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"Minimizing the Sequenced Delay Time for Escape from High-Speed Flight Profiles"

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NORTH ATLANTIC TREATY ORGANIZATION

MINIMIZING THE SEQUENCED DELAY TIME FOR ESCAPE FROM HIGH-SPEED, LOW-LEVEL FLIGHT PROFILES

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The time delay that occurs between the actuation of an escape system and the actual initiation of the ejection catapult acceleration to separate the crew from an aircraft is one of the critical factors in the design of escape systems for high-speed low-level (HSLL) flight conditions. This delay may preclude what could otherwise be a successful escape from certain HSLL profiles. The purpose of this paper is to examine the significance of current operational delay times and describe techniques to minimize the delays. Operational through-the-canopy ejection data are presented to assess the risk of injury incurred in eliminating the delay time altogether. Experimental data from tests with human volunteers are presented to demonstrate the potential for significantly reducing the time required for upper torso retraction. Finally, the implications of available aeromedical evidence are evaluated in the definition of the most promising approaches to minimize the time required for a HSLL escape sequence.

INTRODUCTION

The problem of providing a successful means of escape from a disabled aircraft is quite severe when the aircraft is operating in the high-speed low-level (HSLL) flight regime. Many contemporary escape systems are capable of providing survivable ejection from a variety of flight profiles, including an aircraft parked on the ramp or one flying at high speed and high altitude. However, when high speed and low altitude are confronted in combination, these same systems may function poorly. This result derives primarily from considerations of available time. Low altitudes and high speeds imply the potential for ground contact before the escape system can complete its function. The circumstances are particularly crucial in the face of other adverse factors such as terrain variations, high sink rates, or unstable flight conditions.

A timely decision to eject is particularly important in the HSLL regime. However, once that decision has been made (either by the pilot or by an automatic system) the crewmember must usually remain in the aircraft unwillingly while the pre-ejection sequence takes place. This period typically involves approximately 300 milliseconds, during which the canopy may be jettisoned and the upper torso and/or extremities pre-positioned for ejection. When these activities are completed, the seated crewmember is accelerated out of the aircraft. It must be emphasized that this 300 milliseconds is added to variable delays associated with recognition of the emergency, decision making, attempts at corrective action (if any), and actuation of the escape system.(1) The interaction of the various escape factors is diagrammed in Figure 1. Several of the factors will be discussed in greater detail later in this paper.

In a high performance aircraft, 300 milliseconds can be a significant period of time depending upon situational variables such as the nature of the aircraft emergency and the component of aircraft closing velocity with an obstruction. If the aircraft is breaking up or departing from stable flight, much can be said for exiting the aircraft promptly, even at high altitude. When the aircraft is approaching an obstruction, successful ejection must generally occur well before aircraft impact since the ejected mass must clear the aircraft, decelerate, and accomplish parachute deployment before its residual velocity carries it into the obstruction as well. As an example of the significance of a 300 millisecond delay, it can be seen that an aircraft moving at a velocity of 400 knots will travel approximately 200 feet in 300 milliseconds. At 600 knots, the distance covered will be approximately 300 feet. The critical parameter is not the scalar speed, however, but the vector component of velocity in the direction of the most serious obstruction. In the majority of cases, the aircraft vector velocity is such that a significant velocity component is parallel to the obstruction. In order for the 300 millisecond delay to be significant in determining successful ejection, the trajectory must be such that, with the delay, an otherwise survivable ejection is compromised. One simplified way to assess the importance of this parameter may be seen in Figure 2. The maximum recoverable dive angles are plotted as a function of speed for various altitudes, with and without the 300 millisecond delay. These figures are computed from published performance data for the A-10 ejection seat in the high speed mode at 0° roll.(2) Each shaded area represents the range of constant dive angles at that altitude for which the 300 millisecond delay is decisive. For each altitude, dive angles above the shaded area are all non-recoverable ejections. Dive angles below the shaded area are all recoverable ejections, with or without the delay. At 300 feet, it can be seen that the dive angles for which the delay is decisive are limited to a 3.5° to 5.5° band, depending on the aircraft speed. For example, at 450 knots, the delay is decisive only for constant dive angles between 15° and 18.5°. On either side of that band in this simplified case, the outcome is independent of the presence or absence of a 300 millisecond delay. As altitude increases, the delay at first becomes more significant, as at 700 feet in which the critical band ranges from 8.5° to 20° depending on the speed. For example, at 250 knots, the delay is decisive for constant dive angles between 63° and 83°. Here, however, the dive angles involved are much steeper, and consequently less often encountered. As ejection altitude is increased still more, the presence or absence of the delay eventually becomes completely inconsequential with respect to terrain impact avoidance.

Similar families of curves can be generated for other flight profiles, incorporating various roll angles, roll rates, or more complex trajectories such as a parabolic curve with increasing dive angle. Such analyses will continue to demonstrate that the 300 millisecond delay is decisive in only a small percentage of potential ejection trajectories. This remains true since the delay is significantly smaller than the time from ejection initiation to parachute opening. During this time, the ejected mass

