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BIODYNAMIC RESPONSE TO WINDBLAST

D. H. Glaister

Advisory Group for Aerospace Research and Development

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15. Abstract

This volume contains the text, discussion and technical evaluation of papers presented at the AGARD Aerospace Medical Panel Specialists Meeting which was held at Toronto, Canada, 6 May 1975.

The specific problem of windblast was considered as it affects human tolerance to high-speed ejection.

Injury mechanisms were discussed in several papers and it was shown that most injuries are caused by excessive motion of the limbs, rather than by the direct effect of wind pressure. Ejection injury mechanisms were also considered in relation to windblast from conventional and nuclear explosions.

Protection was considered along two lines. The prevention of limb motion by means of restraints was shown to be as practical for the arms as for the legs, and could be extended to provide the arm retraction needed in safe command ejection. It was also shown that the provision of a stable ejection seat would greatly ameliorate the windblast problem.

The problems of head restraint and helmet loss were also considered. Loss was attributed to the aerodynamic lifting moment which had been measured in wind-tunnel tests, and could be reduced by appropriate aerodynamic design.

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

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BIODYNAMIC RESPONSE TO WINDBLAST

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Papers presented at the Aerospace Medical Panel Specialists
Meeting held at Toronto, Canada, 6 May 1975.

1-2

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SUMMARY

The specific problem of windblast was considered as it affects human tolerance to high-speed ejection. Statistical data from 5 nations proved the prevalence of windblast injury, particularly in the combat situation where ejection speeds are higher. Thus, an overall 5 - 10 percent injury rate rose to 40 percent or more.

Injury mechanisms were discussed in several papers and it was shown that most injuries are caused by excessive motion of the limbs, rather than by the direct effect of wind pressure. Ejection injury mechanisms were also considered in relation to windblast from conventional and nuclear explosions.

Protection was considered along two lines. The prevention of limb motion by means of restraints was shown to be as practical for the arms as for the legs, and could be extended to provide the arm retraction needed in safe command ejection. It was also shown that the provision of a stable ejection seat would greatly ameliorate the windblast problem.

The problems of head restraint and helmet loss were also considered. Loss was attributed to the aerodynamic lifting moment which had been measured in wind-tunnel tests, and could be reduced by appropriate aerodynamic design.

PREFACE

In June of 1971, the Aerospace Medical Panel held its specialists' meeting in Oporto, Portugal, on the subject of Linear Acceleration of Impact Type, a topic selected by the Biodynamics Committee of ASMP some two years earlier. Whilst most presentations relevant to ejection from aircraft related to injuries caused by catapult and rocket accelerations, two were concerned with windblast. The first reviewed the biodynamics of windblast, and serves as a useful introduction to the current conference proceedings, and the second concerned the blast testing of aircrew escape equipment (see AGARD Conference Proceedings No.80 on Linear Acceleration of Impact Type, papers 14 and A4). Among the recommendations which followed this meeting was the suggestion that further studies should be made of the mechanisms of injuries which result from accelerations acting along the ±Gx axes. In high-speed ejection, windblast leads initially to high levels of −Gx acceleration.

At a meeting held in Soesterberg in September 1973, the Biodynamics Committee of ASMP discussed possible topics for future meetings and noted that windblast still produced a relatively large number of injuries at ejections made over 300 kt, and considered that seat stability, harness configuration and personal equipment all contributed to this overall situation. They, therefore, proposed a specialist meeting to deal specifically with the biodynamic response to the windblast environment, and requested that their Deputy Chairman, Wing Commander David Glaister, RAF, act as organiser and chairman.

To this end a number of potential authors were contacted, with encouraging results, and a call for papers was circulated. Eventually, 10 papers were selected for presentation in a one day session of the 1975 Spring Specialists meeting of ASMP, to be hosted by the Defence and Civil Institute of Environmental Medicine in Toronto, Canada. These papers were arranged in three groups covering statistics and mechanics (papers B1, B2, B4 and B10), pathology (papers B5 and B6), and protection (papers B9, B7, B8 and B11). However, for convenience, they are presented here in numerical order and as there was a considerable amount of overlap in subject material, the division was indeed more theoretical than useful.

CONTENTS

TECHNICAL EVALUATION REPORT

The AGARD-NATO Aerospace Medical Panel Specialist Meeting on 'Biodynamic Response to Windblast' was held at the Defence and Civil Institute of Environmental Medicine, Toronto, Canada on May 6th 1975. The meeting lasted all day, but included a short tour of DCIEM at the end of the morning session, arranged by the Host Coordinator, Colonel A.C. Yelland. The ten papers which were presented were arranged, on the basis of their abstracts, into three groups to cover Statistics and Mechanics, Pathology, and Protection. In this way the subject matter introduced itself, after the chairman had briefly mentioned the disparity between the amount of research that had been carried out on the +Gz acceleration of the ejection gun and rocket, compared with the little work done on the -Gx of windblast deceleration.

Incidence

Statistical data on the incidence of windblast was presented from five countries, Canada, the US, Italy, France and Sweden, and some earlier UK data was also discussed (paper B9). Pertinent features are summarised in the table with additional RAF data from Fryer (FPRC No. 1166 of 1961) and from Reader (personal communication).

Aircrew population	Reference	No. of Ejections	Mean speed at ejection	Incidence of major flail injury	Ratio, upper to lower limb injury
USAF Non-combat 1968-1973	B1	631	240 kt	3.4%	1.2:1
IAF 1954-1974	B2	100	NS*	21%+	0.5:1
CAF 1966-1974	B4	90	30% > 400 kt	1.1%	-
FAF 1960-1970	B6	256	9% > 400 kt	12.5%	0.8:1
USAF POWs	B9	162	388 kt	+ 24.6%	NS
USN POWs	B9	94	438 kt	+ 33.8%	NS
SAF 1967-1974	B11	74	11% > 540 kt	+ 5.4%	NS
RAF 1949-1960	Fryer	294	224 kt	2.3%	0.4:1
RAF 1960-1973	Reader	355	198 kt	5.9%	0.6:1

* Indicates that the relevant data was not stated.

\+ High incidence due to selection of cases for study.

Several points of interest may be noted in the table. In peace time operations, ejection speeds tend to be low, around 200 to 250 kt and the incidence of major flail injury is also low, around 5%. The IAF cases were a selected series and the average speed of ejection for the 21 windblast injuries was 364 kt. In combat, on the other hand, ejection speeds are considerably higher and one third or more of ejectees may suffer major windblast injury. An ejection speed of 700 kt leads to the virtual certainty of a major flail injury (paper B9). Generally speaking, the lower limbs suffer more than upper limbs, though with more effective leg restraint in the later series, injuries are becoming more evenly distributed. These data, based upon 2,056 ejections, provide a sound basis for the statement that windblast injuries are a major component of overall ejection morbidity, and that this component increases greatly with aircraft speed at ejection. The lack of windblast injuries in the Canadian series was attributed to low ejection speeds, though their 27 ejections made at over 400 kt would have been expected to have provided several cases by comparison with the other data. Equations relating injury rates with ejection speed are given in papers B1 and B9.

Mechanism

The common injury mechanism was considered to be windblast forces taking the limbs beyond their range of normal movement (joint injuries, dislocations), or causing limbs to strike against parts of the ejection seat (fractures, fracture dislocations). Details of observed injuries were given in paper B6. The direct action of windblast (petechial, or subconjunctival haemorrhage) was considered less important, and in an appendix to paper B9 it is shown that in high dives, peak dynamic pressures of 2,000 to 4,000 lb/ft^2 (15 - 30 psi, 100 - 200 kNm^{-2}) may voluntarily be experienced without injury. This level is some two times the presently accepted tolerance limit.

The forces which tend to displace limbs exposed to windblast were described in paper B10, and the findings confirm the earlier underwater studies of Fryer (FPRC Report No. 1167 of 1967). A film showing some of these pioneering experiments was shown to the delegates at the start of the afternoon session. Also measured and reported in paper B10 were helmet lift forces - some 460 lb (210 kg) at 600 kt. Whilst these forces could be reduced by turbulence within the cockpit, it was considered that they would represent the real-life situation upon leaving the aircraft, and thus account for the frequent loss of protective helmets. A simple aerodynamic solution was offered.

Also included in the proceedings, but not presented in Toronto, is a paper (B5) which provides a useful comparison between windblast injury mechanisms relevant to high-speed ejection, and those which result from conventional and nuclear explosions. In the latter case, the lung is the critical organ. Lung damage is relatively rare in ejectees. Thus, there is no instance in the 21 cases of windblast injury discussed in paper B2, though two cases, one of them fatal, are referred to in paper B6.

Protection

Several possible techniques for restraining the limbs were discussed, attention being directed more towards the arms, since leg restraint has been used successfully for many years. Paper B8 described tests carried out on an arm retraction and restraint system using cords and powered by seat movement. A similar system, but extended to embrace legs and head, was also described (paper B11), but had not been introduced into service. Effective restraint is more readily obtained if the arms are initially on a between-the-legs D-ring (paper B8). If the seat is stable, simple entrapment of the limbs with nets would prevent injury (paper B9). When ejection is initiated by the other crew member (command ejection), arm retraction may be required in addition to restraint. This problem was raised by several speakers and the proffered solutions included the cord systems already mentioned, as well as airbags inflated on the cockpit walls (paper B11).

The importance of seat stabilisation was also stressed by several speakers - for example paper B10 shows how wind tunnel measurements of drag forces can lead to an understanding of seat instability (ejection seats are inherently unstable) and paper B9 refers briefly to methods for the aerodynamic stabilisation of seats in the critical period prior to deployment of a drogue parachute. An example of a seat stabilised in pitch was seen in action on film during the presentation of paper B11.

The problem of head restraint was discussed, but most ejection seats rely, at the best, upon energy absorbing padding on the headrest (paper B11). However, a self erecting fabric hood, the efficacy of which was seen in films taken during 750 kt windblast exposures (paper B7), could be used to give head restraint as well as to prevent inadvertent loss of headgear.

CONCLUSIONS AND RECOMMENDATIONS

The average low speed of current aircraft ejections is a feature of non-combat operations - ejection speeds increase markedly in the combat situation, and high speed usage must be allowed for in the development of ejection systems.

The potential for windblast injury increases as the square of windspeed. Thus, windblast becomes a major source of morbidity and mortality in high-speed ejection.

Man's ultimate tolerance to windblast could be considerably higher than presently accepted, and does not theoretically limit current ejection performance. Precise figures are required for human tolerance to windblast, but it is considered that these will only come, as at present, from accurate reporting of high-speed ejection experience.

Current ejection seats are inherently unstable and impose omnidirectional windblast forces necessitating the most complex restraint systems. The development of stable ejection seats is considered essential for safe high-speed ejection. The aerodynamic performance of current seats should be evaluated with a view to achieving stability over a wide speed range.

Restraint systems currently in service, or in development, should reduce the incidence of leg and arm injuries, but only at the cost of greater complexity of aircrew equipment assemblies.

Whilst improved seat stability should simplify the solution of limb injury, head restraint and helmet loss are areas which will increase in relative importance, and these require further study.

The present high level of sophistication in ejection seat design should not be allowed to inhibit the search for other means for abandoning aircraft at high speed.

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USAF NON-COMBAT EJECTION EXPERIENCE 1968-1973 INCIDENCE, DISTRIBUTION, SIGNIFICANCE AND MECHANISM OF FLAIL INJURY

By

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SUMMARY

The USAF non-combat ejection experience during the period 1968-1973 has been reviewed attempting to characterize the incidence, distribution, significance and mechanism of flail injuries. From a total of 784 ejections, 631 have been selected based on several criteria outlined in the paper. The overall incidence of flail injury is 7% (44 cases) in which 4% (25 cases) involved injuries of a major type. The incidence rose dramatically above 300 KIAS suggesting that flail injury is a significant problem at higher airspeeds. The distribution of injuries is characterized by (1) an absence of major head and neck flail injury, (2) a predominance of proximal over distal injury and (3) in marked contrast to earlier data, a slight predominance of upper over lower extremity flail injury. The importance of analyzing the forces acting upon the limbs as well as having a clear understanding of the mechanisms of failure is discussed and the need for improved limb restraints is emphasized.

INTRODUCTION

Since the earliest days of the ejection seat following World War II it has been apparent that high velocity ejections are associated with a characteristic injury pattern quite different from that found in low velocity ejections (Ref 16). These injuries are related to the aerodynamic forces experienced immediately upon entering the airstream. Stapp (Ref 14,15,17), Fryer (Ref 6) and Brinkley (Ref 1) have conducted research attempting to characterize the magnitude and effects of these forces. The magnitude of this force is expressed as:

$$Q = 1/2\ \rho\ V^2 \qquad \text{Eq (1)}$$

where:

Q = dynamic air pressure in Newtons/M^2
ρ = air density in Kg/M^3
V = velocity in M/sec

This relationship is expressed in Figure 1.

