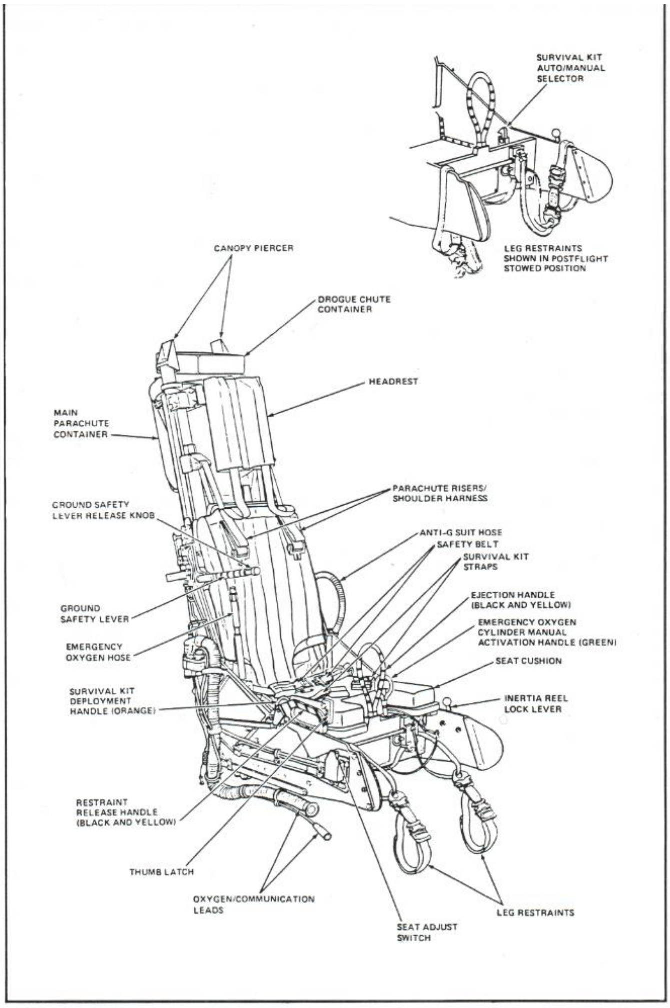
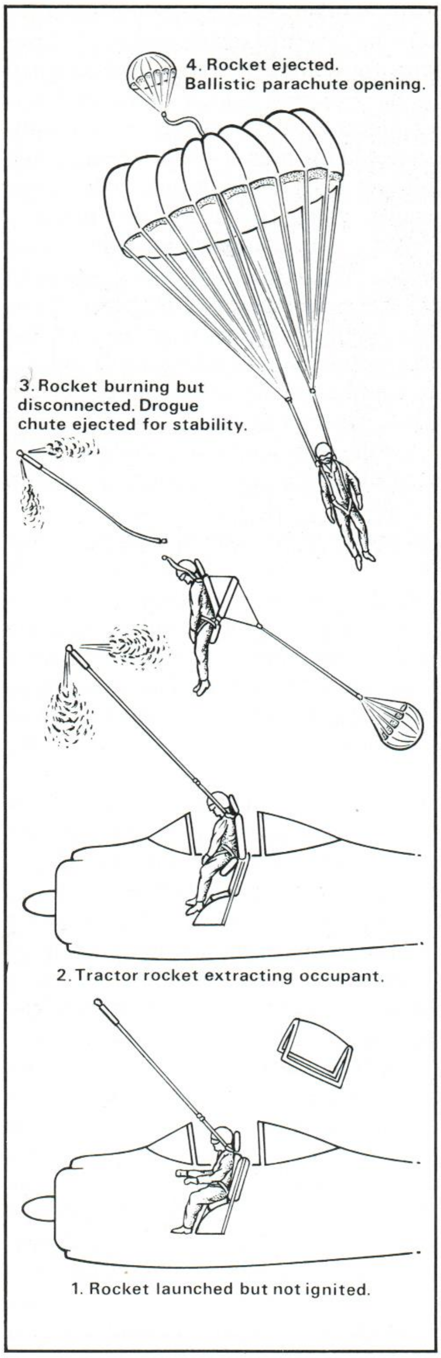
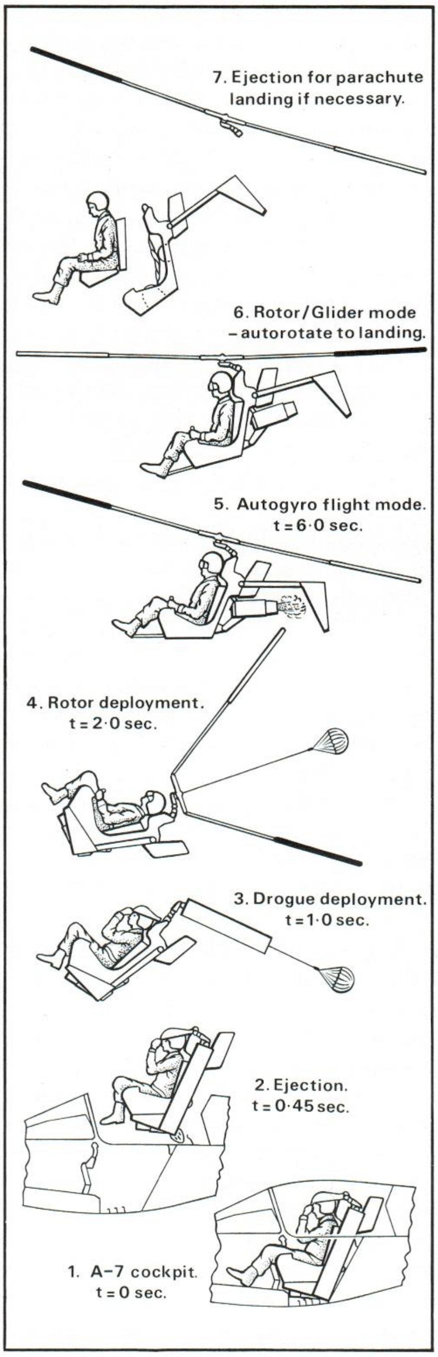


Figure 7 Diagram of the Stensel S111S ejection seat

Ejection seats had a relatively high failure rate in the Vietnam war due to low altitude deployments. One of the alternates for deploying at low altitudes was the Stanley Yankee system. It was built and tested but not put in operational use. Another concept that was investigated during Vietnam war was the Karman SAVER (Stowable Aircrew Vehicle Escape Rotoseat) rotoseat that used active propulsion to land the pilot out of harm’s way using rotors. The principles of the Stanley Yankee system and the Rotoseat are displayed below.