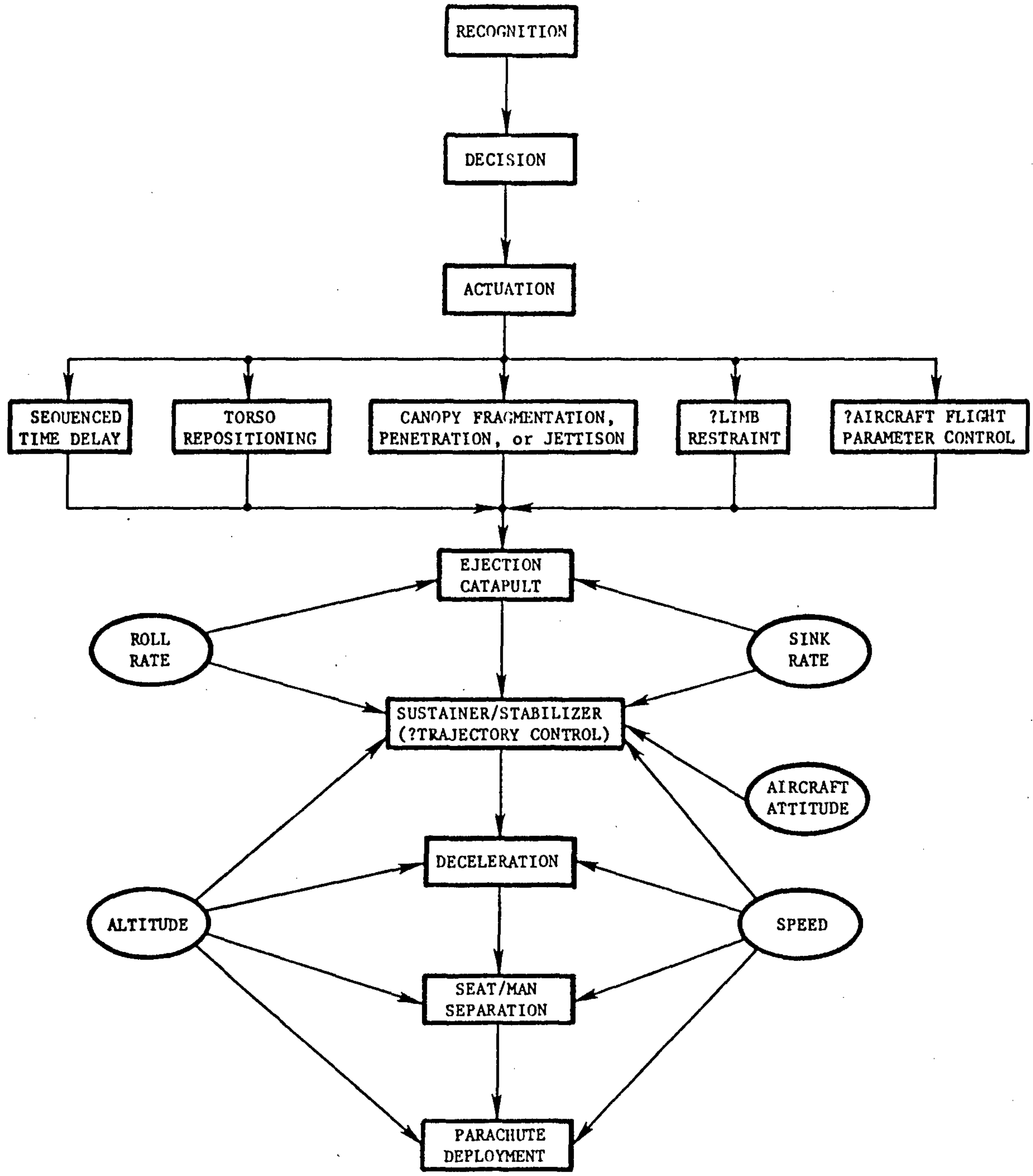


Figure 1. EJECTION SEQUENCE FLOW CHART

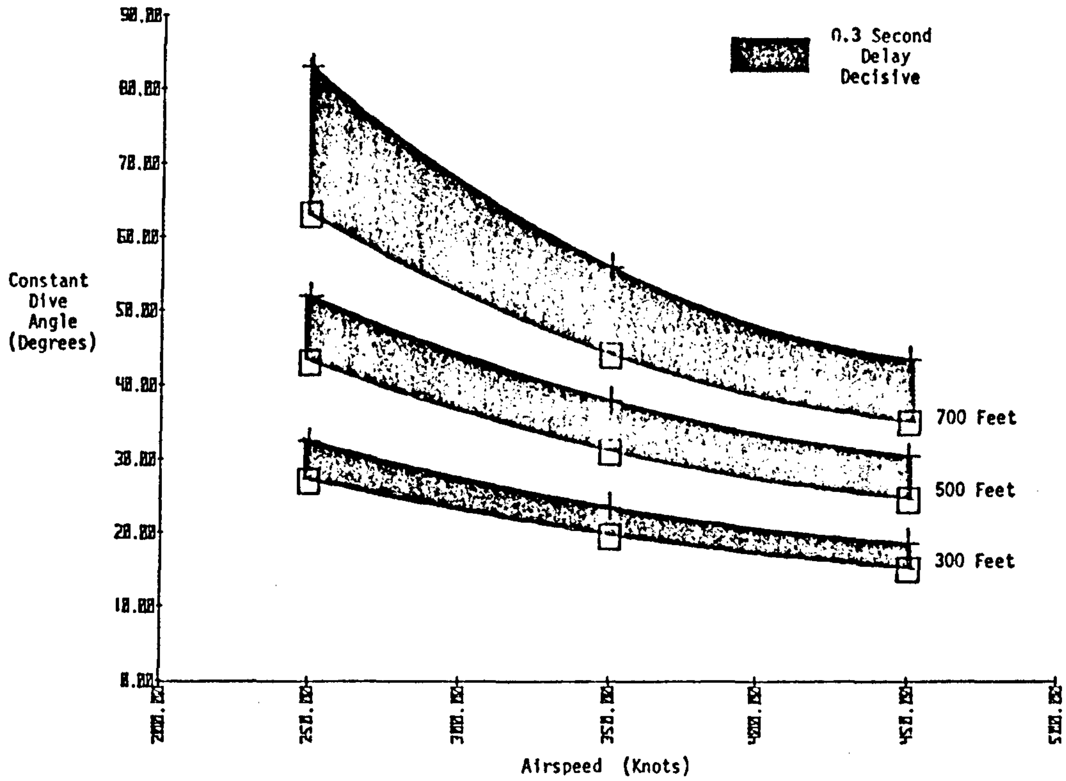


Figure 2. TRAJECTORIES FOR WHICH 0.3 SECOND DELAY IS DECISIVE

may travel great distances in the direction of the aircraft flight path at ejection. This is precisely why techniques which delay parachute opening in order to produce complex trajectory changes may be deleterious in some cases. The difficulty is most easily seen with trajectories in which the closing velocity with the ground is greater than can be overcome by the available ejection seat thrust and in which the initial ejection direction is already favorable, which is usually the case.

Therefore, when we consider a problem such as the 300 millisecond delay which is expected to be decisive in only a small minority of potential ejection scenarios, we must take great care to avoid instituting a solution to the problem which would compromise safe performance of the escape system in the majority of situations.

TECHNIQUES FOR FASTER EJECTION

The sequenced delay problem could be attacked by reducing the effects of the delay, reducing the delay, or by a combination of both. The potential for reducing the effects of the delay will be briefly examined first. The techniques will include more rapid escape system actuation and aircraft trajectory modifications before and after escape system actuation.

In spite of the significance of the short time intervals of the ejection sequence, it remains true that the most significant delays occur prior to ejection sequence initiation. These delays occur as a result of the time required to recognize an emergency, decide on a course of action, and initiate escape. Furthermore, the course of action may include one or more attempts at corrective efforts which involve further reaction times to accomplish these efforts and assess results. The importance of a timely decision to eject is frequently stressed to aircrew members, and appropriately so. However, significant benefits may be realized by automatic systems to facilitate this function, particularly in the HSLL flight environment. An example of this approach is the pitch-up maneuver that is automatically engaged when failure is detected in a terrain following autopilot. This maneuver allows the crewmember additional time for assessment and, if necessary, escape initiation. More sophisticated sensing of aircraft flight parameters and terrain clearance could allow automatic initiation of emergency aircraft maneuvers, short of actual ejection, even when the aircraft is being manually flown. The philosophy for such systems would require special attention to limit their actuation to situations in which a clear departure from controlled flight has occurred. Optional manual initiation could be employed. Their function could be to deploy speedbrakes and seek to gain favorable altitude and flight path with respect to terrain. Actual ejection initiation could be left to the pilot or accomplished automatically in clearly irrecoverable departures from controlled flight. Such systems may allow safe recovery from otherwise impossible situations. Their use seems more reasonable under HSLL flight conditions when it is recalled from Figure 1 that a 19° dive angle leads to an irrecoverable ejection from 300 feet at 450 knots, even without sequenced delay.