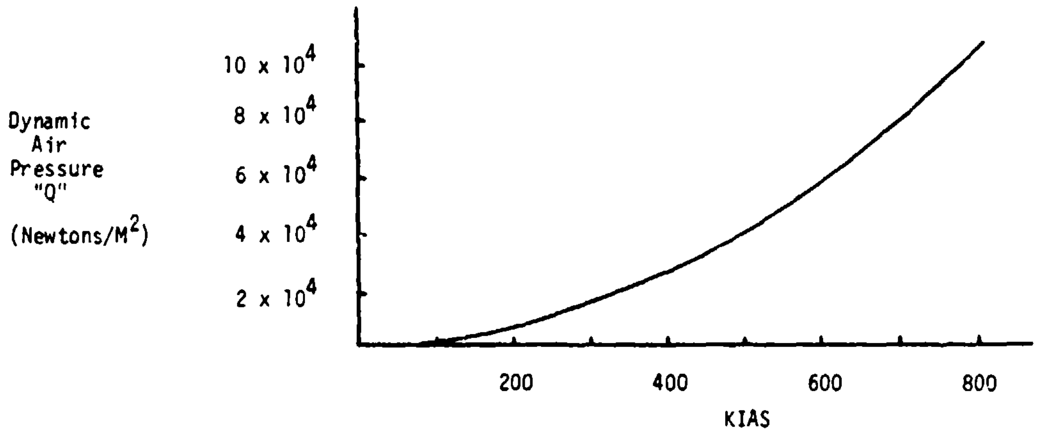

FIGURE 1. Dynamic Air Pressure vs. Airspeed

Two distinctive injury patterns have been attributed to the "Q" forces experienced in high velocity ejections. The first, generally referred to as "windblast", is characterized by soft tissue injury resulting from localized dynamic air pressure and turbulence. These forces produce surface burns, ecchymosis, edema and petechial hemorrhages -- usually minor injuries. Although it has been suggested that a pulmonary blast-type injury may also be produced, convincing evidence for this is lacking. The second and more significant injury pattern associated with "Q" forces is generally referred to as "flail injury". Whereas windblast injuries result from relatively small locally applied forces, flail injuries result from the summation of force over larger areas producing differential decelerations of the head and extremities relative to the torso. According to Payne (Ref 10) the differential decelerations result from drag forces according to the following relationship:

$$\text{Deceleration} = \frac{\text{Drag Force}}{\text{Weight}} \qquad \text{Eq (2)}$$

where:

$$\frac{\text{Drag Force}}{\text{Weight}} = \frac{(\text{Dynamic Pressure})\times(\text{Drag Coefficient})\times(\text{Frontal Area})}{\text{Weight}} \qquad \text{Eq (3)}$$

It may be seen from these relationships that a greater frontal area/weight ratio for the extremities relative to the torso will result in a more rapid deceleration of the extremities. If the area/wt ratio for the torso is further reduced by the addition of an ejection seat, as it is in operational practice, the relative deceleration of the extremities will be even greater. Flail injury appears to occur when the decelerating head or extremity impacts the ejection seat or when the appendage exceeds the limits of motion of a particular joint. The resulting extent of injury may range from soft tissue contusion or laceration to major debilitating fracture or ligamentous injury.

Recent reports have expressed a growing concern with the incidence of windblast and flail injuries associated with (1) the increasing operational performance envelope of USAF aircraft (Ref 2,13) and (2) the higher airspeed of combat ejections (Ref 3,4,7,8,9,12). However, there is as yet incomplete information on the spectrum of injury produced by windblast or flailing. By reviewing the seven year USAF ejection experience from January 1968 through December 1973, the present study attempts to define the incidence, mechanism, significance, and character of windblast/flail injury.

METHODS

Since 1957 the Air Force has maintained a data bank at the Directorate of Aerospace Safety, Air Force Inspection and Safety Center, Norton AFB, California. This data bank contains information about all aircraft accidents involving USAF aircraft. Pertinent data derived from aircraft accident reports have been encoded and are stored in computer memory for rapid access and retrieval of information. The original reports are maintained for several years before being reduced to microfiche for permanent storage. In addition, the Aerospace Medical Research Laboratory maintains an abbreviated version of the computerized Norton Data Bank containing pertinent injury and personal equipment data (AMRL Life Sciences Data Bank).

The present report represents an update and extension of the original study by Buschman and Rittgers (Ref 2). All ejections from USAF aircraft during the period from 1 January 1968 through 31 December 1973 have been selected from the AMRL Life Sciences Data Bank based on the following criteria:

(1) Only open ejections are included (i.e., no capsules, no bail-outs).

(2) Only non-combat ejections are included.

(3) Cases where the crew member is missing are excluded.

(4) Fatalities which resulted from ejection below the lower boundary of the ejection envelope have been excluded because of the difficulty in separating flail from impact injury.

From this data base, all injuries which occurred during the ejection, parachute deployment or descent phases were reviewed as potential windblast or flail injuries. Review entailed searching for further details within the computerized record or narrative summary and in many cases returning to the original accident report for further clarification. Injuries were attributed to windblast/flail only if it could be determined with reasonable certainty that the injury was not caused by other factors such as striking the aircraft, parachute deployment or landing impact. Therefore, "probable" windblast/flail injuries are included whereas those which can only be classified as "possible" have been excluded. The result of these strict criteria for inclusion as a windblast/flail injury means the overall incidence is probably considerably underestimated.

Stapp (Ref 14,15,17) and Fryer (Ref 6) have demonstrated that with proper helmet protection and adequate limb restraints serious "Q" force injury can be prevented. The soft-tissue injuries ascribed to "windblast" are usually minor injuries. Review of the 1968-1973 operational experience supports this. In fact, true windblast injuries are only infrequently noted in the accident data file. Rather than infrequent occurrence, this probably represents failure to note these relatively minor injuries especially since they would frequently be associated with the more major flail injuries. As such, the incidence of windblast injury is probably greatly underestimated and, therefore, only flail injuries will be included in the subsequent analysis.

RESULTS

Utilizing the selection criteria described, from a total of 784 ejections during the period 1968-1973, 631 have been selected for further evaluation. Table 1 characterizes these ejections in terms of airspeed and the overall severity of injury. As shown by Buschman and Rittgers (Ref 2) the probability of flail injury becomes significant only above 300 KIAS. However, in the non-combat operational experience reviewed here, only 20% of the ejections occurred at greater than 300 KIAS. From this finding the overall incidence of flail injury would be expected to be quite low in the operational (non-combat)series of ejections. For this series, 44 cases of probable flail injury were found for an overall incidence of 7% (see Table 2). This corresponds closely with the incidence of 6.6% found by Buschman for the USAF experience (Ref 2) and the incidence of 6.8% found by Fryer for the RAF experience (Ref 5). Figure 2 reveals that the probability of flail injury for the current series closely approximates that predicted by Payne (Ref 10) based on Buschman's data.

TABLE 1. USAF Non-Combat Ejections 1968-1973:Severity of Injury vs. Airspeed

KIAS	Minimal or None	Minor	Major	Fatal*	Total Ejections	Percent Total Ejections
0-49	11	1	3	2	17	3.0
50-99	13	1	6	0	20	3.5
100-149	46	12	7	2	67	11.8
150-199	69	12	37	3	121	21.3
200-249	81	26	39	7	152	26.8
250-299	37	17	19	2	75	13.2
300-349	23	10	14	3	50	8.8
350-399	6	2	8	1	18	3.2
400-449	4	6	11	6	27	4.8
450-499	4	1	4	3	12	2.1
500-549	1	0	5	0	6	1.1
550-599	0	0	0	1	1	0.2
>600	0	0	1	0	1	0.2
TOTAL	295	88	154	30	567	100%
UNKNOWN	34	8	11	11	64	
TOTAL	329	96	165	41	631	
PERCENT	52%	15%	26%	7%	100%	

*Fatalities from ejections outside lower boundary of the ejection envelope have been excluded.

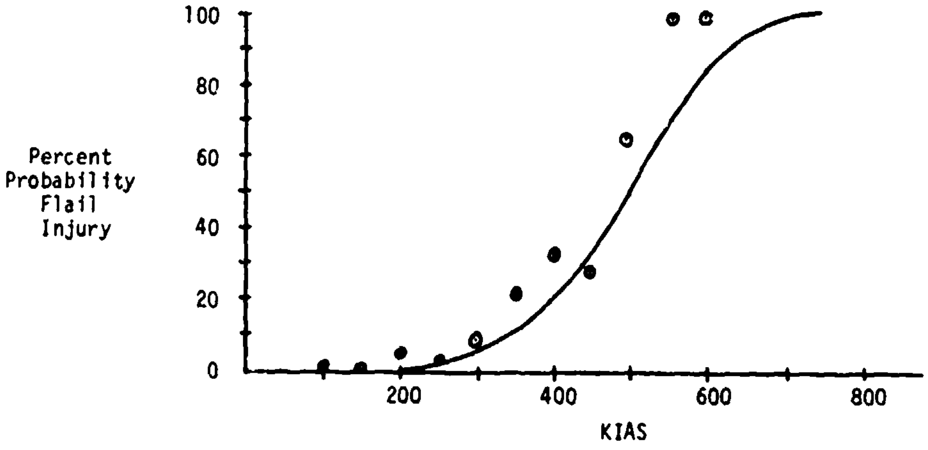

FIGURE 2. Probability of Flail Injury vs. Airspeed

TABLE 2. USAF Non-Combat Ejections 1968-1973: Incidence of Flail Injury

KIAS	No. Ejections	Minor Flail Injury		Major Flail Injury		Total Flail Injury	
		No.	Incidence	No.	Incidence	No	Incidence
0-49	17	0	0.000	0	0.000	0	0.000
50-99	20	0	0.000	0	0.000	0	0.000
100-149	67	0	0.000	1	0.015	1	0.015
150-199	121	1	0.008	0	0.000	1	0.008
200-249	152	5	0.033	2	0.013	7	0.046
250-299	75	1	0.013	1	0.013	2	0.027
300-349	50	2	0.040	4	0.080	6	0.120
350-399	18	0	0.000	4	0.222	4	0.222
400-449	27	3	0.111	6	0.222	9	0.333
450-499	12	0	0.000	3	0.250	3	0.250
500-549	6	2	0.333	2	0.333	4	0.067
550-599	1	0	0.000	1	1.000	1	1.000
>600	1	0	0.000	1	1.000	1	1.000
TOTAL	567	14	0.025	25	0.044	39	0.069
UNKNOWN	64	5	0.078	0	0.0	5	0.078
TOTAL	631	19	0.030	25	0.040	44	0.070

From Table 1 it should be noted that the fatality rate is only 7% due to the exclusion of fatalities resulting from ejection below the lower limit of the ejection envelope. In addition, although 52% received minimal or no injury, 33% received major or fatal injuries in what should have been survivable situations. This represents the area of greatest concern to the Air Force. Although the overall incidence of major or fatal flail injuries is only 4%, the significance of these injuries becomes apparent when ejections over 300 KIAS resulting in major injury or fatality are considered separately. Of these cases, 37% received major flail injuries.

As mentioned previously, one purpose of this paper is to characterize flail injuries. Table 3 presents the nature and distribution of flail injuries found in the present series of ejections. Several observations should be noted. First, there were no major head or neck injuries attributed to flailing this series. In addition, most minor injuries of the head and neck were attributed to flailing of the head during helmet loss. Second, as would be expected, proximal limb injuries tended to predominate over distal injuries. Third, major joint injuries (22) occurred almost as frequently as long bone fractures (27). Fourth, upper extremity injuries (34) were more frequent than lower extremity injuries (28). This latter finding is in contrast to the findings of Buschman for 1964-1970. Table 4 reveals that this difference represents a reduction in lower limb injuries rather than an increase in upper limb injuries.

A more complete characterization of the flail injuries from the earlier period (1964-1970) is not available. However, a review of unpublished Buschman data reveals that while all types of lower extremity injuries were more frequent during the earlier period, the major discrepancy lies in the number and extent of knee injuries. Where the present series contains no dislocations or fracture dislocations, Buschman's series contained at least ten. Although the two series are not strictly comparable because of slight differences in the method and criteria for selection, this discrepancy could result from several factors. First, the method of injury classification has changed. Second, the system of limb restraints has been altered in several aircraft. Third, the usage of restraints by the aircrew members may be different. Finally, there has been a shift in the USAF aircraft inventory producing an alteration of the aircraft/ejection seat combinations represented among the flail injuries.

DISCUSSION

The importance of flail injury should not be underestimated. Although the overall incidence of major flail injury is only 4%, the incidence rises to 22% in those ejections over 300 KIAS. The significance of this figure becomes apparent when the Southeast Asia combat and POW experience is considered. Shannon (Ref 12), Till (Ref 13), Kittinger (Ref 8) and Lewis (Ref 9) have attempted to review the USAF combat and POW experience. Table 5 summarizes the USAF data and the Navy experience as reported by Every (Ref 3,4) and Kinneman (Ref 7). The combat ejections occur at much higher airspeeds with a corresponding rise in the incidence of flail injury. However, the incidence of major flail injury over 300 KIAS appears to be decreased. This may be explained by the fact that the POW's represent a very select population - those who were able to survive ejection as well as withstand the rigots of captivity. It is quite conceivable that a significant number of flail injuries resulted in ejection fatalities or deaths while in captivity. If this were the case, the need for improved limb restraints to prevent flailing becomes even more imperative.