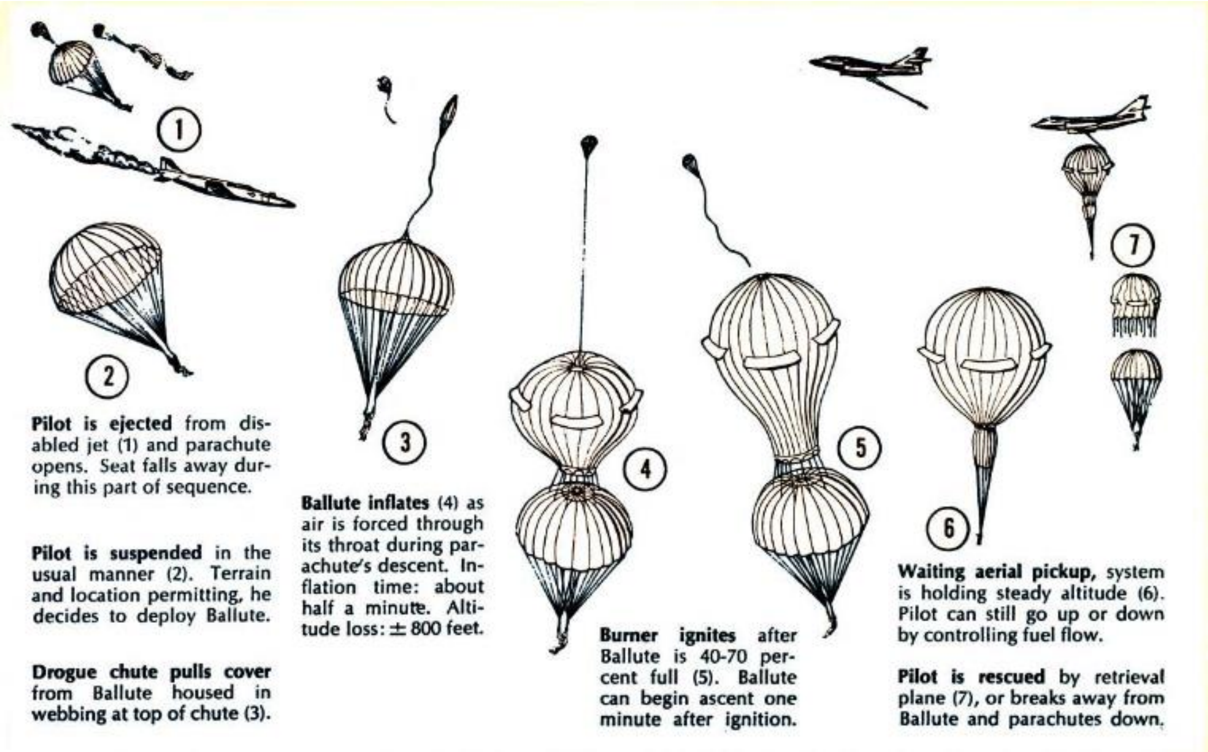
Stanley Yankee system.



Karman Saver Rotoseat.

Americans also investigated downward deployment at high altitudes. It was especially convenient for aircrafts with tall tail fins. In 1953, Col A.M. Henderson was the first man to eject downwards from B-47 aircraft. The usual problem of flailing limbs was observed in consequent tests. Colonel described it as “like a Saint Bernard dog shaking a rabbit in its mouth”. This was later addressed using automatic arm and foot restraints.

Another unique concept investigated by the Americans was the PARD (Pilot Airborne Recovery Device). This concept was developed with Goodyear who is famous for their Ballutes. The goal was to keep the pilot buoyant for at least 30 mins to avoid small arms fire and to be rescued from the air. A butane burner is used to ignite a Ballute above the main parachute to keep the pilot floating in air. The pilot could control the fuel rate for a slow descent or ascent. Successful tests were carried for both floating and mid-air retrieval without exceeding the g limits using a C-130. The end of the Vietnam war led to the halt in further development.



Ballute is housed behind pilot. The 65-lb. rig fits ejection seat of F4 Phantom.

Ballute maintains altitude (buoyancy). Chute, hanging limply, can still be used.

3 Ejection Shock

Ejection shock is the first major shock in the ejection sequence. It occurs when the cartridge fires and pushes the seat along the rail out of the plane. As planes have got faster, the ejection speed requirements to clear the aircraft structure (especially the tail fin) have increased.

3.1 Jolt & Acceleration

The requirements for design are generally the ejection velocity(v) and vertical distance(s) within which the velocity must be reached. Assuming constant acceleration, it is easy to obtain required acceleration using $a=v^2/2s$. However, this assumption implies instantaneous acceleration or infinite jolt (rate of change of acceleration) which isn't feasible.

There have been various estimations on the limit of maximum acceleration a seated human body can sustain along the spine since the invention of ejection seats. The importance and limit of Jolt was evaluated after the second world war. After years of dummy & ethically dubious human testing, the RAF has settled on a maximum Jolt of 300 g/s and a maximum acceleration of 25g.

While the maximum limits are set, injury is still possible during ejection. Figure 1 shows different thrust profiles and their impact on the human body. It can be seen that a gradual increase in acceleration (position **f**) is the ideal profile with least symptoms. It is also interesting to note that the total energy of the gun in position **f** is greater than that in position **a, b & c**.

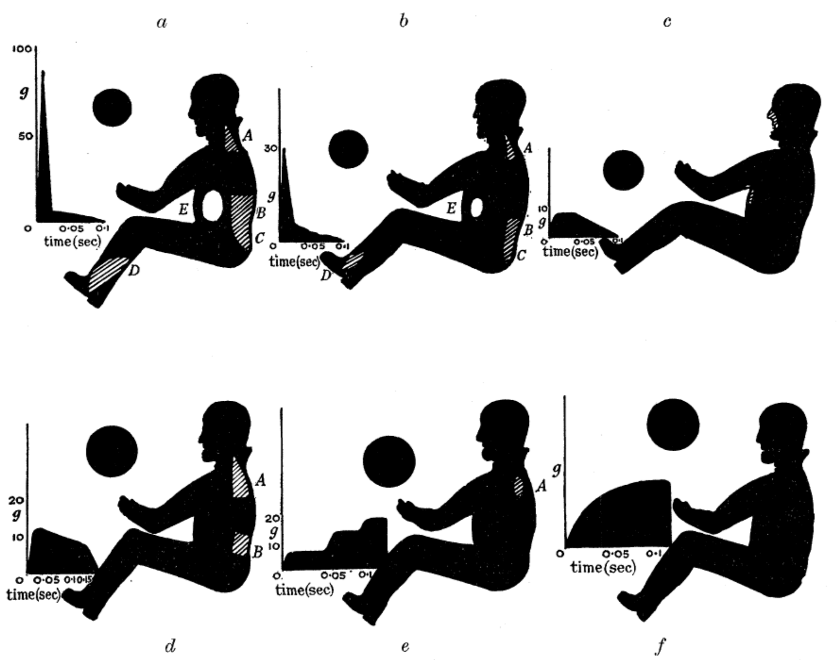
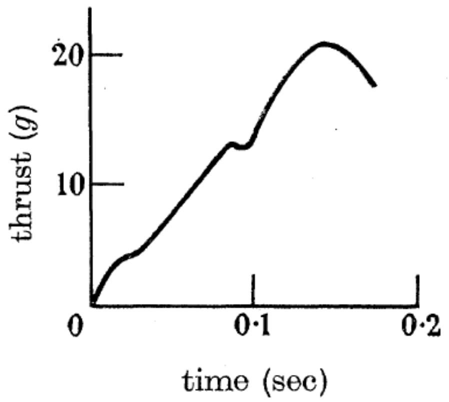


Figure 8: Physiological response to vertical impact acceleration over time. The area of the circle is proportional to the total energy of the thrust. The shaded (hatched) regions on the body represent the locations of injuries/pain measured using the respective Thrust profile.