If consideration is limited to manual escape initiation, the aircraft may still be designed to automatically sense critical flight profiles, display warnings, and allow escape system actuation from the crewmember's flying position with minimum motion consistent with protection against inadvertent operation.

The basic intention of this paper will now be served by pursuing an examination of techniques to reduce the 300 millisecond sequenced delay time. Since the delay is normally used to jettison the canopy and accomplish upper torso repositioning, reducing the delay must affect the performance of both functions. Three basic approaches suggest themselves:

1. Decrease canopy removal time;
   Decrease torso repositioning time.

2. Eliminate canopy removal;
   Decrease torso repositioning time.

3. Eliminate canopy removal;
   Eliminate torso repositioning.

A fourth permutation (decrease canopy removal time, eliminate torso repositioning) can be discarded if it is assumed that torso repositioning is desirable and that it can be accomplished at least as rapidly as a faster canopy removal. An additional assumption is that limb restraint must not necessarily be complete before firing of the ejection catapult.

Strictly from time considerations, the third alternative appears preferable since it allows immediate ejection initiation with system actuation. However, based on conclusions from the previous discussion, such a "solution" would only be preferable if the improvements to be realized outweighed any costs to be incurred in terms of ejection morbidity and mortality. The improvements to be realized cannot be clearly quantified without a knowledge of the population statistics of the ejection parameters to be encountered in future HSLL operations. From the previous analysis, however, it could reasonably be expected that the delay will be critical in a minority of cases. On the other hand, it is intuitively desirable to increase the safe ejection envelope, by no matter how small an amount, with the expectation that it will help sooner or later. The basic question is then related to the possible costs incurred in eliminating upper torso retraction and ejecting immediately through the canopy.

THROUGH-THE-CANOPY INJURY DATA

Operational data are available to assess the experience with several through-the-canopy (TTC) ejection systems in which upper torso retraction was not performed. These data were analyzed in order to assess the potential risk associated with a proposed modification to a low-level aircraft which would introduce a TTC system as the primary escape mode. Figure 3 demonstrates a comparison of the results of 16 pairs of ejections from the United States Navy A-6 aircraft.(3) The pairs were formed by utilizing 16 available canopy jettison ejections and obtaining a best match for altitude and speed at ejection from among 114 ejections through-the-canopy. The adequacy of the matching can be seen in Table 1. The summary in Figure 3 indicates significantly increased injury rates for lacerations in the TTC data ($p = 0.1$). Spinal fractures appear to be increased in the TTC data but are not found to be significant at the 90% confidence level for this small sample. A similar match was performed using 22 non-fatal TTC ejections from the United States Navy A7 aircraft (3). These were matched with A7 canopy jettison data from among 152 ejections. The matched parameters are shown in Table 2 and the injury comparison in Figure 4. In this case, the TTC ejections showed a significantly increased rate of spinal fractures ($p = 0.1$) and lacerations ($p = 0.05$).