TABLE 3. USAF Non-Combat Ejections 1968-1973:Nature and Distribution of Flail Injuries in 44 Cases

	Minor Injuries				Major Injuries						
	Sprain	Contusion	Laceration	Total	Fracture	Disloc	Fx-Disloc	Nerve	Ligament	Total	Total Flail Injury
HEAD-NECK											
Head	--	4	4	8	0	--	--	0	--	0	8
Neck	2	6	0	8	0	0	0	0	0	0	8
UPPER EXTREMITY											
Shoulder	2	0	0	2	2	3	3	1	0	9	11
Upper Arm	--	1	0	1	10	--	--	1	--	11	12
Elbow	0	0	0	0	0	4	1	1	0	6	6
Forearm	--	1	0	1	4	--	--	0	--	4	5
Hand	0	0	0	0	0	0	0	0	0	0	0
LOWER EXTREMITY											
Pelvis	0	0	1	1	1	1	0	0	0	2	3
Hip	0	0	0	0	0	1	0	0	0	1	1
Thigh	--	0	0	0	4	--	--	0	--	4	4
Knee	3	1	0	4	0	0	0	0	7	7	11
Leg	--	0	1	1	6	--	--	0	--	6	7
Ankle	0	0	0	0	2	0	0	0	0	2	2
Foot	0	0	0	0	0	0	0	0	0	0	0
TOTALS	7	13+4*	6	26+4*	29	9	4	3	7	52	78+4*

* Four cases involved multiple contusion

TABLE 4. Comparison with Buschman Data

	USAF 1968-1973 (Ring)	USAF 1964-1970 (Buschman)
Data Base	631	940
Total Flail Cases	44	62
Flail Injuries		
Head and Neck	6	21
Upper Limb	34	64
Lower Limb	28	115

TABLE 5. Comparison of Combat and Non-Combat Ejections

	USAF 1968-1973 Non-Combat (Ring)	USAF POW (Lewis)	NAVY POW (Every)
Data Base	567	162	97
Ejections > 300 KIAS	20%	72%	83%
Ejections > 500 KIAS	1%	33%	29%
Flail Injury	7%	12%	30%
Major Flail	4%	9%	25%
Major Flail >300 KIAS	22%	13%	

The lack of major head or neck flail injury is in agreement with the findings of Kittinger (Ref 8) and Lewis (Ref 9). In addition, most minor head and neck injuries appear to be caused by torsion of the head and neck resulting from aerodynamic forces acting on the helmet. Although the series under study is fairly small, this finding does suggest that the current system of head restraint by the ejection seat headrest may be sufficient to minimize the possibility of major head and neck flail injury.

The predominance of proximal versus distal extremity injuries and the distribution of bone and joint injuries requires an understanding of the mechanisms of bone and joint failure. As a result of the external forces which are applied to the limb in the form of Q-forces, the tissues (bone, ligament, tendon, etc.) develop internal forces and displacements. Displacement of the limb occurs until motion is limited by either anatomical constraints (e.g., muscle resistance or joint capsule limitations) or external constraints (e.g., contact with the seat or limb restraints). Depending on the anatomical, structural and mechanical properties of the tissues involved, failure occurs when a critical stress or strain (or both is reached. Classical engineering concepts involving equilibrium considerations and free body analysis can be used to define the forces operative on the extremity and those which lead to failure. This laboratory is presently conducting failure tests on bone and joint structures to define these critical failure limits at the structural and tissue level.

From a knowledge of the anatomical, structural and mechanical properties it is frequently possible to retrospectively determine the forces and displacements from analyzing the injury itself. For example, an anterior dislocation of the shoulder is usually produced by forced abduction and external rotation of the humerus. Similarly, a spiral fracture of the femur is produced by torsion forces as might be seen with flailing of the lower leg whereas a transverse fracture is usually produced by directly applied bending forces as might be seen with impacting the seat (without torque).

In summary, an understanding of the mechanisms of failure is essential in the design of protective equipment and restraint systems. In addition, analysis of the mechanisms of failure of the musculoskeletal system involves (1) knowledge of the resultant forces and displacements of limbs from externally applied forces, (2) definition of constraining factors (both external and internal) which resist these applied forces and (3) analysis of the anatomical, structural and material properties at the tissue level which define the ultimate failure limits of the anatomical part.

CONCLUSIONS

1. Flailing results from differential deceleration of the limbs relative to the torso. Injury occurs when the internal forces and displacements produced by the applied "Q" forces reach critical levels and result in tissue failure.

2. Although the overall incidence of flail injury in USAF non-combat ejections appears low, it remains a significant operational problem in open-seat high-speed ejections. This is supported by the combat and POW experience in Southeast Asia.

3. Although there appears to be a decrease in lower extremity flail injuries during more recent ejections, the cause of this is uncertain and probably results from a multiplicity of factors. A continuing effort must be made to improve the methods of limb restraint.

4. Analysis and understanding of the mechanisms of failure is essential to the design of protective equipment and restraint systems. This requires a knowledge of (1) the forces and displacements involved, (2) the constraining factors which resist these forces and (3) the structural and material properties of the tissues which determine the ultimate failure limits.

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DISCUSSION

In reply to questions from Limbury (U.K.), Ring agreed that the 25 or so cases of major flail injury occurred in ejections using a multitude of ejection seat types, though they were predominantly from F4 and B52 aircraft. He did not at present have data which would relate the incidence of leg flailing to the presence or absence of leg restraint, nor the incidence of arm flailing to the system of ejection initiation employed (over-the-head, between the legs, or outboard D-rings, or command ejection). He stated that some recent work had indicated that use of the over-the-head D-ring was, however, associated with a higher incidence of arm and shoulder injuries.

SURVEY ON BIODYNAMIC RESPONSE TO WINDBLAST IN EJECTIONS : PATHOGENETIC MECHANISM, ANALYSIS AND PREVENTION OF INJURIES.

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SUMMARY.

In order to give a clinical contribution to the study of injuries caused by windblast during escape by ejection seat from high speed jet-aircraft, the author comparatively analysed the results of ejections, observed by himself during 20 years, where Italian pilots suffered injuries particularly due to windblast.

Of the total number of 100 cases of escapes analysed, 47 pilots successfully ejected without injury and 11 ejections proved fatal. The remaining 42 pilots suffered traumatic injuries after ejection, and of these 21 sustained injuries exclusively due to windblast, and precisely : these injuries were due to direct aerodynamic pressure on the body in 9 cases, to violent dislocation of head in 1 case, and to flailing of limbs in 11 cases. In no case the author could find injuries certainly and exclusively due to some other factors also connected to windblast, as wind drag deceleration or spinning and tumbling of the body during free fall.

Analogous analysis is carried out about 7 cases of traumatic injuries suffered by aircrews within the cockpit of aircrafts following accidental loss or sudden opening of the canopy or after its explosion in-flight.

Then the author analysed the pathogenetic mechanisms of the injuries caused by windblast, the relative limits of tolerance of human body and the systems which could be employed and ulteriorly improved in order to increase the human resistance to aerodynamic pressure of the wind, for the prevention and the reduction of lethality of these injuries, typical in Aviation accident pathology.

INTRODUCTION.

Injuries after ejection from high speed jet-aircrafts are of great importance in Aviation pathology.

In addition to the spinal fractures, caused by initial considerable acceleration-ejection jolt applied to the pilot's body in the direction from buttocks to head by the explosion of the ballistic or rocket devices, the ejected subject may sustain other injuries caused by different remarkable forces acting on his body during the subsequent phases of ejection, as : the deceleration chest to back, due to the air impact and the wind drag encountered on entering the slipstream when he is ejected out of the cockpit ; the aerodynamic pressure usually referred to as windblast or ram pressure, and the consequent blunt action of relative wind, the speed of which is about the same of abandoned aircraft ; the possible further acceleration forces, sometimes complex ones, due to particular and abnormal attitudes of aircraft in the ejection phase, caused by the critical emergency conditions under which escape from aircraft usually occurs ; and so on.

STUDY OF INJURIES CAUSED BY WINDBLAST.

The purpose of the present survey is fundamentally to contribute to the study of injuries due to windblast in the phase of escape immediately following the seat's and pilot's ejection, and of their relative frequency, through a comparative analysis of the results of escapes from aircraft by ejection seat, carried out in emergency conditions by some Italian military and civil jet-pilots over a fairly long period of time.

For the same purpose analogous analysis is made about the injuries suffered by aircrews within the cockpit of aircrafts following accidental loss of the canopy or after its explosion in-flight.

1.- Injuries sustained during ejection.-

For the purpose described above 100 ejections, personally observed in a period of 20 years, were taken into consideration in the present survey.

Of this total number 11 ejections proved fatal : in these cases the pilot's death was generally brought about by the violent impact of his body on the ground because of failure or delay in the opening of the parachute due to the low or very low height at which ejection was carried out or other causes.

Of the remaining group 47 pilots successfully ejected from aircraft without injury, and 42 pilots sustained traumatic injuries during the various phases of ejection : of these, 15 sustained single or multiple vertebral fractures (due to initial acceleration-ejection jolt), associated or not with other non-vertebral lesions, and 27 sustained other traumatic injuries different from spinal fractures.

However, in this total number of 42 subjects injured during ejection, traumatic injuries exclusively due to windblast (and associated or not with other injuries due to different phases of escape) were sustained on the whole by 21 subjects, as shown by the following Table I :

TABLE I

- Total Number of Ejections	:	100
- Number of Dead Pilots	:	11
- Number of Unhurt Pilots	:	47
- Total Number of Injured Pilots (of whom 15 with spinal fractures, associated or not with other non-vertebral injuries), and of these :	:	42
- Number of Pilots with injuries exclusively due to windblast (associated or not with other injuries due to different phases of escape)	:	21

The details of these last 21 cases, with the description of the respective traumatic injuries sustained by each pilot, are shown in the following Table II :

TABLE II

No.	Type of aircraft	Altitude of escape ft	Speed of aircraft kts	Injuries exclusively due to windblast (associated or not with other injuries due to different factors)
1	F.104G	1.500	430	fracture of T.12°; fracture of right tibia and fibula
2	F.104G	3.000	460	fracture of T.12° ; fracture of left humerus
3	FIAT G.91	3.000	350	fractures of T.7, T.8, T.12, L.1° ; fracture of right tibia and fibula
4	F.104G	15.000	380	fracture of L.1°; fractures of both ankles
5	T.33	6.000	350	contusion of chest, fractures of 10th and 11th left rib
6	T.33	10.000	not known	fracture of left elbow
7	F.84F	2.000	380	contusion with haematoma of the back, wounds of elbows
8	F.84F	3.000	370	contusions of right shoulder and both temporo-mandibular regions, subjunctival haemorrhages
9	F.86K	5.000	280	contusion of left mastoid region and left ear
10	F.84F	17.000	360	distorsion of left knee
11	F.84F	4.000	340	contusion of chest, wound of chin, subjunctival haemorrhages
12	F.84F	9.000	370	fracture of left tibia and fibula
13	F.86E	3.500	not known	fracture of nasal sept, contusion of chest, petechial haemorrhages of face
14	F.84F	2.000	320	contusion of left leg, wound of right mastoid region
15	F.86E	3.000	290	contusions of chest and left mastoid region
16	F.86K	15.000	340	distorsion of right ankle; burns of both hands°°
17	F.86K	6.000	360	distorsion of right shoulder, contusion of left foot
18	F.84F	not known	350	distorsion of left ankle
19	F.104G	8.000	450	contusion of head with commotio cerebri, large wound of scalp, subjunctival haemorrhages
20	F.104G	35.000	400	multiple ecchymotic contusions on the face ; congelation of both hands°°
21	F.104G	18.000	380	distorsions of left knee and right ankle

Notes :

° The vertebral fractures, sustained during the first phase of escape, were due to acceleration-ejection jolt.

°° The associated injuries (burns, congelation) were obviously due to other causes, different from windblast (fire aboard before escape, exposure to very low temperature of escape altitude).

In the Table described above, after excluding the first 4 cases (in which the subjects <u>also</u> sustained single or multiple vertebral fractures, due to the initial acceleration - ejection jolt buttocks to head), <u>only</u> the pilots who sustained traumatic injuries exclusively due to windblast after ejection are listed.

In fact, according to the purposes of the present survey, the Table II does not include all the cases (especially bone fractures of the lower limbs, strong contusions of various parts of the body, as face, chest, limbs ; burns, and so on, besides the vertebral fractures by ejection) of single injuries which were likely sustained during the various phases of ejection with mechanisms different from aerodynamic pressure of wind, as for example : impact of various parts of the body against the structures of aircraft during escape from cockpit ; violent action of retaining straps of protective helmet and oxygen mask, sometimes violently pulled away by the wind ; abrupt traction of parachute harness on underlying parts of body at the moment of considerable deceleration following the opening shock of parachute canopy ; violent or incorrect ground impact at the moment of landing ; burning effects of flames or heat of fires breaking out on board before escape, and so on.

The present case survey has been therefore intentionally limited to the study of the biodynamic response to windblast in ejections by seat.

2.- Injuries sustained after accidental loss or explosion in-flight of canopy.

The present survey has been completed with an analogous analysis carried out about the injuries suffered by aircrews within the cockpit of military aircrafts following accidental loss or sudden opening of the canopy or after its explosion in-flight.