Using the data from the study above, Martin Baker implemented the Thrust curve in Figure 2 using a dual cartridge system to achieve a nominal Jolt of 240g/s with a peak acceleration of 15g.

Figure 9: Thrust profile adopted by Martin Baker to minimize injuries of 60 ft/s gun

3.2 Vibrational Response

The simplest way to model the vibrational response of an ejection shock is to use a double mass spring coupled system as shown in Figure 3.

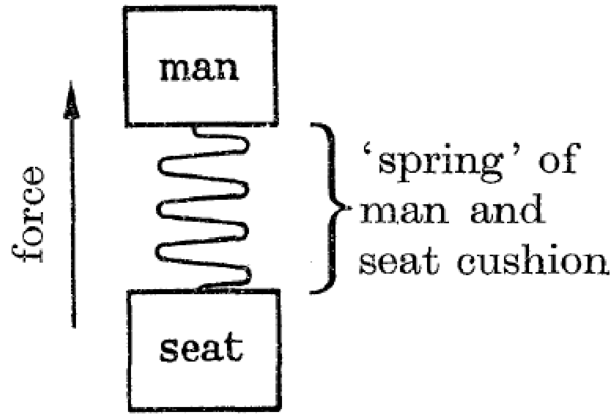


Figure 10: Mechanical approximation of ejection shock

With lack of damping, the acceleration on Pilot is a function of elastic characteristics of the seat. Any energy stored in the system will get released and can cause overshoots in acceleration. Therefore, the general design principle is to have the seats as stiff as possible. While a stiff seat is important to prevent overshoot, it is also important for the top layer of the seat to be compressible to spread the load.

Research has been conducted on cushion materials such as Sorbo Rubber, J-Pack & Multiprene foam. J-Pack is moulded cushion of rubberised horse-hair mounted on top of a water cushion and folded rubber dinghy. It was observed that the Multiprene foam had the best results because of its damping characteristics. The impact of the seat material was more significant on the Jolt and compared to its impact on Acceleration.

3.3 Body Alignment & Restraints

It is ideal that line of thrust is along the line of the spine, but it is not always possible. An inclination of up 18 degrees have been demonstrated to be safe during deployment.

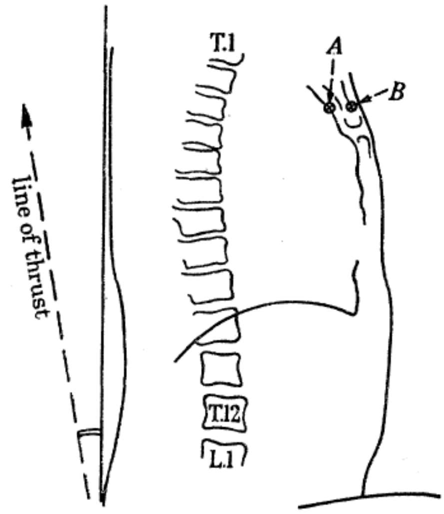


Figure 11: Inclination angle of thrust relative to the angle of the spine

Research along the years have focused on different types of actuable restraint systems that don't impede normal operation. These restraints are generally divided into the following categories i.e., Arm restraint system, Leg protection system and Head protection system. Example of restraints are displayed below:

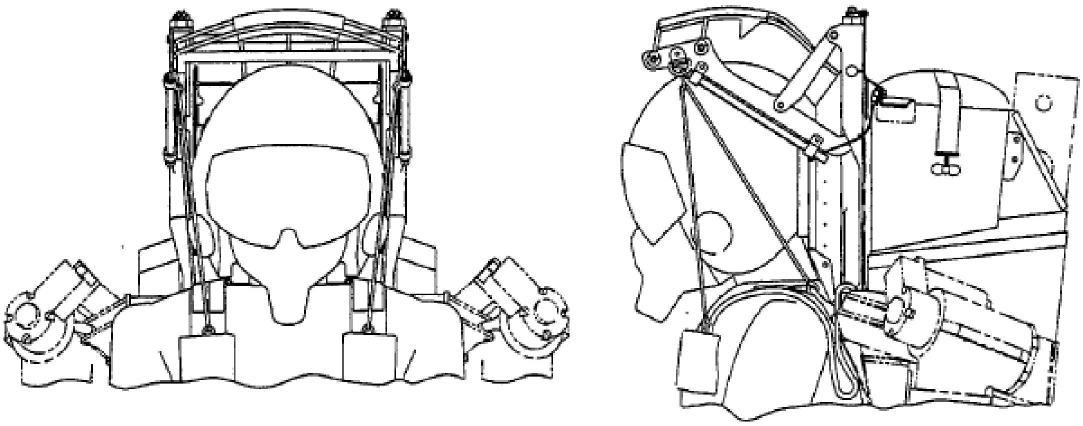
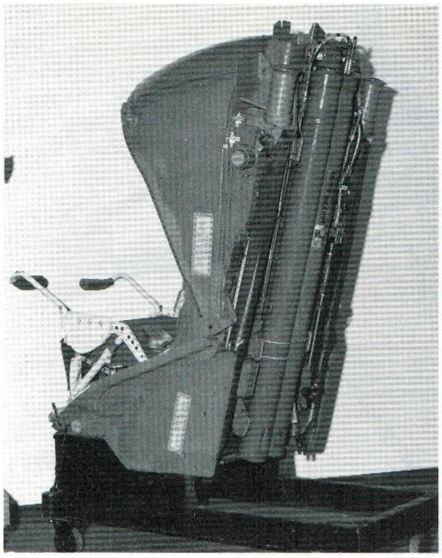
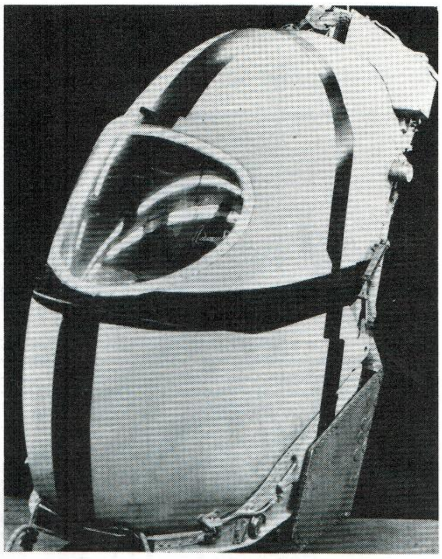