These data are particularly significant when the ejection equipment is taken into account. In both comparisons the TTC system had milder ejection seat thrust profiles than did the canopy jettison systems. This should tend to produce fewer spinal injuries in the TTC experience but, in fact, the reverse was true.

A further interesting finding in these data was the distribution of spinal fractures observed. A total of 394 ejections were examined from a variety of United States Navy aircraft, including 224 TTC ejections. The resulting spinal fractures are summarized in Figure 5.(3) The bimodal distribution is in contradistinction to the large sample of United States Air Force spinal fracture data shown in Figure 6. (3) This data is modal about a peak which occurs in the lower thoracic-upper lumbar region. The mid-thoracic peak in some data samples has been previously reported elsewhere, (4) but in this sample was found to derive largely from the TTC systems. A similar mid-thoracic peak has been claimed for Air Force F/FB-111 and F-4 ejection data.(4,5) Surprisely, available data from 64 United States Air Force inadvertent TTC ejections did not demonstrate the mid-thoracic peak (Figure 7).(3)

The operational injury data does not delineate cause and effect mechanisms; however, it does indicate that a cost in terms of morbidity and mortality may be incurred when the sequenced delay time is eliminated altogether. The cost may well be out of proportion to the small benefit to be gained from eliminating the delay. This cost may derive from ejecting through the canopy or from failing to retract the upper torso or from a combination of the two. If the source of spinal injury is related to ejecting through the canopy, the question remains as to the mechanism of injury production. Downward loading through the head or shoulders may be implicated. Alternatively, temporary retardation of the seat, as it forces its way through canopy material, could produce a surge in the acceleration of the seat and, therefore, the force transmitted to the spine through the seat pan. A third possibility is flexion of the spine during catapult firing in the absence of windblast force until clearing the canopy. This mechanism is based on the supposition that the head and torso of the ejectee are benefited by the restraining force of aerodynamic pressure acting on the ejectee after canopy jettisoning. Newer approaches to TTC ejection incorporate various designs of canopy weakening or canopy fragmenting pyrotechnics using mild detonating cord (MDC). Whatever the postulated mechanism of injury, it would appear that active dispersal of the canopy by a pyrotechnic system would minimize the likelihood of the canopy being a contributor if a clear path for the seat/man combination could be provided.

Without a clear definition of cause and effect in the observed injury data, it is unlikely that a test approach could be proposed which would prospectively assure that a given TTC system would not produce similar injuries. The best that can be reasonably expected would be to design a system which avoids the imposition of forces that appear most likely to be implicated and await an operational assessment.