For this purpose the Table III lists seven cases, personally observed by the author, with the respective circumstances of each flight accident and the description of the injuries particularly due to windblast (1).

TABLE III

No.	Type of aircraft	Altitude ft	Speed of aircraft kts	Circumstances of flight accident	Injuries due to windblast	Injuries due to rapid decompression or other factors
1	F.84F	18.000	450	opening of canopy	multiple contusions and abrasions on the face	
2	F.84G	24.000	320	loss of canopy	multiple contusions and abrasions on the face, palpebral ecchymosis	
3	F.84G	20.000	420	breach of canopy	multiple ecchymotic contusions on the face	bilateral aero-otitis
4	F.84G	33.000	380	opening of canopy	subjunctival and facial petechial haemorrhages, nose-bleeding	bilateral aero-otitis, slight left bradyacusia
5	F.86K	15.000	400	loss of canopy	subjunctival haemorrhages, wound of lower lip, facial congestion	slight bilateral aero-otitis
6	D.H.100	30.000	320	explosion in-flight of canopy	nasal and subjunctival haemorrhages	
7	F.86E	30.000	430	explosion in-flight of canopy	subjunctival haemorrhages, facial congestion	bilateral aero-otitis, congelation of hands

Note :

(1) This Table doesn't include all the other cases, also observed by the author, in which the pilots did not suffer any important injuries due to windblast, after opening or explosion in-flight of the canopy.

The Table described above shows therefore that, besides the frequent barotraumatic injuries due to sudden decompression of pressurized cockpits, almost all the subjects of the cases examined here had sustained some congestive and/or haemorrhagic distresses at level of the conjunctival and nasal mucous membranes and of the face skin, associated or not to traumatic facial injuries (as contusions, abrasions, wounds), the last ones generally being due to violent compression of oxygen mask and protective helmet exerted on the subject's face by strong external slipstream or to direct blast of the lateral airstream violently entered within the cockpit.

PATHOGENETIC MECHANISM OF THE WINDBLAST INJURIES.-

As the seat separates from the aircraft after ejection, both the ejection seat and its occupant are immediately subjected to continually changing combinations of wind drag deceleration, windblast, tumbling and spinning of the human body during the following free fall.

A.- Wind drag deceleration.

On leaving the aircraft the seat, which is still travelling forward at the speed of the aircraft, enters stationary air and is subjected to a rapid deceleration due to wind drag. The extent of this deceleration depends upon the equivalent airspeed, the combined mass of the seat and man, and the effective cross-sectional area exposed. In particular, the higher the indicated airspeed, the greater is the deceleration effect. For a given indicated air speed, the maximum linear decelerations are not affected by altitude but as the ejection altitude is increased, the deceleration time is more prolonged : this is due to the fact that for a given indicated air speed, increased altitude causes a greater kinetic energy which must be dissipated as a function of time in an atmosphere of lower density.

Ejection seats are usually provided with some form of stabilisation system so that this deceleration takes place in a relatively "straight" line ; an unstable seat system produces a complex variety of forces on the seat occupant. There are many factors which affect the drag characteristics of the man/seat complex and it is not possible to lay down a maximum indicated air speed for safe ejection. Assuming a maximum safe peak linear deceleration of 35 G, it has been calculated that this might be experienced at an indicated air speed between 600 and 700 knots (DOBIE, 1972, 5).

STAPP (1957, 28) has defined these tolerance limits as : a magnitude of 50 G attained at 500 G/sec. with a maximum duration of 0,2 sec.; a rate of change of 1500 G/sec. up to 40 G with a maximum duration of 0.16 sec.; and a duration for forces greater than 25 G of not more than 1 sec. at a rate of onset of 500 G/sec.

However, the upper limit of human tolerance probably lies in the region of an indicated airspeed of 600 knots. The deceleration might be made more tolerable, and this limit raised, if the area of the seat presented to the airstream were reduced by aerodynamic shaping, or if a forward thrust were applied to counter the deceleration. In either case, to give the same overall velocity change, the lower peak deceleration would have to be applied for a longer time and the advantage obtained would be very small.

As regards the present survey, no case of traumatic injuries seems to be certainly and exclusively due to wind drag deceleration, this depending upon the circumstances of the ejections examined here : airspeeds not exceeding 460 knots, acceleration-ejection jolt of 14 to 18 G for a duration of 0.5 to 0.15 sec., acceleration gradient not exceeding 350 G/sec.

B.- Windblast.

The airstream encountered by the ejected man exerts on him an aerodynamic pressure usually referred to as "windblast", "ram pressure" or "q". The extent of this pressure varies with the density of the airstream and, therefore, for the same true speed it is reduced as altitude increases. It is thus related to the indicated airspeed rather than the true airspeed (being the force measured by the pitôt-airspeed indicator system) and varies with the square of the velocity (for example, the force at 400 knots is approximatively 16 times greater than that at 100 knots). The aerodynamic pressure is therefore greater at high speeds and low altitudes. For instance, the speed of sound at sea level, 660 knots (Mach = 1), is associated with a "q" value of 13 lb/in^2 (the measured "q" being about 5-4 lb/in^2 at 450 knots).

The effects of this aerodynamic pressure or force "q" can be divided in those produced by direct pressure on the body, such as petechial and subjunctival haemorrhages and various contusive injuries, and those produced by flailing of the head and extremities, such as articular distortions or dislocations and bone fractures.

At speeds up to 400 knots the direct pressure of wind is unlikely to cause injury to the face, particularly if the face is covered ; the oxygen mask prevents the entry of air into the lungs and stomach. The unprotected face begins to suffer from the effects of blast at about 100 knots of indicated airspeed ; at this speed the soft tissues of the face begin to flutter and distort, the distress so caused increasing progressively, until at about 300 knots traumatic lesions begin to occur. The risk of laceration is considerably increased if the mouth or eyes are open at the time the blast is experienced. Moreover, although the face is normally protected by flying clothing, conventional head gear, which includes oxygen mask, helmet and goggles, is liable to be stripped off at speeds above 150 to 200 knots, exposing the subject to the possibility of anoxia, in addition to facial injury.

The flailing of the head and extremities is probably a much more serious problem. Head's violent flailing may cause unconsciousness, or even fatal brain or cervical cord damage, while flailing of the arms and legs can lead to fractures or joint dislocations. With the body unsupported, a "q" of 4-5 lb/in^2 or more leads to flailing of a force which cannot be controlled by muscular effort (STAPP, 1957, 28). The onset of flailing can be so rapid that muscular reflex action is ineffectual even at ram pressure below 4-5 lb/in^2. At 450 knots full abduction of the hip joints can take place in 0.1 sec. and at greater speeds the load on unsupported limbs may exceed the strength of the major joints.

The aerodynamic forces acting on the crewman during ejection can dislodge the limbs, and because of the differences between the ballistic characteristics of the limbs and the torso-seat combination, the limbs will decelerate more rapidly and may be injured when the rearward motion is stopped. Either the limits of the limb joints are exceeded or the limbs are injured by impacting the seat, which is decelerated less rapidly.

The equation governing the deceleration of each body or seat segment is expressed by the following drag/weight ratio ; if the ratio (drag/weight) were therefore the same for limbs as well as the torso and seat, all segments would slow down at the same rate and the injuries would be less serious and less frequent :

$$\text{DECELERATION} = \frac{\text{DRAG FORCE}}{\text{WEIGHT}} = \frac{q\ C_D\ S}{W}$$

where

DECELERATION - G units
q = DYNAMIC PRESSURE - Lb/ft^2
C_D = DRAG COEFFICIENT
S = FRONTAL AREA - Ft^2
W = WEIGHT - Lbs

Experimental data of various authors (BUSCHMAN, 1972, 3 ; BRINKLEY, PAYNE, 1973, 2), who accomplished detailed analysis of many accident reports and comprehensive analysis of flailing injuries experienced during the period of 1964 to 1972 in USAF, showed that the incidence of flail injury increases exponentially with airspeed as might be expected ; but, while previously the threshold of flail injury was thought to be placed at airspeed of 400 to 500 knots, they have ascertained that the incidence of these injuries is significant in the 300 to 400 knot range, and in the 400 to 500 knot range the flail injury rate can exceed 30 percent, and approximately 60 percent of the injuries identified were either major injuries requiring extensive hospitalization or were fatal. Besides, many of the major injuries, such as leg fractures, are life threatening during parachute landing and reduce the probability of survival during the period prior to rescue.

This analysis has therefore clearly shown that the flail injury is a serious problem in the intermediate speed ranges as well as the high speed ranges, and that the threshold of injury occurs at a lower airspeed than originally estimated, as well as at 600 knots, the currently accepted limit of the open ejection seat, there is a 100 percent incidence of flail injury.

If we now comparatively analyse the data resulting from the present survey, in which the biodynamic response to windblast has been studied in 100 cases of escape by open ejection seat carried out by Italian pilots, on the whole 21 subjects (= 21 percent) sustained traumatic injuries exclusively due to windblast. The equivalent airspeeds of escape, at which major injuries (especially bone fractures) were sustained, are included between 350 and 450 knots ; these results give a further evidence and confirm that the threshold of the windblast injuries occurs approximately at 350 knots of equivalent airspeed and their incidence increases as airspeed increases.

As regards the influence exerted by single biodynamic factors which are efficient causes of these injuries, among 21 cases described above no injury seems to be certainly due only to rapid wind drag deceleration, while all the traumatic lesions on the contrary are prevalently to be ascribed to the effects of aerodynamic pressure or force "q" : these effects can be divided, as said before, in those produced by direct aerodynamic pressure on the body (in the present survey 9 cases, precisely the cases no. 5,7,8,9,11, 13,14,15,20) and those produced by flailing of the head (1 case : case no. 19) and by flailing of limbs and/or their impact against the seat (11 cases, precisely the cases no. 1,2,3,4,6,10,12,16,17,18,21).

Of these last 11 cases, related to injuries due to flailing of limbs, it may be interesting to analyse the location of injuries which, in the present survey, prevalently consisted of bone fractures (6 cases) and joint distortions (5 cases). Such lesions were most frequently localized in the lower limbs, particularly in the legs and ankles (4 fractures of tibia and fibula, 4 single or multiple distortions of which 2 only localized in a knee, 3 only in an ankle, and 1 at the same time in a knee and in an ankle), and less frequently in the upper limbs (1 fracture of humerus, 1 fracture of elbow, 1 distortion of shoulder).

These results lead to the conclusion that two areas of vulnerability appear to exist, both localized in the lower limbs. In fact, whilst the upper part of the femur, including the acetabular joint, may also be fractured or dislocated when the thighs are raised and abducted, more frequently the bones of the leg and the joints of knee and ankle appear to be more vulnerable, perhaps because the thighs are in some way restrained (as by thigh guards if the seat is in a nose-down attitude). On the contrary the legs and the feet are more easily subjected to movements of violent lateral dislocation, because in general the forces that tend to move the limbs laterally are larger than anticipated and are dependent upon a number of factors including the proximity of other segments of the body and proximity of the ejection seat structure.

Particularly in case of lateral flailing of legs the medial collateral ligament, joint capsule, synovia and cruciate ligaments of knee may be torn, and the medial meniscus completely detached from the ligament. The same distortional lesions may occur with the same mechanism at level of the joint of ankle in case of lateral dislocation of feet.

As regards the less frequent injuries localized in the upper limbs, it seems that some difficulty is experienced in maintaining a grip on the handle of a face-blind or a seat trigger at indicated airspeeds in excess of about 450 knots. When an arm is allowed to flail laterally, dislocation of the scapulo-humeral joint or fracture of the upper third of the humerus may result. This type of injury clearly jeopardizes survival if the person escaping is required to perform any manual action, such as the release of a parachute harness or manual separation from the seat.

Afterwards in the first 9 cases of 21 analysed in the present survey, that is the cases of injuries due to direct aerodynamic pressure on the body, these injuries consisted of face contusions with petechial facial and subjunctival haemorrhages sometimes also with nasal fractures, multiple contusions in various parts of body.

These injuries, therefore of prevalently contusive type (that is by impact with relative wind), for frequency and magnitude proved to be directly related to the indicated airspeed of ejection (the aerodynamic pressure, or ram pressure, or force "q" varies with the square of the velocity) and inversely related to the altitude (the aerodynamic pressure increases proportionally to the increase of density ratio, that is it is increasing as the altitude of escape decreases).

C.- Spinning and tumbling.

Following ejection, rotation of the seat or occupant can take place during two phases of the escape sequence. On leaving the aircraft, the seat together with its occupant may undergo a head-over-heels motion at rates of up to 180 rev/min. Tumbling can also occur during free fall, usually taking the form of a flat spin. This is initiated by any slight asymmetry in distribution of the aerodynamic loads and can then build up rapidly to very high rates. For a given indicated airspeed tumbling rates increase with altitude, and are inversely proportional to the square root of the density ratio.