Figure 12: Head Protection System





Above:
The Stanley capsule installed in the bombardier and navigator's positions in the B-58. The front closes like a clamshell just prior to ejection. *Bryan Wilburn*

Above right:
The Stanley escape capsule in the closed position. This particular example was used for tests from a rocket sled. *Bryan Wilburn*

Figure 13: Combined head and windblast protection system

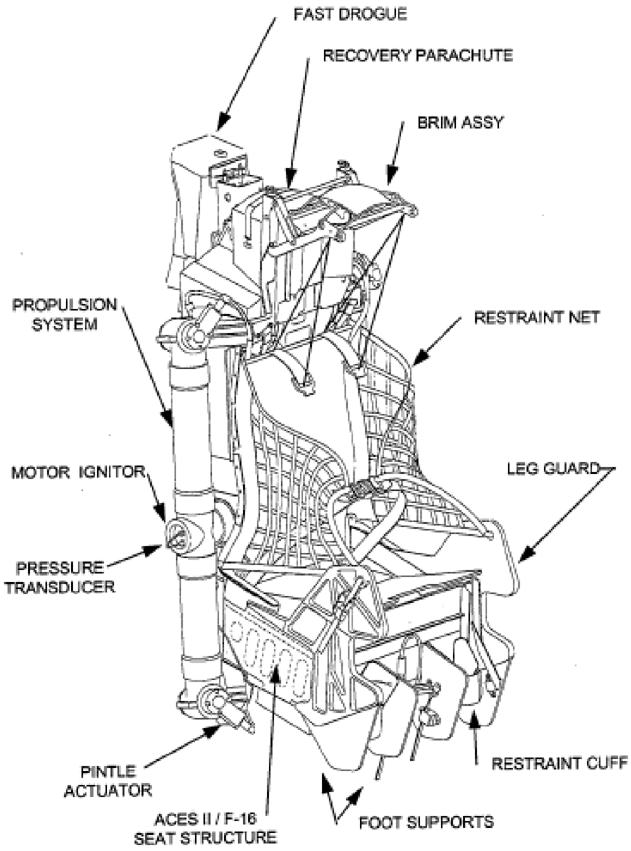
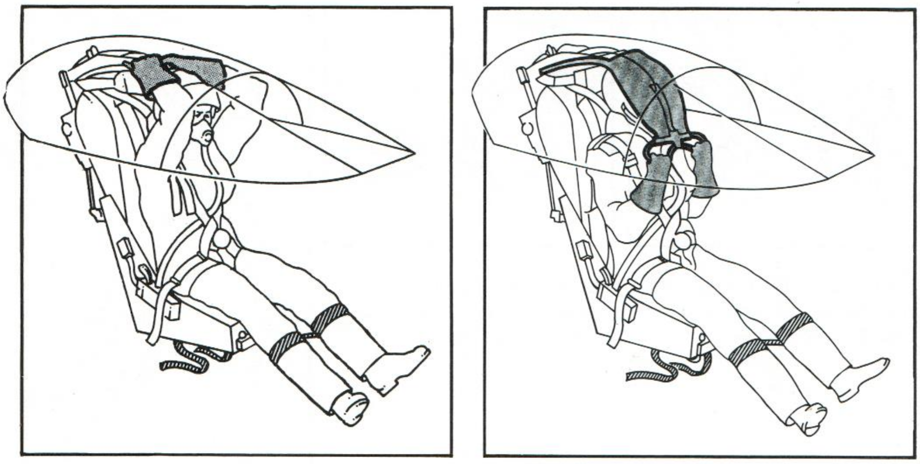


Figure 14: Net-based arm restraints.

3.4 Wind Blast

Windblast is the sudden force of the wind that the pilot faces during ejection. It is directly proportional to the dynamic pressure during deployment. The simple solution is to cover the face. Different strategies such as face shield or deploying the complete cockpit (eg: PRESS configuration) have been used. Examples of the strategies is displayed below:

Below and overleaf:
Mk 4 Martin-Baker seat: sequential diagrams to show its operation.



Preparing to eject.

Face screen pulled to commence ejection sequence.

Figure 15: Face Shield triggered deployment

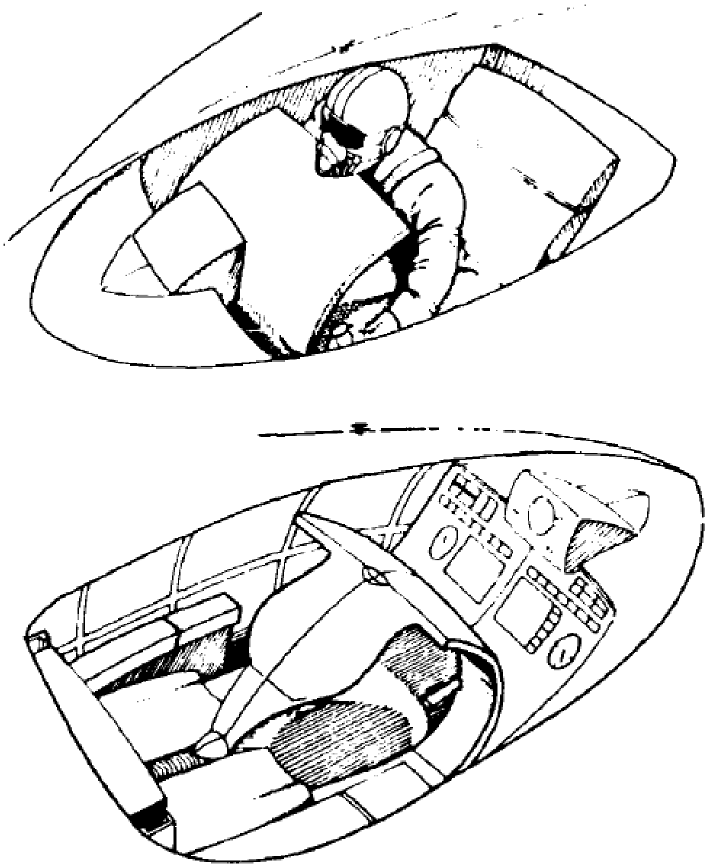


Figure 16: PRESS (Pronated Escape System) complete cockpit ejection

4 Case Study ACES II Ejection Seats

ACES II (Advanced Concept Ejection Seat) developed by Douglas Aircraft company for US Airforce. The seat had its qualification testing in 70s was in turn used in the following aircrafts: F-15A/B, F-16A/B, A-10. B-1, B-2, F-117 and F/A-22. It has a deployment envelope of 0-600 KEAS. It uses a slug gun deployed Hemisflo Drogue parachute and a mortar Deployed Main Parachute. The seat mass is Seat Assembly 157 pounds. A functional breakdown of the seat is shown below:

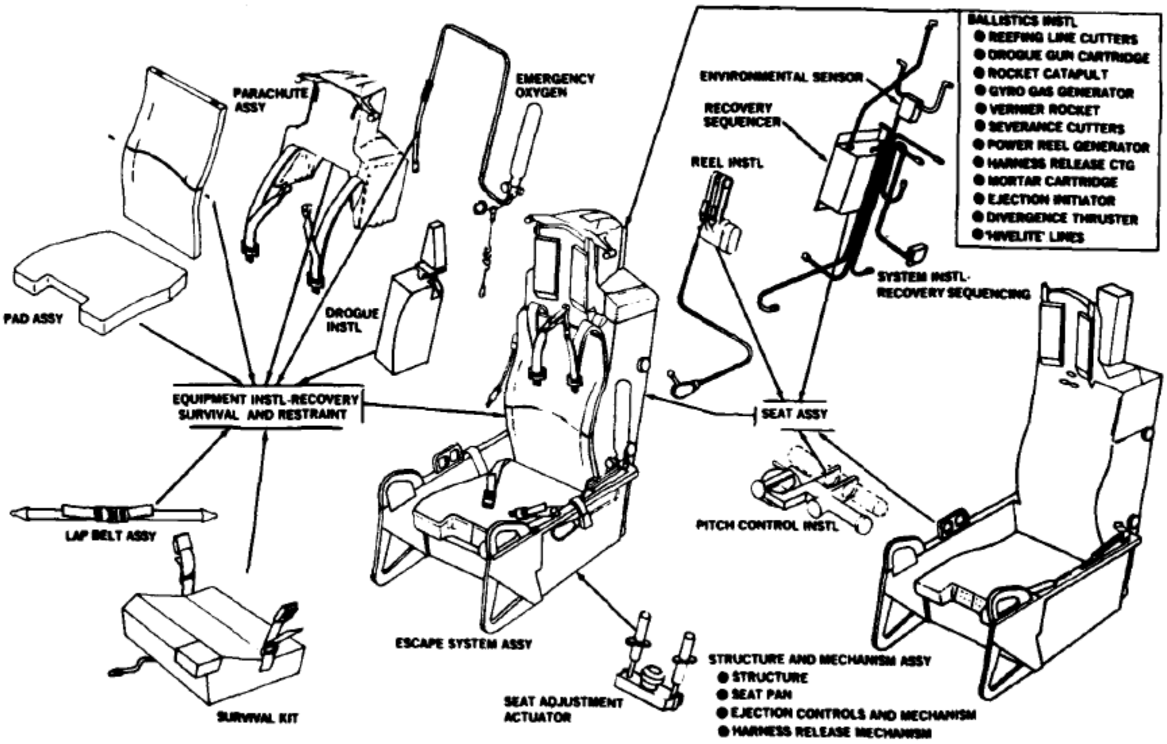


Figure 17: ACES II functional breakdown

The seat uses pyrotechnic actuation mechanisms and redundant electrical control circuits for high reliability. Vernier rockets provide stabilisation at low speeds and drogue provides stabilisation at high speeds. Drogue parachute is attached to allow for the highest shock loads in the "eye-balls out" orientation and reefing is used to minimise the shocks.

Ejection Sequence

1. Actuation of ejection control handles mounted on the sides or the centre energises the escape system.
2. The aircraft sequence selector valve directs gas pressure to power the inertial reel, to jettison the canopy and to ignite the rocket catapult.
3. The pressure from rocket catapult activates the recovery power sequence power supply.

4. Upon firing of the rocket catapult, the seat moves up the guide rails and the emergency oxygen system is activated.
5. As the pitot tube and pressure sensor are exposed to the Windstream, the recovery sequencer selects the appropriate mode for the environment.
6. A striker at the top of the guide rails initiates the recovery sequence which fires the STAPAC (vernier rocket motor for pitch stabilisation) system.
7. The further steps of the ejection sequence are dependent on the Operational Mode.

4.1 Operational Modes

As the seat as a wide deployment envelope, it has a built-in environmental sensing unit which is used to fire the seat in either of the 3 Modes shown below:

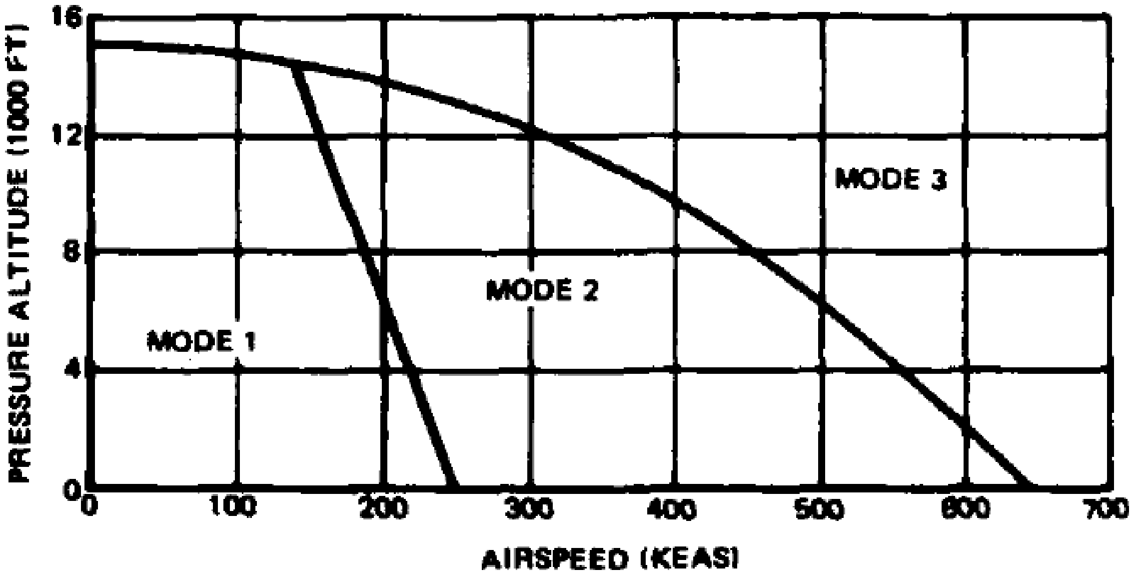


Figure 18: Mode Envelopes

The sequence of the 3 modes is described in the table below:

Table 1: Recovery sequence events and their timings of different modes

Sequence	Typical Event Timing	Time (Seconds)			
		Mode 1	Mode 2 (A-18)	Mode 2 (F-16)	Mode 3
1	**Rocket Catapult Fires**	0.00	0.00	0.00	0.00
2	**Drogue Deploys**	NA	0.17	0.17	0.17
3	**STAPAC Ignites**	0.18	0.18	0.18	0.18
4	**Parachute Deploys**	0.20	0.97	1.17	*
5	**Drogue Releases from Seat**	NA	1.12	1.32	*
6	**Seat Releases from Crewman**	0.45	1.22	1.42	*
7	**Parachute Inflates**	1.35	2.60	2.80	*
8	**Survival Equipment Deploys**	5.50	6.10	6.30	*

- *Sequence is interrupted until seat crosses Mode 3 boundary. Then Deploys Parachute after 0.8 Second Delay (A-10) or 1.0 second delay (F-15, F-16)

The electronic time delays are precise to +- 3%. The figures below provide an illustration of the 3 modes.