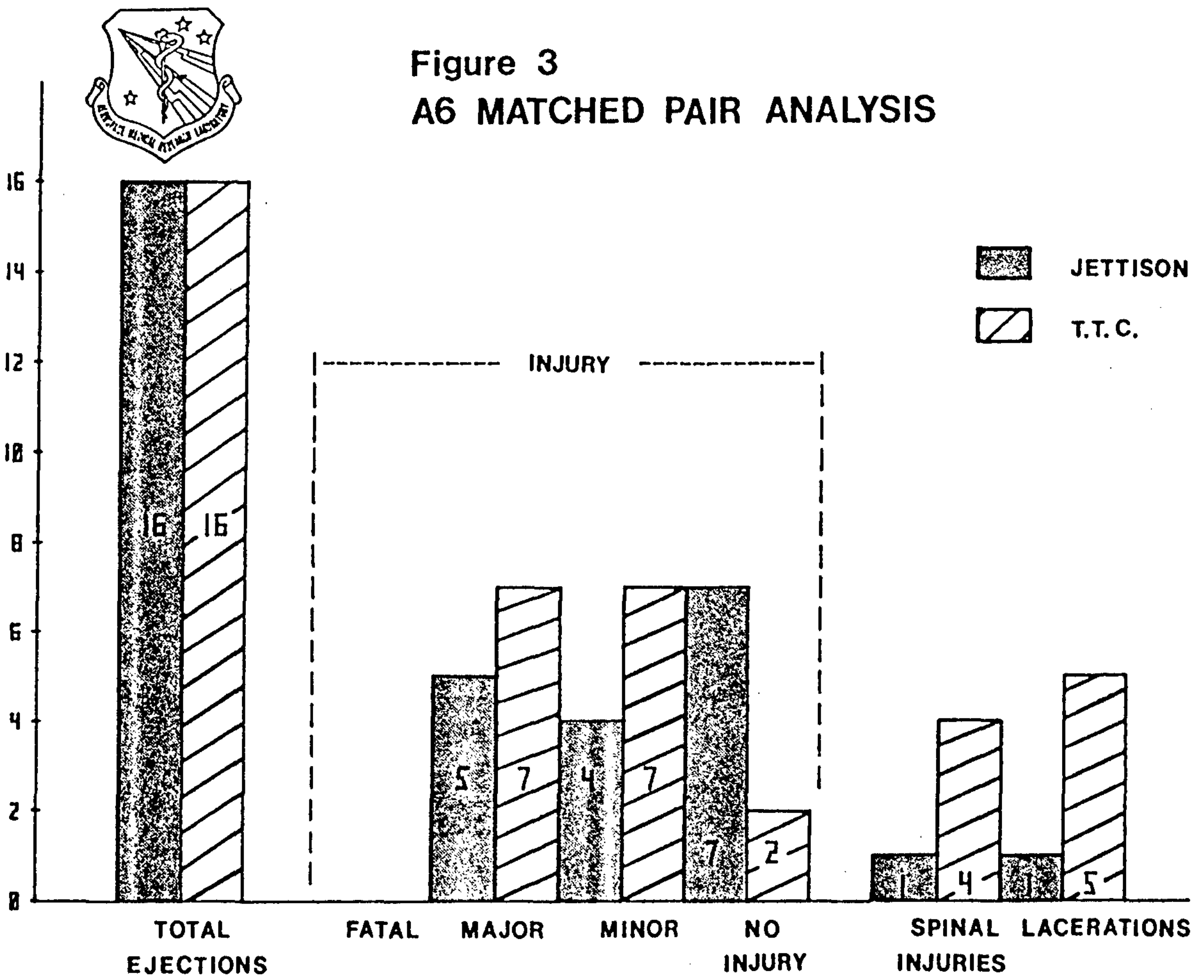


Figure 3
A6 MATCHED PAIR ANALYSIS
JETTISON
T.T.C.
INJURY
16
14
12
10
8
6
4
2
0
16
16
5
7
4
7
7
2
1
4
1
5
TOTAL EJECTIONS
FATAL
MAJOR
MINOR
NO INJURY
SPINAL INJURIES
LACERATIONS

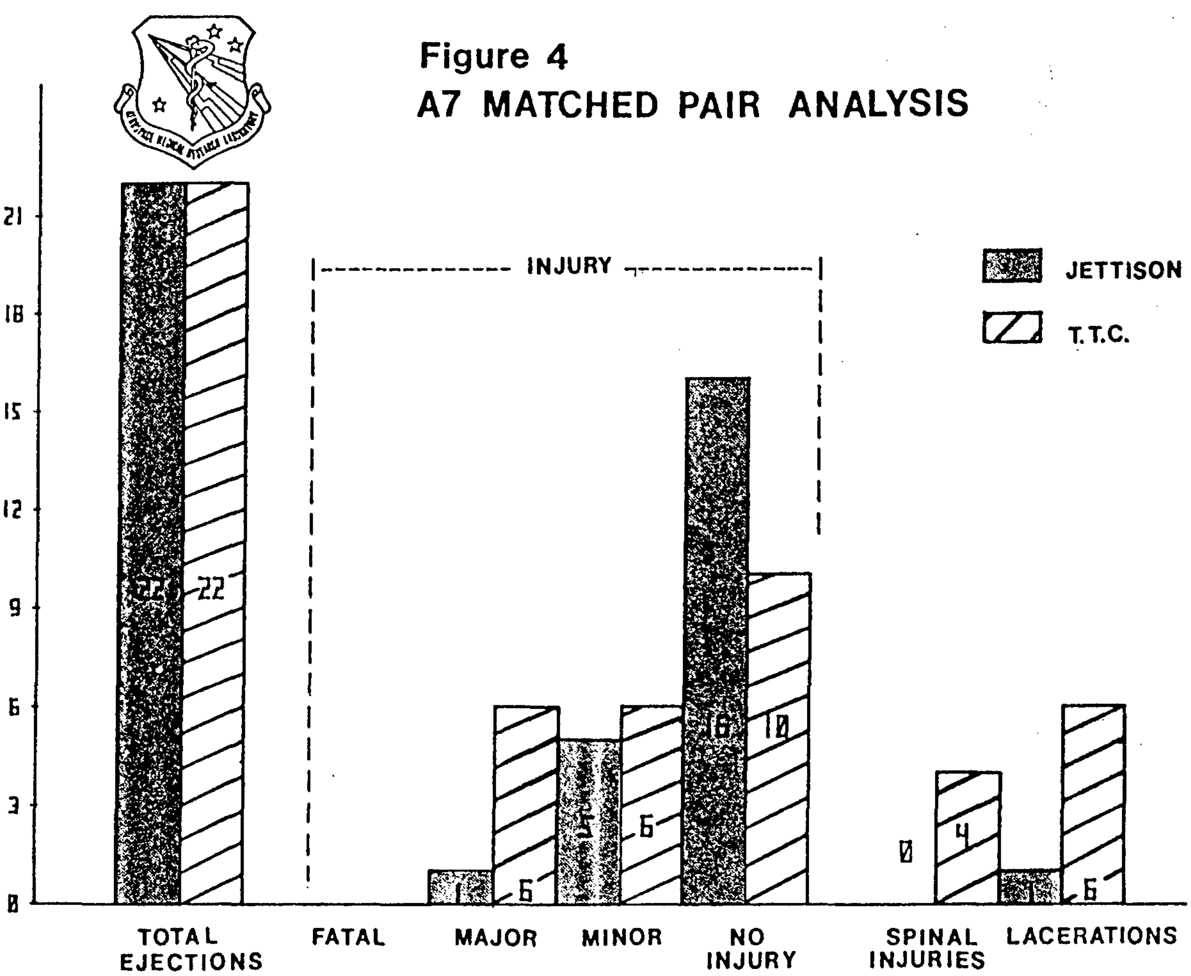


Figure 4
A7 MATCHED PAIR ANALYSIS
JETTISON
T.T.C.
INJURY
21
18
15
12
9
6
3
0
22
22
1
6
5
6
16
10
0
4
1
6
TOTAL EJECTIONS
FATAL
MAJOR
MINOR
NO INJURY
SPINAL INJURIES
LACERATIONS