The effects produced depend upon where the centre of rotation lies in the body, varying combinations of positive and negative G thus resulting. Pooling of blood in the head, in the feet or, if the centre of rotation passes through the heart, in both the head and the feet at the same time are all potential results. Rates of tumbling between 180 and 240 rev/min may result in forces in excess of - 30 G at head level (EDELBERG et al., 1954, 6). Human tolerance is dictated by nausea and, at higher rates of spin, by the centrifugal fluid shifts and by loss of consciousness. With the heart at the centre of rotation, a human subject lying on his side is rendered unconscious after between 10 and 12 sec. at 160 rev/min. (WEISS et al., 1954, 30). Under the same conditions, 200 rev/min. has proved fatal to animal subjects in 2 min. (EDELBERG et al., 1954, 6).

Stabilisation can be ensured by the use of a small drogue to orientate either the man or the seat, reduce the speed and lower the rate of spin, in order to reduce the risk of rotation which may occur around three bodily axes particularly if an initial rotating force is applied, and in order to reduce the relative effects which consist in petechial subcutaneous and subjunctival haemorrhages, diffused oedema, mechanical cerebral damage with loss of consciousness, and further violent dislocation of the limbs not restrained.

The time at which this stabilisation system is deployed is critical ; if too early the opening shock may exceed human tolerance, if too late the spinning may already be too firmly established. It is also important that spinning should be controlled before deployment of the main parachute in order that the body should be in the best attitude to receive the parachute opening shock. If the body in unstable at this time, it is possible for a sudden snatch to occur and for very high angular accelerations to be imposed on the man, with consequent possible injuries also at spine level.

In fact, besides the considerable acceleration-ejection jolt buttocks-head, the successive chest-back deceleration due to the air impact and the wind drag, and at last the aerodynamic pressure of windblast, the body of ejected pilot may be subjected to further acceleration forces, sometimes also very complex ones, due to the particular - often abnormal- attitudes of aircraft before escape, which act in variable directions. The resultant of the various effects of these multiple vectors, combined with the first more important vector due to acceleration-ejection jolt, can represent - at very high speeds of aircraft- an acceleration factor which may even be considerably superior to 20-22 G and, therefore, to the average vertebral break load.

This resulting force, especially if the body's attitude is not correct, could act on the spine with an inclination angle of even more than 45° ; this angle would then become more and more acute as the seat tumbles during fall so that a peak of compression on vertebrae and, therefore, the possibility of vertebral fractures may occur also in the phase immediately following the actual ejection.

In the present survey, however, we could find no case of injuries certainly and exclusively due to spinning and tumbling during free fall following ejection.

Some cases of contusive injuries (petechial facial and subjunctival haemorrhages, chest contusions with costal fractures, and so on) were found and described, but for the reasons previously explained these injuries are likely to be ascribed to the direct dynamic pressure on the body, that is the impact with relative wind ; whilst in the first 4 cases listed in Table I, in which the subjects sustained single or multiple vertebral fractures, these traumatic injuries were certainly caused by initial acceleration - ejection jolt.

PREVENTION FROM WINDBLAST INJURIES.

Besides by means of careful and preventive training of jet-fighter pilots to assume and maintain the most suitable and correct positions of body and spine during the critical phases of escape, also in the field of the designing and use of the aircrafts and the relative flying equipment measures can be taken to prevent and reduce the injuries due to ejection.

Before all, the initial hazard in the sequence of escape from an aircraft is incurred when the canopy is jettisoned, since even at moderate speeds aerodynamic forces can thrust a released canopy violently into the cockpit. A well designed canopy should therefore have aerodynamic characteristics which ensure its being lifted well away from the cabin and aircraft structure when jettisoned in flight.

The structural and functional features of ejection seats, which are necessary to prevent the vertebral fractures due to acceleration-ejection jolt, are already well known: to them, and particularly to the type of propulsion employed for ejection, that is blast charge and/or rocket, many factors (number of G, duration of exposure to acceleration - jolt, acceleration gradient, and so on) are related especially for the incidence of vertebral fractures due to ejection. But this incidence may be affected also by other factors, often voluntarily variable or adjustable, as :

a) functional factors of use (right regulation of the height of seat back according to individual size, particularly the height of torso and the torso/limbs ratio ; improvement of restraining straps, foot-rest and head-rest ; suitable location of emergency handle of the ejection device, and so on) ;
b) occasional factors, namely speed, altitude and attitude of aircraft at the time of ejection ;
c) individual factors, namely body height and torso/limbs ratio of subject, body weight/ ejection jolt ratio, position and attitude of head and torso during ejection, and so on.

As regards particularly the reduction of lethality and the prevention of injuries due to windblast and to various factors connected with it (rapid deceleration for wind drag ; direct aerodynamic pressure on the body, and flailing of head and limbs ; tumbling and spinning of the body during the following free fall), the means which could be ulteriorly studied and improved are the following ones :

1) a simple and effective system of automatic retaining, restraining and blocking of limbs at the moment of ejection in order to avoid their flailing, with automatic releasing at the moment of separation ;
2) an effective system of stabilisation of the man/seat complex, deploying after ejection and before separation, in order to reduce the airspeed, the rotations and the tumbling;
3) an automatic separation system man/seat, acting in a subsequent phase of ejection, in order to reduce the incidence of the consequences of unsuccessful separation (impact of body parts against the structures of seat, entanglement of parachute into seat, and so on) ;
4) a zero-lanyard and an automatic timer, which automatic releasing of harness and opening of parachute after deceleration and stabilisation of seat ;
5) a system of sure opening and rapid deployment of parachute canopy.

By means of the combined use and further improvement of these systems, and of the careful clinical and medico-legal study of injuries due to ejection and the dynamics of their production, it will be possible to achieve rapid and considerable further results in the field of flight safety for the purpose of preventing these typical occupational injuries and reducing their harmfulness, which is still quite high in Aviation accident pathology.

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ACCIDENT STATISTICS RELEVANT TO WINDBLAST

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SUMMARY

During the period 1966-1974 injuries were significant problems in ejections from Canadian Forces (CF) aircraft. There were ninety non-fatal ejections. Of these, eight crew-members escaped free from injuries, sixty-three received minor injuries, and nineteen received serious injuries. An analysis of the injury patterns indicates that they occurred at both low and high speeds. Specific problems are addressed and recommendations are made to enhance aircrew safety during ejection.

INTRODUCTION

The purpose of this paper is to report on the injuries experienced by CF aircrew relevant to windblast during ejection, and to make recommendations aimed at the prevention of injuries in future ejections.

Many analyses (1, 2, 3 & 4) have been conducted over the years in an attempt to identify conditions that cause or contribute to injury in ejection from jet aircraft. These analyses have been instrumental in identifying escape-system modifications that would enhance aircrew safety when crewmen are forced to use the last means available to them for survival.

The CF has recorded ninety non-fatal ejections from 1966 through 1974. Of these, eight crew-members escaped free from injuries, sixty-three received minor injuries and nineteen received serious injuries. There were ten fatalities, but these are not relevant to this paper.

TABLE I

NON-FATAL EJECTION STATISTICS 1966-1974 - TOTAL = 90

AVERAGE Q FORCE (PSI)	NO. OF EJECTIONS	INJURIES		
		NIL	MINOR	SERIOUS
.56	23	3	15	5
1.3	26	3	17	6
2.4	14		12	2
4.5	6		4	2
7.5	4		2	2
Unknown	17	2	13	2
TOTALS	90	8	63	19

DEFINITION OF SERIOUS AND MINOR INJURIES (5)

For the purposes of this paper, a serious injury is defined as any injury which:

1. requires hospitalization for more than 48 hours within seven days of the accident;
2. results in a fracture (except simple fracture of fingers, nose or toes);
3. involves severe hemorrhages due to lacerations, and/or severe nerve, muscle, or tendon damage;
4. injuries to an internal organ; or
5. produces second or third degree burns over more than 5% of the body.

A minor injury is defined as any injury which does not meet the criteria for serious injury.

TABLE II

MINOR INJURIES - TOTAL = 63

AVERAGE Q FORCE (PSI)	NO. OF EJECTIONS	TYPE OF INJURY
.56	15	Facial
1.3	17	Facial
2.4	12	Facial
4.5	4	Facial/Muscular Aches
7.5	2	Facial/Muscular Aches
Unknown	13	Facial

From Table II our data disclose that:

a. minor injuries are experienced through all recorded ranges of Q Forces; and

b. the predominant minor injuries were facial, i.e., cut noses, lips, foreheads and muscular aches including non-specific pain with soreness behind the legs.

Detailed investigation of each ejection has revealed that the following six factors could contribute to minor injury and that windblast was not the sole factor causing minor injury:

a. Certain equipment was not used or fastened properly, i.e., loose restraint systems and/or loose parachute harness. For example, and I quote: "When my parachute opened, the Quick Release Box (QRB) moved up over my chest and struck me a severe blow on the chin". An investigation revealed that his parachute did not fit him properly.

b. The failure to use visors. For example, another quote: "My visor was up at the moment when the birds smashed through the canopy". The pilot had facial injuries from the bird and canopy debris.

c. The absence of a negative "G" strap. Quote: "I was in a negative "G" situation and was being forced upwards with the result I had difficulty reaching down for the D-ring".

d. A less than satisfactory oxygen-mask suspension system which contributed to facial injuries. Quote: "The windblast seemed quite severe; my helmet came off and the next thing I felt was the chute opening and blood running down my face". Medical examination revealed that the pilot's face was cut by the oxygen-mask suspension system.

e. The design of our ejection seats requires that the user reach (and look) down and grasp ejection seat handles or D-rings. This posture enhances the chances of injury by placing the body, particularly the head and neck in an awkward position.

f. The ejectees had insufficient time to position themselves properly prior to ejection. Their immediate concern was to get out of the aircraft.

In addition, it must be recognized that some causes of minor injuries remain obscure because the investigating medical officers may have had a problem in determining in what phase of the ejection sequence the injury occurred, i.e., during egress/windblast, tumbling, parachute opening shock or landing.

TABLE III

SERIOUS INJURY - TOTAL = 19

AVERAGE Q FORCE (PSI)	NO. OF EJECTIONS	TYPE OF INJURY
.56	5	Contusion to kidney Compression fracture T-10, T-12 Compression fracture T-4, T-6 Fractured ribs/torn bladder Burns
1.3	6	Fractured skull Compression fracture T-11, T-12 Compression fracture T-12, L-1 Compression fracture T-10, T-11 Compression fracture T-8 Compression fracture D-9, 10, 11, 12
2.4	2	Compression fracture T-8 Burns
4.5	2	Compression fracture T-12, L-2, fracture upper arm, broken ribs Compression fracture L-1
7.5	2	Burns Burns
Unknown	2	Compression fracture T-11 Compression fracture T-10, T-11

From Table III our data disclose that:

a. serious injuries, like minor injuries, are experienced through all recorded ranges of Q Forces and surprisingly, there is little difference in type of injury in the higher Q Forces; and

b. thirteen of the nineteen (68%) serious injuries occurred at a Q Force less than 4.5 psi.

In addition, detailed investigation of each accident indicates that except for the burn injuries, the ejectees were poorly positioned at the time of ejection or interrupted the man/seat separation process by holding onto the ejection seat handles, or flailing as a result of windblast. For example:

a. "Q Forces .56 psi". Quote: "I saw the houses ahead and pulled back on the stick as I pulled the alternate handle. There was a second delay and I thought the seat hadn't fired. I reached for the control column and the next thing I was conscious of was falling toward the ground". He suffered compression damage to T-10, T-12.

b. "Q Forces 2.4 psi". Quote: "I told the Major I was going to eject. I leaned slightly forward to grasp the D-ring with both hands and sat upright as I pulled. In retrospect, I believe I never made it all the way back to the upright position". He suffered compression fracture T-7 and T-8.

c. "Q Forces 4.5 psi". Quote of the medical member's statement. "The pilot was uncertain of his position at the time of ejection. He believes he may have been looking over his left shoulder and down when he pulled the D-ring with his left hand. His poor position in the ejection seat combined with windblast results in the ejectee receiving a fractured right arm, two broken ribs and compression fracture T-12, L-2".

DISCUSSION

Our data analysis indicate that the effects of windblast are primarily minor facial injuries. There is little evidence of flail injury, however, in our opinion, this is related to peacetime flying when aircrew manage to lower the speed of the aircraft prior to ejection. Conversely, it is postulated that there would be an increase in injuries from windblast in time of hostility due to higher speeds and uncontrollable situations. This postulate is based on the ejection experience of the United States Navy in Southeast Asia (6).

It is perplexing to those involved with the design of escape equipment to learn that one pilot may eject at a speed in excess of 300 knots and escape relatively free from injuries, whereas another may eject under similar circumstances and suffer serious injuries. Fifty-five percent of CF ejections studied occurred at less than 300 knots and seventy percent at less than 400 knots.

This study of each ejection indicated that where maximum use was made of the restraint system and the time available to prepare for ejection, the ejectee decreased his chances of serious injuries. Furthermore, the types of serious injuries illustrated in Table III indicate that the position of the aircrew prior to ejection is much more significant than windblast. While there may be cause for concern over the potential injuries as a result of windblast at high Q Forces, our experience has been that these injuries have been minor in nature and were similar at all Q Forces. Thus, although windblast has major injury potential, our evidence points to the inadequacy of helmets, restraint systems or lack of positioning devices as major factors resulting in serious injuries during ejection.