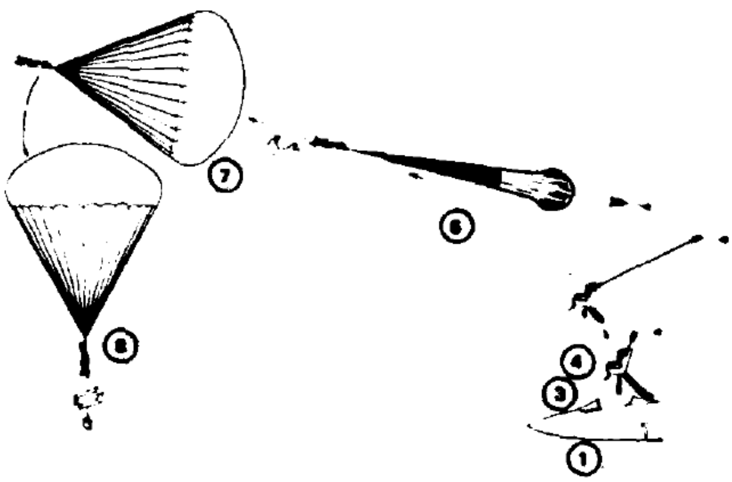


Figure 19: Mode 1 Operation

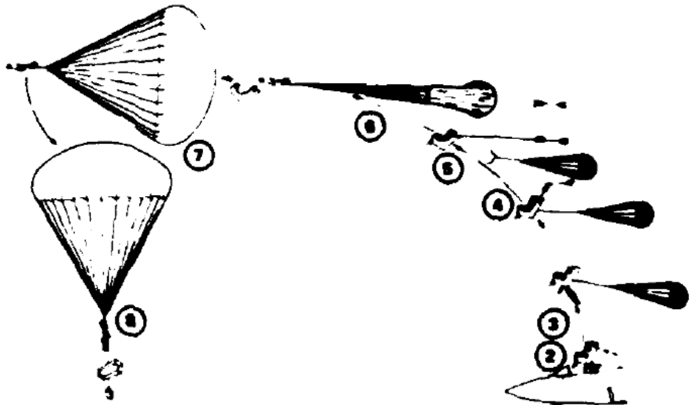


Figure 20: Mode 2 Operation

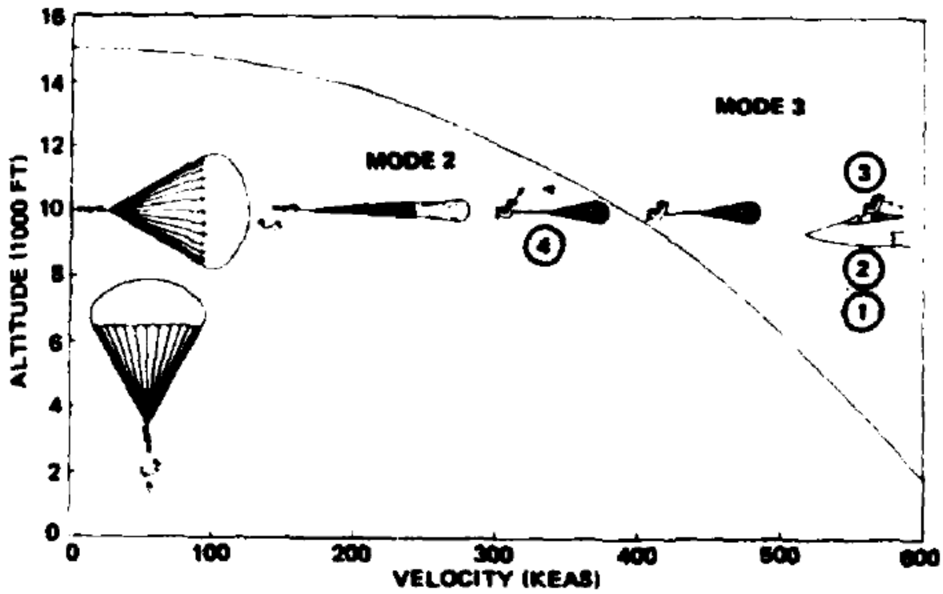


Figure 21: Mode 3 Operation

4.2 Key Ejection Seat Sub-systems

- **Firing Controls:** They are connected to a JAU8 initiator which sends a pressure signal to initiate the ejection system.
- **Propulsion:** A solid propellant powered CKU-5/A rocket catapult is used to eject the seat from the aircraft. Peak catapult acceleration is 12 g and seat velocity at end of catapult stroke is about 13m/s.

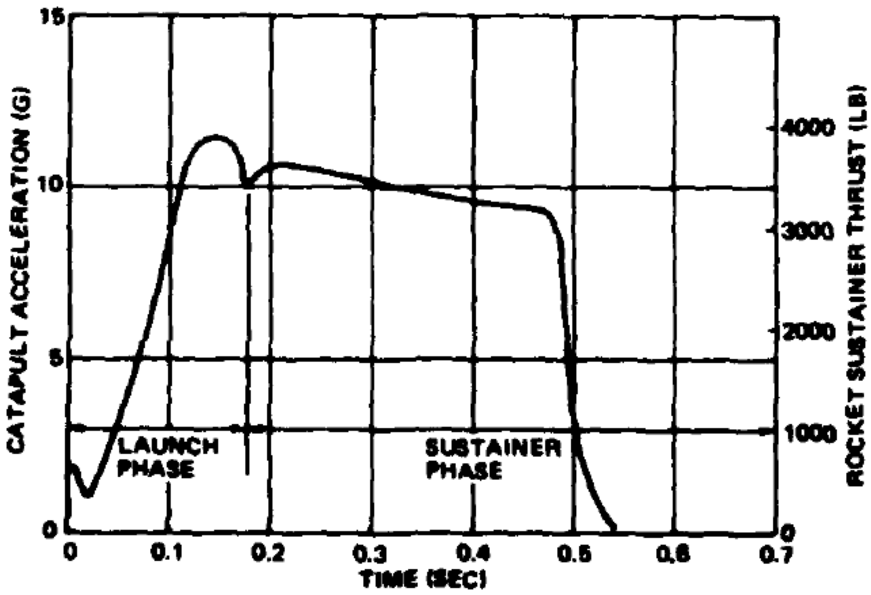


Figure 22: Typical rocket catapult acceleration and rocket motor thrust vs time curve

- **Pitch Control Sub-system**: STAPAC (vernier rockets) & a pitch-rate gyro is used to stabilise the ejection seat. The gyro is driven using an electrically actuated gas-generator.
- **Trajectory Divergence System (Multi-seat ejection):** A small rocket is used in the event of multiple ejection seats on an aircraft to cause the seats to roll in opposite directions resulting in subsequent lateral motion and trajectory displacement.