Figure 5
KNOWN SPINAL FRACTURE LOCATIONS (NAVY)

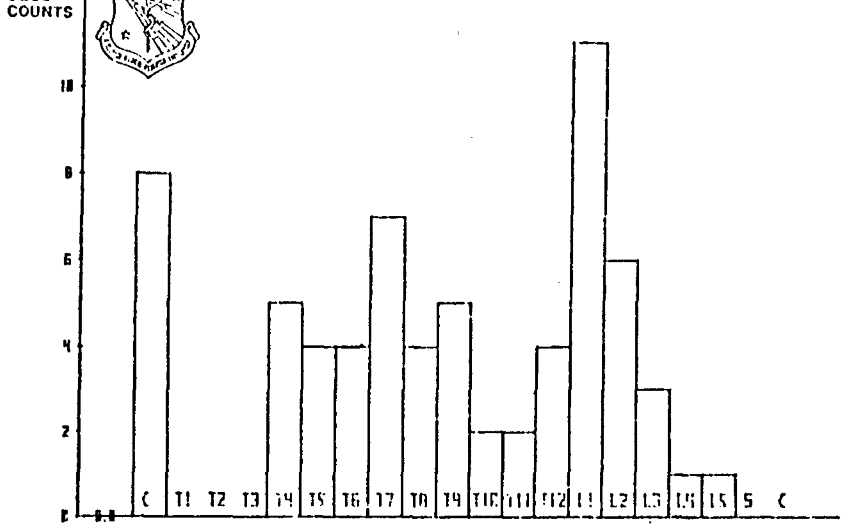


Figure 6
KNOWN SPINAL FRACTURE LOCATIONS (AIR FORCE)
(1964-1970)

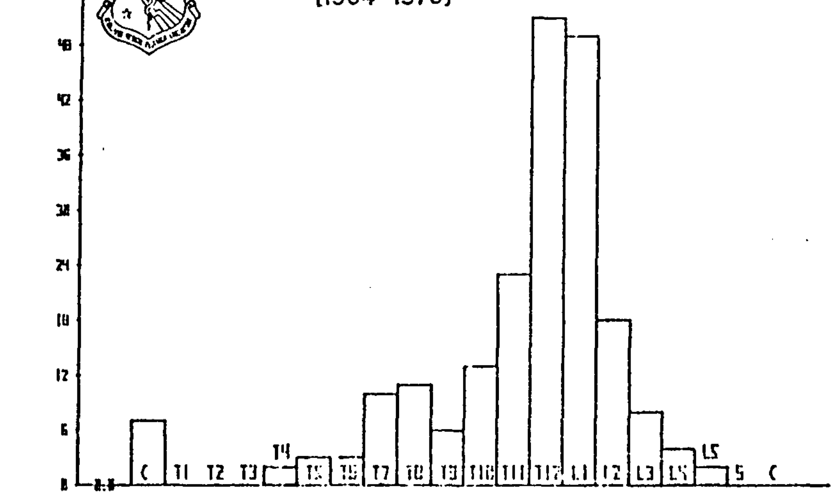
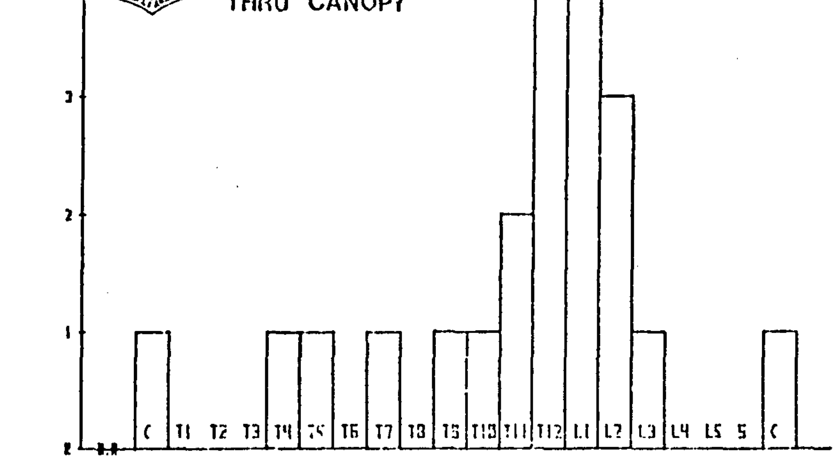


Figure 7
KNOWN SPINAL FRACTURE LOCATIONS (AIR FORCE)
UNPLANNED
THRU CANOPY



An alternative to the TTC approach is more rapid canopy removal. Some newer systems achieve this, but the residual time delay penalty seems to be about 160 milliseconds even at high speed. The most desirable system would produce a greater decrease in the delay. Since we are dealing with a problem where a solution may yield only a small benefit, it seems ill-advised to spend large sums to correct half of it.

TORSO RETRACTION EXPERIMENTAL DATA

Turning to the problem of upper torso retraction, current ballistic inertia reel specifications appear to be based on present canopy removal times rather than on human tolerance to the retraction provided by the reel.(6) In order to assess the potential for shortening this time, a series of human volunteer tests was performed at the Aerospace Medical Research Laboratory (AMRL) at Wright-Patterson Air Force Base, Ohio. These tests included 179 human exposures during the period from January 1978 to April 1979.