The high incidence of facial injuries is in our opinion unacceptable. There are helmets available that will provide facial protection. However, except in special applications, the expense and trade-offs, such as visual restrictions and weight of these helmets, exclude them as an item in the aircrew personal clothing inventory.

The number of aircrew receiving serious injuries is equally disturbing. True, the design and production of ejection seats is complex and expensive. Nevertheless, to protect our aircrew the ejection seats should have better leg restraints, and especially, arm and head restraints. The additional cost would be trivial.

Because we have very few ejections, it is possible that our aircrew become complacent about their escape equipment. Aircrew should be (and in most instances are) kept informed of the merits of their escape equipment, particularly the action they can take to enhance their chances of an injury-free ejection. But in addition to this there should be a greater emphasis on the periodic use of the ejection seat trainer.

Our data indicate that the present ejection seat equipment will perform reasonably well though with some risk of injuries. The threat of injuries is compounded in times of hostility when a crewmember may be concerned with escape and evasion following a parachute landing. The ultimate prevention of injuries during ejection is the elimination of the need for ejection. Until this is achieved, however, we must be concerned with the protection of the man to the very best of our ability.

CONCLUSION

The problem of aircrew receiving injuries from windblast during ejection may never be fully resolved. However, the provision of improved helmet equipment and restraint systems combined with an education program on all aspects of ejection, can greatly enhance the possibility of escaping injury on ejection.

RECOMMENDATIONS

Based on the CF Accident Statistics Relevant to Windblast, it is recommended that:

a. helmet designers and manufacturers produce a helmet that will provide facial protection but not at the expense of other requirements;

b. ejection seats have not only leg but arm and head restraints; and

c. responsible authorities ensure that aircrew are kept fully informed on all aspects of ejection with emphasis on the use of the ejection seat trainer.

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PATHO-PHYSIOLOGICAL EFFECTS OF WIND BLAST FROM CONVENTIONAL AND NUCLEAR EXPLOSIONS *

BY

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SUMMARY

The patho-physiological effects of wind blast resulting from conventional and nuclear explosions are analysed and related to the effects of wind blast encountered in high-speed aircraft ejections and in airborne aircraft break-up, and to some instances of ground impact. It is suggested that data derived from studies of explosive blast effects may contribute to the analysis of aircraft accidents, and to the development of protective equipment for the crews of high performance aircraft.

INTRODUCTION

It may seem at first sight that a presentation of the patho-physiological effects of blast from explosion has no place in an exchange of information concerned with the problem of escape from aircraft. On reflection, however, it will be appreciated that the wind velocities which may be encountered by aircrew who are forced to eject from current high speed aircraft may be as great or greater than those which are known to cause lethal or sub-lethal injuries in explosive blast. Also that the various subsidiary effects of explosive blast can be identified with similar effects occurring in airborne high speed escape or during airborne break-up of high performance aircraft.

An understanding of the patho-physiology resulting from explosions in air may therefore contribute to the analysis of injury sustained in certain aircraft accidents, and hence to the development of protective measures.

In passing it is worthy of note that the effects of wind blast can be effectively simulated by the use of shock tubes or were by exposure to water drag at appropriately lower velocities (Fryer 1961), in the same way that underwater blast effects can be accurately reproduced in animals by exposing them to water 'slugs' of brief duration from high-powered water cannon. Hence the field for experimentation in blast effects remains open and offers a rather wide variety of techniques.

DEFINITIONS

Blast is a general term used to convey the effect produced when an explosive is detonated in any medium. Blast-produced injury implies those detrimental changes occurring in an organism whilst it is being subjected to the pressure field produced by an explosion, whether such changes are produced directly or indirectly by the explosive phenomena.

This article examines briefly the physical and patho-physiological effects of blast resulting from detonations in air. Air blast is further sub-divided into blast from conventional and from nuclear explosion.

PHYSICAL FACTORS

Detonation produces a high-speed chemical decomposition of a solid or liquid explosive into gas. Almost instantaneously the space previously occupied by the explosive is filled with gas and there is release of large amounts of thermal energy. The hot gaseous products develop a very high pressure which is transmitted to the surrounding medium and propagated in all directions as a shock wave, travelling at about the speed of sound. Typically this is a steep-fronted wave rising in a few microseconds and decaying over a period of milliseconds, depending upon the nature of the explosive and the medium which surrounds it. These also determine the character of the shock pulse and the subsequent phenomena.

EXPLOSIONS IN AIR - See Table 1

These result in:

1. A pressure pulse which emanates radially from an explosive source at the speed of sound in air.
2. A negative pressure component immediately following the pressure rise.
3. High transient winds which accompany the pressure variations and whose direction may be either positive or negative with respect to the explosive source.
4. Other effects such as fire and ground shock which are major contributions to the explosive damage.

A pressure gauge sideways-on to a conventional or nuclear explosion will record pressures that rise almost instantaneously to a maximum and then decay exponentially with time to reach a minimum which is less than the previous ambient pressure. The time constant is a function of the type of explosion and the range from the point of detonation. For conventional explosives an overpressure of 100 psi may be associated with duration of 2 m sec. and 10 m sec. for charges of 50 and 4,000 pounds respectively. In contrast for yields of 1 kiloton the pulse duration is of the order of 100 msec., and for 1 megaton of the order of 1 sec. This is highly significant when considering blast effects for whereas a conventional explosive pulse travelling at 1000 ft./sec. will pass a given point in 1 msec., so that the pressure pulse is 1 ft. in length, that from a kilo-ton explosion might take 100 msec. to pass the same point, representing a pulse 100 ft. in length. So that an object in the path of the shock wave would be subjected to a high pressure squeeze over a considerable period of time.

The duration characteristics also govern the displacement ('translation') of objects by blast winds. Short duration overpressures are accompanied by winds of short duration and the period that the blast winds have to accelerate an object is much shorter than is the case for long duration pressures and winds. In the latter case much higher displacement velocities are likely to be attained.

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* This paper was not presented at the Specialist Meeting, but is included in the Proceedings for reference.

Table 1 relates wind velocities to the dynamic pressures which they exert upon an object in their path. It will be noted that an over-pressure of over 16 psi may be exerted on aircrew forced to eject at Mach 1 at low level, and it is conceivable that even greater wind velocities could be encountered during ejection from current high performance aircraft at some altitudes. The lower wind velocities may not seem very alarming but it is instructive to realise that a hurricane of 120 mph exerts a dynamic pressure of only 0.25 psi, which emphasises the destructiveness of comparatively low wind over-pressures.

BLAST PRODUCED INJURIES

The biological effects of blast are customarily divided into:

1. Primary - due to sudden variation in local pressure.
2. Secondary - associated with the impact of debris energised by blast, shock, over-pressure, blast winds and often gravity.
3. Tertiary - comprising injuries resulting from gross body displacement ('translation').
4. Miscellaneous or indirect, eg thermal injuries resulting from fires initiated by hot gases or damage to structures and material.

All these aspects are of equal importance to medical organisations but this short article will deal only with the direct effects. It will examine:

(a) the nature of blast-produced injuries.
(b) development of criteria for predicting different levels of biological responses.
(c) application of these criteria to nuclear explosions.

It will also indicate how these factors may be related to aircraft wind blast effects.

PRIMARY EFFECTS

Primary effects have been defined above as those due to sudden variation in local pressure, and are ascribed to 'the pressure pulse which emanates radially from an explosive source at the speed of sound in air'. We have already noted that the wind velocity encountered in a high-speed air ejection may well be that of the speed of sound in air and hence the effects of the sudden over-pressure may be expected to resemble those produced by the shock wave from an explosion. I cannot claim, however, to possess evidence to confirm this possibility. There may, however, be some present with more recent and detailed experience of high speed ejection who are able to evaluate this point.

Typically damage resulting from a sudden variation in environmental pressure due to explosions produces lesions at or near the interface between tissues of different densities. Air containing organs are especially affected and the mechanism of injury may be that sometimes referred to as "Spalling", an effect produced when a shock wave travelling through one medium reaches an interface with another in which the speed of sound is substantially lower. In underwater explosions the shock wave travelling through the water at approximately 1450 m/sec traverses unimpeded through the tissues, but there is a negative reflection at the interface with an air-containing cavity across which the shock wave velocity will be substantially lower (about 1/5th), resulting in turbulence and disruption of the tissue medium. Since roughly similar effects are found in air explosions it would appear that the airborne shock wave accelerates when traversing the tissues but undergoes a similar negative reflection when it encounters an air-containing body cavity.

In the lungs there may be massive haemorrhage, especially sub-pleural, rupture of alveoli and the formation of sub-pleural bullae. Air escapes into the circulation and travels to the mediastinum, thence to the heart and azygos system and results in embolism in various organs of the body. It is likely that the central nervous system symptoms of widespread brain haemorrhages observed in World War II blast victims who had no external injury resulted from air embolism. Air embolism within the coronary arterial system leads to myocardial ischaemia and perhaps cardiac failure, a cause of early demise in many cases of exposure to blast.

Late deaths may result from pulmonary insufficiency due partly to the direct effects of the over-pressure and interstitial haemorrhage, partly to multiple small embolic foci within the lungs leading to pulmonary oedema. Comparison of these injuries with those of lethal high speed ejections would be most instructive.

SECONDARY EFFECTS

Secondary missiles produce a variety of injury including lacerations, contusions, penetrating wounds and fractures, depending upon the mass, profile, velocity and angle of impact of the missiles and the area of the body involved. These have been the subject of extensive studies in wound ballistics laboratories. Natural sequelae include death of tissue consequent upon vascular damage and serious infection, particularly where serous cavities are penetrated. Such typical secondary effects have been observed in aircrew when struck by pieces of acrylic from ruptured canopies, or by pieces of structure in air-to-air collisions. They have also been noted in victims of high speed aircraft breakup.

TERTIARY EFFECTS

Displacement or translation of the body may result in injury, often gross, either directly due to the accelerations imparted by blast winds or indirectly due to the decelerations resulting from impact with other fixed or moving objects. The degree of injury, of course, depends upon the magnitude of the accelerative or decelerative forces, the time and distances over which they act, shape, area and resistance of impact, and so on. There is a good deal of information in the literature relating to quantification of these tertiary effects, mainly emanating from the Lovelace Foundation, which may well be of value in attempting to determine aircraft velocities where aircrew have come into collision with the empennage or other structure, or with fixed objects in the event of ground impacts.

BIOLOGICAL CRITERIA

Biological criteria for blast damage relate levels of biological response to levels of variation in the immediate environment and are established by observation at the scene of actual disasters, by animal and human experimentation, and by derivation and extrapolation from experience of related circumstances such as aircraft seat ejection. In this way a good deal of information has been amassed which permits reasonably valid predictions to be made.

PRIMARY BLAST EFFECTS - See Table 2

Primary blast damage is largely a function of the character, magnitudes and rate of pressure rise and fall, and the duration of the pressure pulse. For classical wave forms, that is to say a steep-fronted wave rising in a few microseconds and decaying exponentially with time in the course of 1 - 1,000 milliseconds, very small overpressures are hazardous, provided that the pulse duration exceed some minimum which is species dependent. With very large over-pressures the duration becomes progressively less critical, and 50% lethality (LD_{50}) plots indicate that for pressures exceeding 100 psi a duration of 10 msec. will exceed the LD_{50} for most species which have been examined.

SECONDARY BLAST EFFECTS -

(a) Penetrating Missiles - See Table 3

Studies of the penetration of a 10 gm. glass fragment at impact velocities of up to 300 m./sec. have been conducted at the Lovelace Foundation. From these observations predictions have been made for glass fragments ranging from 0.5 gm. to 2 gm. mass, with impact velocities of 30 - 300 m./sec. As would be expected, penetration is directly related to both velocity and mass, and is expressed in the equation.

$$\log v = 2.5172 - \log (\log m + 2.3054) + 0.4842p$$

where v = impact velocity in ft./sec.
m = mass of fragment in gm.
p = probability of penetration.

Here again there may be a lesson to be learnt in aircraft accident analysis.

(b) Non-penetrating Missiles - See Table 4

Although blunt impacts over the heart, liver and spleen may prove fatal the most critical area for lethality is the head and a good deal of information relating to skull fracturing loads and impact velocities has been amassed from studies directed at the development of protective helmets.

In general these can be summarised as indicating that fracture of the unprotected adult human skull will result from impact velocities exceeding 518 cm./sec., average decelerations exceeding 500 g., or peak decelerations exceeding 750 g. If the head is regarded as having an average mass of 10 lbs. it follows that impact with a 10 lb. blunt object involving these velocities or accelerations will result in skull fracture. In other words skull fracture will result from a load (force) of 5,000 lbs. (mass x acceleration).

TERTIARY BLAST EFFECTS - See Table 5

Studies of impacts with a hard flat surface to determine LD_{50} velocities in several mammalian species have been extrapolated to give an LD_{50} velocity for a 70 kg. mammal of 800 cm./sec., or, say, an LD_{1} of 430 cm./sec. and LD_{99} of 915 cm./sec.

These extrapolations, although crude, are of the order of those applicable to head injury, and since the latter is the most frequent determinant of translational lethality it has been suggested that these figures may be taken as biological criteria for tertiary blast effects. However, they only apply to direct impact with a rigid, flat surface, and do not take into account the tumbling which is characteristic of bodies displaced by blast winds. For this reason it is now generally conceded that the LD_{50} threshold for tertiary blast effects should be raised by at least 50%. The latter figure is probably more realistic for similar effects in aircraft accidents.