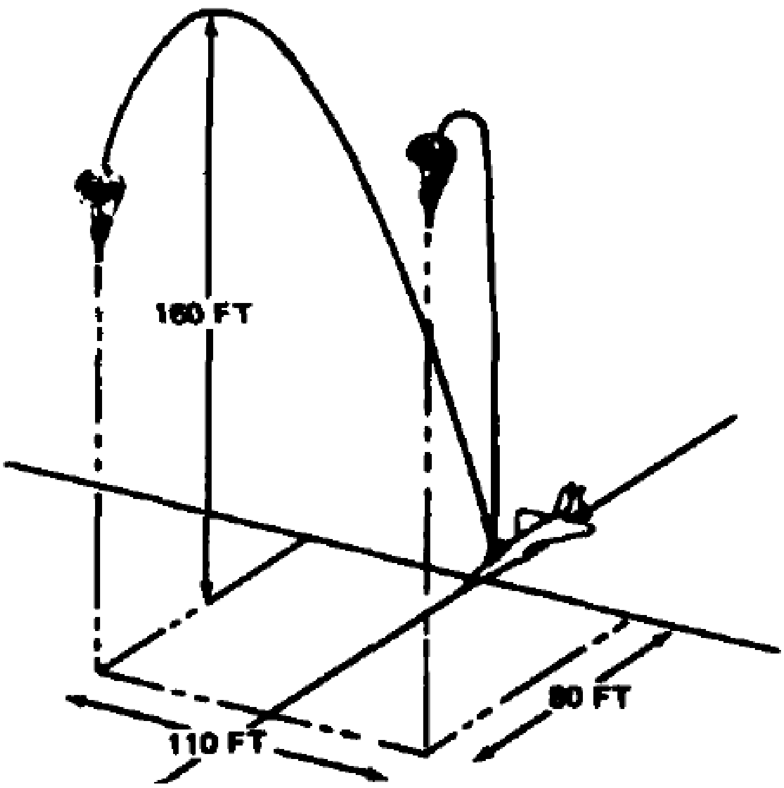


Figure 23: Divergent Trajectories

- **Drogue Parachute:** The goal of the drogue parachute is to stabilise the seat at high velocities. A Hemisflo parachute is used for its reliable performance at high Mach numbers and high dynamic pressures. The deceleration of a seat during drogue deployment is shown below:

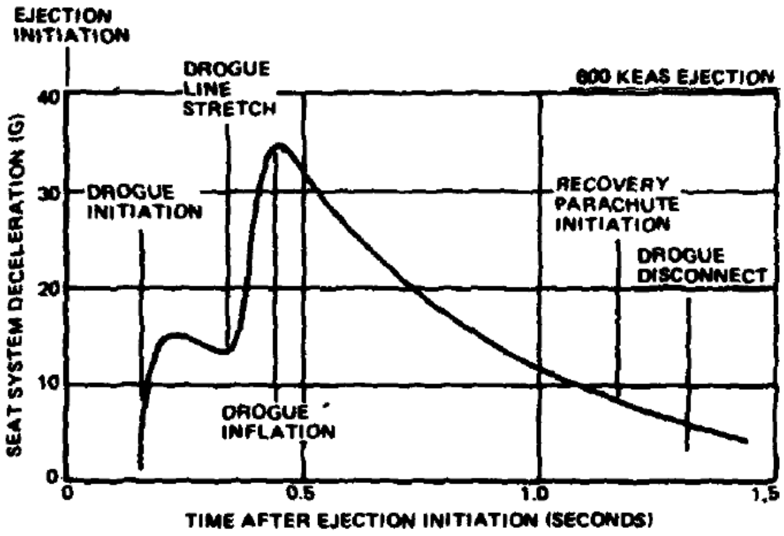


Figure 24: Typical seat deceleration during drogue operations

A slug gun fires a 2.0-foot Hemisflo extraction parachute. The extraction parachute in turn pulls a 5.0-foot Hemisflo drogue parachute as shown in the figure below.

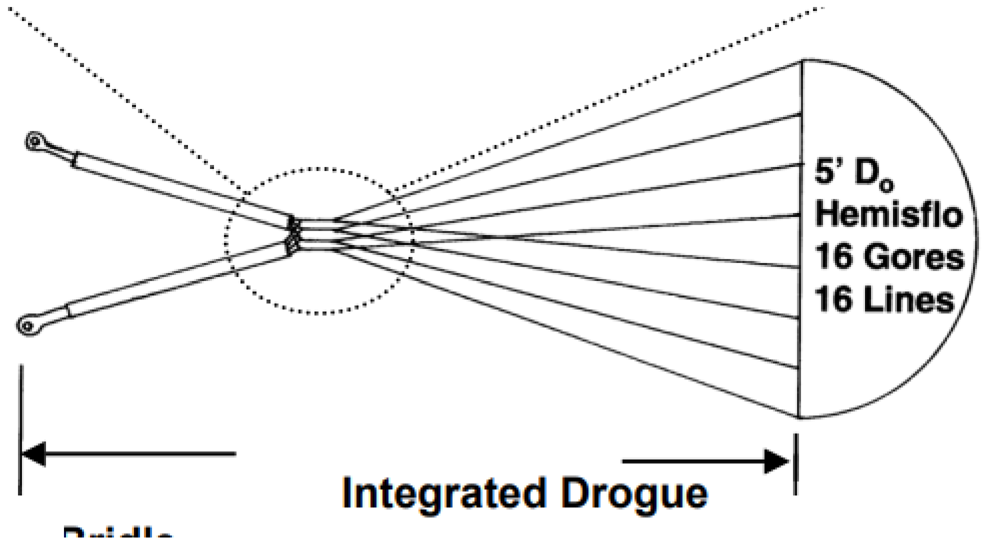


Figure 25: Hemisflo Drogue Configuration

In Product improvement programs it was identified that a faster deployment of drogue led to increased stability and lower shock loads.