The AMRL Body Positioning and Restraint Device (BPRD) was used to accomplish upper torso retraction. The BPRD is a hydraulically actuated retraction system designed to simulate the force-time history of a powered inertia reel.(6) The subject wore a helmet and USAF restraint harness and was seated on an instrumented seat which allowed recording of the inertial forces reacted by the subject into the seat pan and seat back. The subject was restrained by a conventional seat belt and torso harness. Force transducers were used to measure loading applied to the subject. The shoulder straps were attached to the torso harness using standard Koch fittings. The other ends of the shoulder harness were attached to the retraction cable of the BPRD. The cable was extended by a measured amount prior to each test. The subject was asked to lean into the harness and maintain 10 to 20 pounds of force to simulate the normal reel retraction tension. The actual value was displayed to the subject on a digital meter. The signal was derived from a force cell linked to the retraction cable. At initiation, the subject was retracted by the hydraulic actuator and impacted the instrumented seat back. Head and chest accelerations were approximated using triaxial accelerometer arrays applied over the subject's sternum and fixed to the maxillary teeth. Subjects participated no more often than once per week. Medical supervision included pre-test and post-test physical examinations and blood pressure measurements as well as continuous electrocardiographic monitoring with a medical officer in attendance. Twenty-two subjects participated during various stages of the program, 20 males and 2 females. Each subject followed a sequence of gradually increasing retraction lengths and/or hydraulic pressures. A sequence of pictures illustrating a typical retraction is included as Figures 8-11.

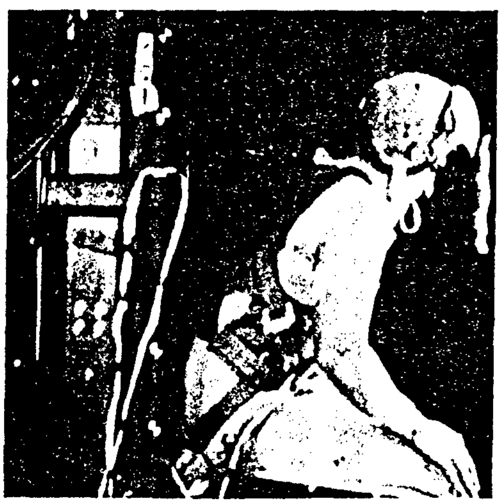


Figure 8
0 Milliseconds

Figure 9
49 Milliseconds

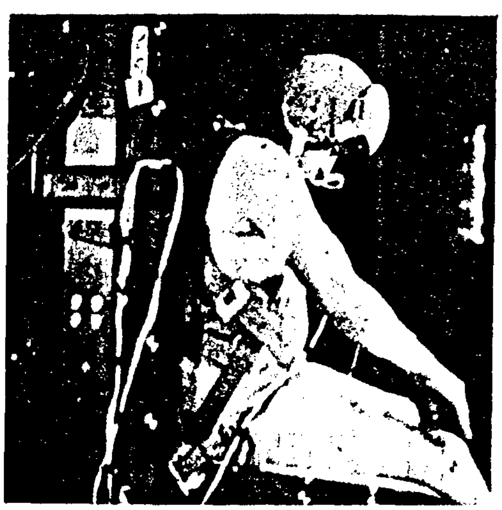


Figure 10
101 Milliseconds

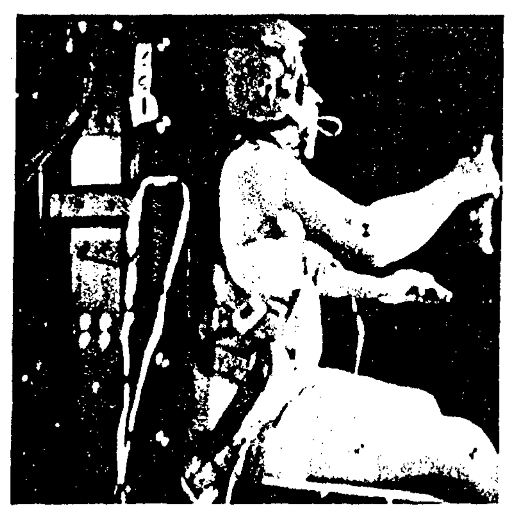


Figure 11
139 Milliseconds

10 INCH (25.4 CM) RETRACTION SEQUENCE

Although operational reels generally provide 18 inches (45.7 cm) of retractable length, it has been found that a portion of that length is used in order to extend the shoulder straps to reach the attachment fittings of the torso harness. The practical maximum retraction distance is approximately 14 to 15 inches for a crewmember grossly out of position. Such a situation is probably most likely in a multiseat aircraft in which a crewmember may be ejected unprepared in an aircraft undergoing high G maneuvers, or in an accidental or automatic ejection. The AMRL experiments investigated retraction distances of 10, 12, and 14 inches (25.4, 30.5, and 35.6 cm).

The results of these tests indicated that retraction of the human torso in a one G field could be safely performed in much less than 300 milliseconds even through large distances approximating the maximum extention of a typical reel. The means and standard deviations for selected parameters are presented in Table 3. (The "PSI" notation denotes the hydraulic pressure used to produce the retraction). Figure 12 presents a plot of peak cable force versus retraction time. It can be seen that a point of diminishing returns is eventually reached in which large increases in cable force produce only small decreases in retraction time. All measured parameters appear to be well within human tolerance. The subjects tolerated the procedure well in all cases and generally reported enjoying the experience.