DISCUSSION

It is my impression that comparative little of the foregoing material has been used either in the interpretation of aircraft accidents, or in the logical development of protective equipment designed to cope with very high speed ejections, (with the exception of the design of crash helmets). It seems likely that the concept of jettisonable cabins will become more and more the escape vehicle of the future, but in the present financial climate there are likely to be many nations which will have to consider the least expensive crew protective devices compatible with an effective air defence force and a cost-effective approach to aircrew loss and aircrew training.

I believe there are useful lessons to be learned from the foregoing and if this brief summary succeeds in stimulating some thought in this direction my purpose will have been accomplished.

ACKNOWLEDGEMENTS

This presentation is derived from my article in the Journal of the Royal Naval Scientific Service, Volume 29, No 3, 1974 which was based largely upon the work of the Lovelace Foundation and particularly upon the air-blast data borrowed from papers by C S White. Other information has been derived from my own work on the design of protective helmets and on aircraft escape, and also from a variety of papers many of which are classified and hence cannot be referenced here. However I am confident that anyone wishing to follow-up the work will have little difficulty in locating further information.

TABLE 1.

APPROXIMATE RELATIONSHIP BETWEEN DYNAMIC PRESSURES AND WIND VELOCITIES CALCULATED FOR SEA LEVEL CONDITIONS (adapted from C S White)

Max overpressure in psi	Wind velocity in mph
0.02	40
0.1	70
0.6	160
2	290
8	470
16	670
40	940
125	1500

TABLE 2.

TENTATIVE CRITERIA FOR PRIMARY BLAST EFFECTS

(Adapted from White)

Critical organs or event	Related max-pressure (psi)
Lung damage threshold	15
Lethality: threshold	30 - 42
50%	42 - 57
95 - 100%	58 - 80
Eardrum failure	5

TABLE 3.

TENTATIVE CRITERIA FOR SECONDARY BLAST EFFECTS*
(Adapted from White et al)

Critical organ or event	Related velocity for 10-gm glass fragment ft/sec
Skin laceration:	
Threshold	50
Serious wounds:*	
Threshold	100
50 percent	180
Near 100 percent	300

TABLE 4.

THE RANGES OF IMPACT VELOCITIES ASSOCIATED WITH EXPERIMENTAL FRACTURE OF THE HUMAN SKULL

(Adapted from White)

Range impact velocities ft/sec	Approx. velocity in mph	Approx. height of fall in.	Number of subjects	Fractures in percent
13.5-14.9	9.5	37	9	19
15-16.9	10.9	48	10	22
17-18.9	12.2	61	12	26
19-20.9	13.6	75	11	24
21-22.9	15.0	91	4	9
Total			46	100

Minimum velocity with fracture - 13.5 ft/sec (9.2 mph)

Maximum velocity with fracture - 22.8 ft/sec (15.5 mph)

Maximum velocity without fracture - unstated.

TABLE 5.

TENTATIVE CRITERIA FOR TERTIARY BLAST EFFECTS

(Adapted from White et al)

Critical organ or event	Related impact velocity ft/sec*
Total body:	
Mostly "safe"	10
Lethality threshold	20
Lethality 50 percent	26
Lethality near-100 percent	30
Skull fracture:	
Mostly "safe"	10
Threshold	13
50 percent	18
Near 100 percent	23

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LESIONS OBSERVEES APRES EJECTION A GRANDE VITESSE DANS L'ARMEE DE L'AIR FRANCAISE.

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RESUME

L'étude présentée porte sur 256 éjections dans les Forces Aériennes Françaises, réparties entre 1960 et 1974 et réalisées à des vitesses comprises entre 0 et 750 noeuds.

Les résultats statistiques globaux donnent :

- 47 éjections mortelles (18 %),
- 209 " réussies (82 %), (le pilote arrivant vivant au sol sans tenir compte des blessures éventuelles qu'il présente).
- 130 casques (51 %) et 30 masques (15 %) perdus à l'éjection.

L'analyse plus détaillée des éjections effectuées au-dessus de 400 noeuds (23 cas) montre que les effets du souffle apportent une accentuation importante des dégâts causés aux personnels et aux équipements de tête. Le pourcentage des morts reste de 18 %, mais celui des blessés est de 78 % contre 35 % dans la statistique générale et celui de la perte des équipements de 78 % pour les casques et de 40 % pour les masques. Dans un seul cas, le pilote est arrivé indemne au sol. Les lésions rencontrées vont de la simple ecchymose aux arrachements de membres.

Ces données correspondent approximativement à celles des statistiques des Armées de l'Air Etrangères.

Dans beaucoup d'accidents, il n'est pas toujours possible de faire la part entre les lésions dues au souffle proprement dit et celles qui ont des causes associées, voire indéterminées.

Trois cas particuliers spécialement démonstratifs des effets du souffle seront analysés en détail.

INTRODUCTION

L'évacuation d'un avion en détresse au moyen d'un siège éjectable offre encore de nombreux dangers et engendre un taux non négligeable de blessures de toutes sortes. Il est clairement démontré que la phase allant de l'éjection proprement dite au déploiement du parachute est de loin la plus délicate, source de près de 70 % des lésions. La vitesse au moment de l'abandon de bord est une cause importante des lésions. En effet dès sa sortie de l'aéronef l'ensemble siège-pilote va se trouver placé brusquement dans un milieu qui se déplace par rapport à lui à la vitesse relative de l'avion au moment de l'évacuation. L'ensemble siège-pilote est ainsi soumis à une force qui va dépendre de sa forme, de sa surface d'exposition, de la vitesse et de la masse spécifique de l'air. La force exercée par cette pression dynamique est donnée par la relation :

$$F = \frac{1}{2}\rho S \; V_c^2 \; C_x$$

ρ = masse spécifique de l'air.

S = surface du mobile.

V_c = vitesse corrigée.

C_x = coefficient de trainée (variable selon la forme de l'objet).

Les effets sur le corps humain au cours des évacuations à grande vitesse est essentiellement dus au vent relatif. En d'autres termes, seule compte la vitesse corrigée du mobile.

Ainsi une force considérable peut s'exercer pendant un temps relativement court sur l'ensemble siège-pilote et occasionner sur l'organisme humain soit directement soit indirectement des lésions graves voire mortelles. Si l'on admet que la surface du couple siège-pilote est voisine de 1 m^2 et que le coefficient de trainée est voisin de 1, à une vitesse corrigée de 500 noeuds un homme sur son siège est soumis à une force d'environ 4.500 kg/m^2. Une telle force de traînée conduit à une décélération extrêmement rapide et si pour une raison ou une autre un membre est projeté sur le côté du siège le simple calcul nous permet de rendre compte de l'amplitude des charges de flexion appliquée à ce membre et d'expliquer les lésions survenant.

Nous avons effectué à cet effet une étude portant sur 256 éjections réalisées dans les Forces Aériennes Françaises au cours de ces quinze dernières années (1960-1974) pour des vitesses comprises entre 0 et 750 noeuds.

I - STATISTIQUE GENERALE -

Les résultats statistiques globaux donnent :

- 47 éjections mortelles (environ 18 %)
- 209 éjections réussies (environ 82 %)

On entend par éjection réussie le fait que le pilote arrive vivant au sol sans tenir compte des blessures éventuelles qu'il présente. Dans notre cas ces blessures, de nature plus ou moins grave, apparaissent dans 35% des éjections.

Les dégâts causés aux équipements sont importants surtout en ce qui concerne l'ensemble de tête, c'est ainsi que 130 fois (51 %) le casque a été perdu et 39 fois (15 %) le serre-tête et le masque ont été arrachés.

Afin de déterminer les effets du souffle nous avons repris et analysé plus en détail 23 dossiers d'éjections effectuées à des vitesses égales ou supérieures à 400 noeuds. Les résultats statistiques globaux indiquent une nette accentuation des dégats causés aux personnels et aux équipements de tête. Sur 23 éjections il y a 4 tués, 18 blessés et une seule fois le pilote est arrivé indemne au sol. La perte des équipements de tête est importante, en effet le casque a été perdu 18 fois, le serre-tête et masque 10 fois bien qu'il ne soit absolument pas possible de relier directement cette perte à l'importance de la vitesse.

De telles données correspondent approximativement à celles des statistiques étrangères. Le pourcentage des éjections au-dessus de 400 noeuds (9 % dans notre statistique) est cependant légèrement supérieur à celui rencontré dans l'U.S. Navy et U.S. Air-Force en temps de paix (6 % des éjections).

II - LESIONS OBSERVEES -

L'étude analytique montre des lésions très différentes entre les abandons de bord effectués à basse vitesse et ceux effectués à très grande vitesse. Les lésions observées lors des éjections à grande vitesse sont souvent causées sous l'effet de la force exercée par le vent relatif.

Dans beaucoup d'accidents il n'est pas toujours possible de faire la part qui revient aux lésions dues au souffle proprement dit et celles dues à des causes associées voire indéterminées. Cependant certaines blessures plus spécifiques, à localisation précise, peuvent être attribuées à l'effet de la force aérodynamique du vent relatif dès la sortie de l'ensemble siège-pilote de l'avion. Elles vont de la simple ecchymose faciale à l'arrachement d'un membre avec mort.

-Perte de connaissance.

La perte de connaissance est un symptome que l'on rencontre souvent lors des éjections à grande vitesse (4 cas sur 23) dans notre étude. Elle dure quelques secondes, parfois plus, le pilote ne reprenant ses esprits qu'une fois suspendu au bout de son parachute. Au cours d'une enquête un pilote raconte les faits suivants : "dès la sortie de l'avion je ressens un coup de vent extrêmement violent contre le visage, j'ai senti que je mourrais en tournoyant ... ensuite j'ai vu mes pieds, la tache d'écume laissée par mon avion et mon masque à oxygène qui pendait ; je n'ai jamais vu le siège et je n'avais pas le rideau à la main".

-Les lésions cutanées et musculaires.

Dans plus de 70 % des cas les sujets présentent des lésions cutanées de type ecchymotique sur les différentes régions du corps imprimant au niveau du thorax et des membres supérieurs des traces de pression et de friction importante du harnais ou des bandes plus ou moins étendues légèrement ecchymotiques avec de petites suffusions hémorragiques et des pétéchies (10 cas dans notre statistique). Les lésions sont parfaitement nottes au niveau de la face et sont accompagnées de plaies (16 cas), de petites hémorragies sous-conjonctivales (10 cas) avec parfois un oedème palpébral plus ou moins accentué (3 cas).

-Les myalgies musculaires diffuses avec des hématomes plus ou moins étendus, les courbatures généralisées sont la règle et persistent pendant plusieurs jours (18 cas).

- Les lésions pulmonaires -

On a pu observer 2 cas de blast pulmonaire l'un relativement bénin avec signes cliniques (sensation d'étouffement, halètement, gène respiratoire) et signes radiologiques (images siégeant aux bases pulmonaires) l'autre mortel avec signes anatomo-pathologiques classiques (suffusions alvéolaires, hémorragies et oedème à l'autopsie).

- Les lésions traumatiques -

Les membres supérieurs et inférieurs sont inégalement touchés, les lésions vont de la simple contusion à l'arrachement d'un membre. La luxation du membre supérieur s'observe de temps en temps. En effet sous l'influence du souffle un des bras tenant le rideau est projeté vers l'arrière et le haut. La combinaison de ce mouvement réalise un point de friction et de pression sur l'aisselle et la face interne du biceps et entraîne une violente douleur de l'épaule et du bras qui pend inerte le long du corps. Tout essai de mobilisation déclenche alors une vive douleur cependant les radiographies ne montrent aucune lésion osseuse, la douleur cesse assez rapidement et la mobilité est récupérée en quelques jours.

A la suite d'une double éjection à une vitesse voisine du son à une altitude estimée de 15.000 à 10.000 pieds les deux rescapés ont présenté entre autre des lésions des membres inférieurs : luxation des deux genoux pour le pilote et luxation du genou gauche et fracture du fémur droit pour le navigateur. Dans les deux cas il y a eu rupture du ligament latéral interne et des ligaments croisés. En outre chez le navigateur il s'agissait d'une luxation ouverte par rupture de la face latérale interne des tissus du genou. Ces lésions sont consécutives au phénomène du souffle. Les genoux ont travaillé en rotation externe et se sont luxés : ceci explique la déchirure des ligaments latéraux internes. La cuisse droite du navigateur fracturée dans un premier temps a protégé les mouvements du genou et explique la non luxation du genou droit.

Cette éjection est ancienne et le type de siège utilisé ne possédait pas de système de retenue des jambes.

Les fractures nombreuses affectant un ou plusieurs segments de membre sont parfois nettes parfois réalisent un véritable fracas osseux. Nous avons pu également observer dans 2 cas un écartèlement de membre inférieur par disjonction de la symphyse pubienne.