In F-22, this was achieved using the FAST Drogue system which fired the 5.0-foot drogue using a mortar. Unfortunately, due to space limitations, a mortar wasn't feasible for other aircrafts and tractor rockets were selected as part of the Enhanced Drogue Configuration which directly deployed the drogue at faster velocities than the slug gun. The Enhanced drogue configuration is shown in the figure below:

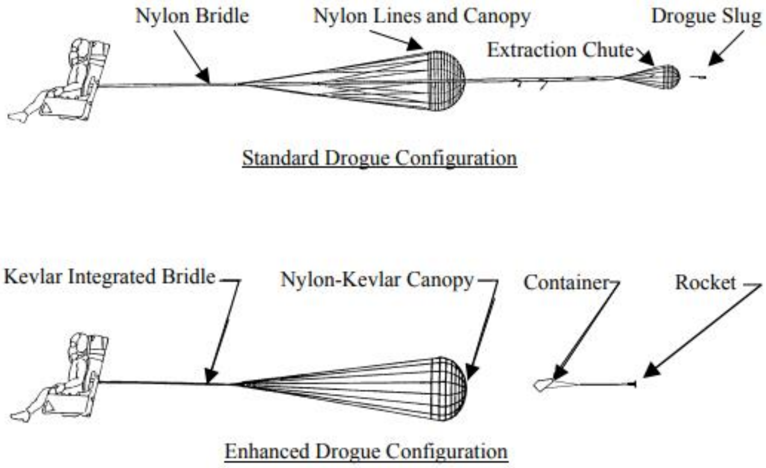


Figure 26: Standard Drogue vs Enhanced Drogue Configuration

The difference in the opening time & the MDRC (Multi-axial dynamic response criteria) risk of using different drogue deployment methods is displayed below. It can be observed that the mortar and the traction rocket were able to achieve significantly lower opening times than the slug gun.

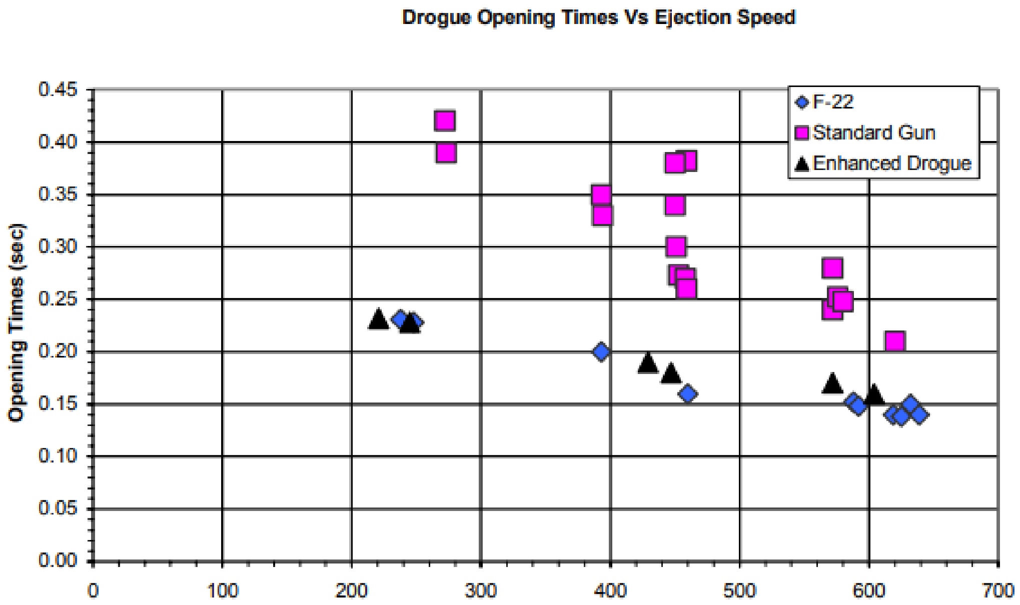


Figure 27: Comparison of ACES II Drogue Opening Times

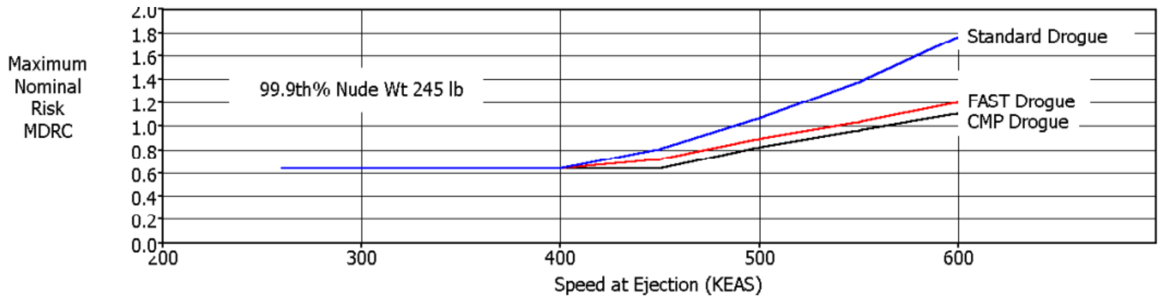


Figure 28: MDRC (Multi-axial Dynamic Response Criteria) risk of different drogue deployment methods

- **Recovery Parachute**: A reefed 28-foot C-9 canopy mortar deployed parachute is used as the main parachute for final recovery. There is an additional spring powered pilot chute to extract the main parachute from its bag. The mortar deploys the main parachute assembly at a speed of about 18m/s.

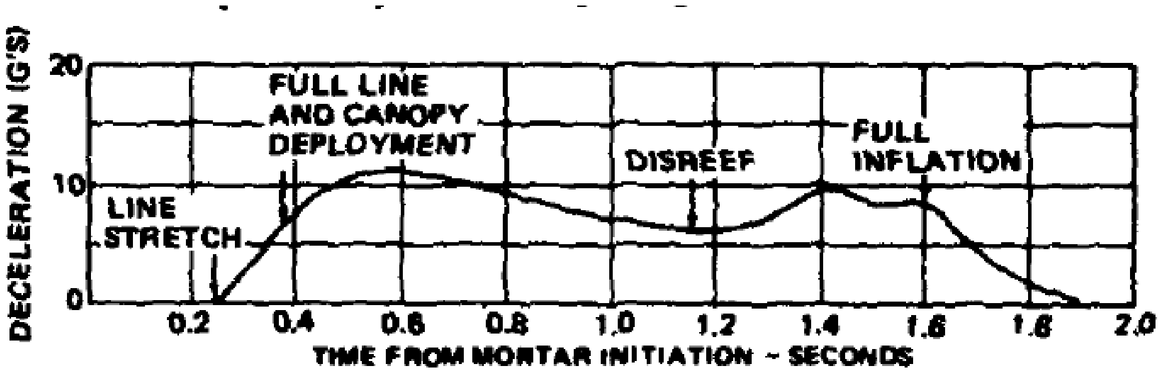


Figure 29: Typical Main Parachute Deceleration Curve

- **Recovery Sequencing Subsystem:** It consists of an environmental sensing unit and a recovery sequencer. The environmental sensing unit uses pitot tubes and pressure signals to provide the inputs for selecting the deployment mode. The original Analog recovery sequencer was replaced by a digital one in mid-2000s after rigorous testing.
- **Restraint Provisions:** A lap belt and powered inertial reel restrain the pilot during ejection. Further improvements to the restraint system have been conducted in improvement programs to include net-based hand restraints.