Several other points are worthy of note. The retraction time was defined as the time from the onset of cable force to the peak of seat back force. Approximately 10 milliseconds should be added to the reported retraction times to allow for the uncertainties in the timing of the pyrotechnic element in the inertia reel. Peak seat back force appeared to be a reasonable retraction completion criterion. Some subjects had continuing head erection movement following this point, but others maintained a head-forward position. The optimum time for ejection initiation, therefore, could not be based on head orientation after retraction. This would be particularly true in retracting a subject whose torso was already on the seat back.

One experimental condition purposely did not reproduce an operational retraction. In our tests, the subject was fastened to the cable with the piston fully retracted and adjusted for comfort. This assured that no significant afterload would be placed on the subject by the hydraulics after retraction. Such is not the case in the cockpit since the inertia reel generally does produce an afterload. A future test series is planned at AMRL with applied afterloads. It is anticipated that the forces and accelerations at seat back contact in this case will be more severe. It should be recognized however, that although the reported experiment does not duplicate the operational system in all respects, the operational configuration could be made to duplicate the experiment, if desired, by a procedural change and the provision of adjusters on the harness.

A final point concerns head impact against the backrest at the end of retraction. During developmental tests for the human test series, anthropomorphic dummies were utilized to determine expected force levels. The dummies experienced head impacts in the range of planned human exposures. Some of the impacts were of such great force that helmet fractures occurred. Our analysis indicated that active neck muscular effects in the human would significantly reduce the head velocity at impact allowing a safe exposure. Furthermore, human tests at low levels indicated that the dummy tests predicted higher accelerations than were observed with volunteers. We therefore proceeded with the planned exposures and, to our surprise, observed no significant head impacts at all. This points up once again the critical need for continued live human subject testing. Particularly when designing systems intended to be safe, knowledgeable developmental testing with living subjects can yield invaluable data for optimized designs, allowing demonstrated safe performance at levels which would appear to be injury levels using dummies, human cadavers, or animals.

Table 3. RETRACTION TEST PARAMETERS

	Retraction Length 10 Inches		Retraction Length 12 Inches		Retraction Length 14 Inches	
	600 PSI	900 PSI	600 PSI	900 PSI	600 PSI	900 PSI
1. Retraction Time (Seconds)	148 (8.2)	134 (11.5)	167 (9)	144 (9)	190 (12)	158 (10)
2. Peak Cable Force (Pounds)	185 (24.3)	250 (28.5)	188 (19.4)	259 (35.6)	198 (24.3)	286 (34.9)
3. Average Reel Retraction Velocity (Feet/Second)	77.9 (2.4)	97.4 (2.7)	87.2 (2.3)	108.5 (4.1)	86.1 (2.5)	110.9 (3.5)
4. Peak Seat Pan Force (Pounds)	75 (18)	102 (23.4)	96 (21)	118 (34)	109 (31)	146 (40)
5. Peak Lower Back Force (Pounds)	*	*	91.2 (41.1)	86.2 (41.4)	106.3 (31.8)	109 (29.8)
6. Peak Upper Back Force (Pounds)	354 (71)	466 (70.6)	365 (77.8)	512.4 (111.2)	326.3 (48.7)	463 (106.6)
7. Peak Chest Acceleration						
a. Retraction (G's)	7.2 (1.4)	11.6 (1.5)	8.2 (1.9)	11.8 (2.6)	6.9 (1.4)	11.5 (2.1)
b. Seat Back Impact (G's)	7.5 (1.2)	11.9 (1.9)	10.6 (2.9)	15.4 (3.4)	9.2 (3.4)	13.3 (2.6)
8. Peak Head Acceleration						
a. Retraction Acceleration (G's)	7.1 (1.8)	11.7 (3.0)	9.4 (2.6)	15.7 (4.5)	8.2 (2.1)	15.9 (5.4)
b. Deceleration (G's)	5.9 (2.3)	10.2 (3.3)	7.7 (1.2)	13.5 (3.5)	5.8 (1.3)	12.0 (2.2)

* No Data

Tabulated values are experimental means with the standard deviation in parentheses.

TABLE 1
NON-FATAL A6 MATCHED

	THROUGH-THE-CANOPY		CANOPY JETTISON	
	ALTITUDE	VELOCITY	ALTITUDE	VELOCITY
	2000	200	2000	200
	2000	200	2000	200
	2500	210	2000	200
	2500	210	2900	221
	800	135	900	120
	800	135	1000	120
	700	210	700	200
	500	180	600	200
	8000	225	5600	230
	8000	225	3800	215
	12000	250	12000	250
	13500	250	12000	250
	1800	180	1200	250
	1000	210	2500	250
	6000	320	2500	250
	6000	320	3000	250
MEAN	4256	216	3419	213
STD DEV	4189	52	3585	42

TABLE 2
NON-FATAL A7 MATCHED

	THROUGH-THE-CANOPY		CANOPY JETTISON	
	ALTITUDE	VELOCITY	ALTITUDE	VELOCITY
	60	30	60	15
	2000	150	2000	150
	7000	300	7800	290
	1200	220	1200	210
	7000	200	7000	200
	200	200	300	200
	1200	220	1200	220
	60	75	60	80
	4000	260	4000	275
	[illegible]	100	[illegible]	90
	2000	350	1900	300
	1000	165	1000	180
	[illegible]	10	[illegible]	30
	800	150	900	140
	8000	350	8000	350
	2000	350	3000	330
	[illegible]	130	[illegible]	125
	60	135	60	135
	150	150	150	150
	2000	180	2000	200
	800	160	900	170
	60	50	60	90
MEAN	1800	179	1890	179
STD DEV	2468	99	2558	91

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