STATISTIQUE GLOBALE

TOTAL DES EJECTIONS	Ejections manquées	Ejections réussies
256	47	209
	18 %	82 %

INFLUENCE DE LA VITESSE SUR LES EJECTIONS SUR LE PERSONNEL ET LE MATERIEL

Vitesse	Nombre d'éjections	morts	blessés	indemnes	casque perdu	masque arraché
400 noeuds et au-dessus	23	4	18	1	18	10

REPARTITION DES LESIONS AU COURS DE 23 EJECTIONS A DES VITESSES EGALES OU SUPERIEURES A 400 NOEUDS

LOCALISATION	NOMBRE DE CAS								
	perte de connaissance.	blast	lésions cutanées-pétéchies-plaies	myalgies diffuses	contusion	luxation	fracture	disjonction	arrachement.
	4	2		18					
crâne - tête			2		3		3		1
face			16				2		
yeux			13						
thorax			4						
sternum-côte						1	2		
membre supérieur			10		8	5	8		1
membre inférieur			3		12	7	10		1
bassin					2			2	
colonne vertébrale							2		

III - OBSERVATIONS PARTICULIERES -

A l'aide de 3 cas particuliers très démonstratifs nous allons reconstituer les mécanismes physio-pathologiques des lésions, grâce aux témoignages, aux études théoriques, aux calculs de trajectoire, à l'examen des équipements (siège, vêtements de vol, parachute, canot), aux clichés radiologiques et aux données de l'autopsie.

OBSERVATION 1

a) circonstances de l'accident.

Au cours d'une mission d'entrainement à l'interception, une collision avec un autre avion se produit à une altitude de 20.000 pieds et à mach 0,9. Le pilote ressent un choc très violent, pensant à une explosion il décide de s'éjecter. Il essaie d'attraper le rideau du siège Martin Baker mais ne peut lever la main gauche en raison des mouvements désordonnés de l'avion, il réussit cependant à saisir la poignée haute de la main droite et à tirer, l'éjection se produit. Immédiatement il ressent une douleur au niveau de la colonne vertébrale, un souffle très violent et une sensation de gène, d' étouffement, de respiration saccadée, d'halètement. L'équipement de tête est arraché. Après quelques sensations brèves de rotations la descente stabilisée a lieu et les séquences automatiques s'effectuent normalement. Le parachute pilote se déploie à une altitude d'environ 6.000 pieds, le choc à l'ouverture réveille la douleur vertébrale. La descente se termine sur un terrain très accidenté et le pilote ressent de nouveau une violente douleur vertébrale.

b) Examen des lésions.

Le pilote très choqué, souffrant énormément, respirant difficilement, présente à l'examen externe des plaies multiples de la face avec ecchymoses et pétéchies.

Les clichés radiologiques indiquent :

- au niveau pulmonaire, des images typiques de blast pulmonaire siégeant aux deux bases affectant un aspect emphysémateux,
- une fracture tassement importante de D_6 avec lésions probables de D_5 et D_7.

c) Examen des équipements.

Le siège n'a pu être retrouvé, l'accident ayant eu lieu au-dessus d'une région très montagneuse et isolée.

Aucun renseignement complémentaire n'a pu également été apporté par l'examen des vêtements de vol et du gilet de sauvetage, car ils ont été découpés lors de l'hospitalisation du blessé.

d) Reconstitution de l'accident et mécanisme pathologique des lésions.

A la suite du témoignage du pilote, de différents calculs, il est possible de reconstituer les événements.

La décision d'éjection par le pilote a été prise aux environs de 20.000. Il s'éjecte à 15.000 pieds à la vitesse de 0,9 mach - vitesse corrigée 470 noeuds. Du fait même de la configuration désordonnée de l'avion, de la position "en catastrophe" du pilote au moment de l'éjection ; la lésion traumatique vertébrale survient au départ du siège. C'est d'ailleurs à ce moment là que le pilote ressent sa douleur. Dès la sortie de la tête du siège la protection faciale par le rideau masque étant insuffisante du fait de la traction dyssymétrique du rideau, l'équipement de tête est arraché sous l'effet du souffle : perte de la coquille, du serre-tête et du masque qui est sectionné au niveau supérieur de la chenille. En effet la partie supérieure du corps du pilote a été soumis à une pression dynamique d'environ 450 millibars.

Ceci permet d'expliquer d'une part la survenue d'un blast pulmonaire et d'autre part les plaies faciales qui peuvent être dues soit à l'arrachement du casque et du masque soit à la force aérodynamique.

OBSERVATION 2

a) Circonstances de l'accident.

Lors d'un exercice de poursuite effectué par une patrouille au-dessus de la mer, le leader perd contact avec son équipier, les éléments de vol sont les suivants : altitude 15.000 pieds, vitesse 390 noeuds. Quelques instants après le leader en virage à gauche aperçoit presqu'en-dessous de lui une gerbe en cours de dissipation qui laisse place à une tâche verte parfaitement ronde d'environ 50 m. de diamètre, il descend et voit le canot pneumatique à une dizaine de mètres à l'extérieur de la tache.

Les plongeurs envoyés sur place découvrent le canot incliné à 90°, au 3/4 immergé. La sangle de liaison descend vers le pilote qui est retrouvé décédé, attaché par son harnais tete dirigée vers la surface, sans équipement de tête, bras et jambes emmêlées dans les suspentes Mae West non gonflée, combinaison et pantalon anti-G déchirés et sans chaussures

b) Examen des lésions.

Le sujet présente de nombreuses ecchymoses avec pétéchies au niveau de la face et du thorax avec prédominance à gauche. Il y a luxation du coude gauche et disjonction de la symphyse pubienne liée à un écartèlement avec plaie profonde et large du périnée et hémorragie importante.

c) Examen des équipements.

La voilure du parachute présente des déchirures et des brulures légères dans l'ensemble, le harnais est en bon état mais sanglé d'une façon dyssymétrique.

Les effets de vol sont endommagés : déchirures des jambes droite et gauche de la combinaison étroite, absence de la jambe droite du pantalon anti G et déchirure de la jambe gauche.

Il en est de même du gilet de sauvetage qui laisse apparaître la vessie à droite et à gauche.

d) Reconstitution de l'accident.

Bien que privé d'informations précieuses telles que la vitesse, et l'altitude d'éjection, les témoignages du leader, l'examen des lésions et du matériel ont permis d'émettre des hypothèses sur les circonstances de cet accident.

L'avion a percuté la surface de l'eau sous une incidence proche de 90° : tache parfaitement ronde. L'éjection s'est faite près de la surface de l'eau, environ 1800 pieds à vitesse élevée, impossible à préciser, mais très supérieure à 400 Kt, vu l'attitude en piqué de l'avion.

Les ecchymoses multiples de la face et du thorax montrent que l'éjection a dû se faire sans la protection du rideau, leur gravité liée à l'arrachement de l'ensemble de l'équipement de tête montre que l'éjection a dû se faire à grande vitesse.

L'écartèlement est la conséquence d'un mouvement des jambes vers l'extérieur et vers l'arrière et indique la non efficience pour une raison indéterminée du système de rappel des jambes au moment de l'éjection.

L'absence d'autres lésions tend à montrer que l'impact à l'arrivée sur l'eau s'est fait parachute ouvert normalement.

Enfin les détériorations de la voilure étant minimes, l'ouverture a donc du se produire dans le domaine d'utilisation du parachute.

Parmi les hypothèses échaffaudées sur le déroulement de l'éjection nous retiendrons celle-ci :

le pilote décide de s'éjecter et actionne la commande haute, le siège part, les rappels de jambe ne jouent pas leur rôle. Dès la sortie de l'ensemble siège-pilote sous l'effet de la force aérodynamique le pilote est écartelé, le rideau et l'équipement de tête sont arrachés. Ensuite l'ensemble des séquences automatiques de l'éjection semble s'être normalement déroulé.

L'importance des lésions au sortir de l'avion suffisent à expliquer la mort du pilote. L'autopsie qui n'a malheureusement pas été pratiquée aurait permis de le confirmer.

OBSERVATION 3

a) Circonstances de l'accident.

Au cours d'un retournement de combat à partir de 30.000 pieds, l'avion se met en piqué à 70° pour une raison indéterminée. Vers une altitude de 15.000 pieds jugeant, compte tenu de sa vitesse (mach 1,2 - 630 noeuds), qu'il n'avait plus la possibilité d'effectuer une ressource, le pilote a pris la décision de s'éjecter. Mise à feu au moyen de la poignée haute le siège s'est séparé de l'avion à l'altitude estimée de 9000 pieds et une vitesse corrigée de 690 noeuds.

Les séquences automatiques de l'éjection s'étant effectuées normalement, le parachute-pilote s'est déployé à une altitude approximative de 3500 pieds. La descente se termine dans un petit étang à 500 mètres de l'impact avion. Le pilote a été retrouvé décédé, flottant à la surface. La jambe gauche arrachée est retrouvée à 300 mètres de l'étang.

b) Description des lésions.

L'examen externe montre :

- des lésions de la face (fracture du nez, ecchymoses périorbitaires bilatérales),
- des fractures des deux humérus,
- un abdomen ouvert avec éviscération partielle du bassin,
- un arrachement du membre inférieur gauche au niveau de l'articulation sacro-iliaque,
- des fractures des deux fémurs dont une ouverte à droite.

L'examen radiologique post-mortem a mis en évidence les lésions suivantes :

- une fracture multifragmentaire du tiers moyen de l'humerus droit,
- une fracture du col chirurgical de l'humerus gauche avec luxation de la tête humérale,
- une fracture transversale sans déplacement du corps des 2 omoplates,

- une luxation sterno-claviculaire gauche,
- une fracture de D_6 tassement latéral gauche,
- une fracture-luxation du sacrum avec disjonction des deux articulations sacro-iliaques (rotation de 90° du sacrum) et disjonction de la symphyse pubienne,
- une fracture symétrique du tiers moyen des deux fémurs,
- une fracture de la styloïde du V° métatarsien gauche.

La radiographie pulmonaire montre des opacités arrondies ou ovalaires à contours flous et estompés, prédominant essentiellement au niveau des bases.

L'autopsie nous a révélé en particulier au niveau des poumons des marbrures importantes avec hémorragies en surface, un aspect emphysémateux, oedémateux. A la coupe les lobes sont crépitants, rosés, spumeux et oedémateux.

Nous avons noté un infarcissement des lobes supérieur et inférieur de chaque poumon. L'examen histologique a conclu à des lésions d'oedème pulmonaire sur un fond d'alvéolites catarrhales et hémorragiques au stade aigu.

L'examen du péritoine, de l'épiploon, des intestins, du mésentère, de la rate, de la vessie, de la prostate et du pénis n'a pu être pratiqué, car ces organes ont disparu à l'éviscération.

Les examens histologiques du cerveau et de la moelle épinière ne mettent pas en évidence de lésions pathologiques.

c) <u>Examens des équipements.</u>

Les déformations très importantes constatées lors de l'examen du siège sont dues aux effets de l'impact sur un sol dur. La structure du siège avait été soumise auparavant aux contraintes sévères de l'éjection à grande vitesse. Il est toutefois fondamental de souligner qu'elles n'ont en rien affecté le déroulement normal des séquences automatiques de l'éjection.

Le fait essentiel à retenir dans l'examen des équipements-siège est la perte en cours d'éjection des deux jarretières des serre-jambes dont une seule a été retrouvée plusieurs jours après l'accident, rompue au niveau de la boucle de serrage, à 7 cms de l'extrémité du bout mort.

Les vêtements de vol sont très endommagés : couture du blouson de cuir éclatée, pantalon anti-G, combinaison de vol et sous-vêtements déchirés et en partie arrachés.

d) <u>Reconstitution de l'accident et mécanisme physio-pathologiques des lésions.</u>

A la suite des témoignages, des études sur simulateur Mirage [illegible] et des calculs de trajectoire il est possible de fixer les paramètres à l'instant où la décision d'éjection a été prise par le pilote : altitude 15.000 pieds, nombre de Mach 1,2 - vitesse corrigée 630 noeuds.

La mise à feu du siège a été réalisée par traction sur la poignée haute. L'éjection automatique de la verrière a été normale. L'enquête a établi que le serrage des sangles du harnais est insuffisant. Le caractère dyssymétrique de la fracture est dû à une mauvaise position du pilote et la lésion traumatique survient au départ du siège.

Toutes les autres lésions surviennent quasi-simultanément et sont dues au souffle. Dès la sortie de la tête du siège, le rideau et la partie supérieure du corps du pilote est soumis à une pression dynamique légèrement supérieure à 1.000 millibars. De ce fait le rideau a été projeté en arrière ainsi que les bras du pilote. Ainsi apparaissent les fractures de l'humérus droit, la fracture luxation de l'humérus gauche, les fractures des omoplates et la désinsertion sterno-claviculaire gauche. Simultanément l'ensemble de tête a été arraché, ce qui a permis d'observer des lésions de blast rencontrées au niveau des deux poumons.

Pour les lésions des membres inférieurs et l'arrachement du membre inférieur gauche, il semble qu'il en soit de même. En effet, à l'éjection du siège, il se produit un mouvement symétrique des jambes vers l'extérieur, cette hypothèse est vérifiée par les empreintes retrouvées dans les logements des embouts coniques de deux sangles de rappel des jarretières.

La jarretière gauche n'aurait pas accompli son office de maintien de la jambe très probablement à cause de sa rupture (en effet une jarretière a été retrouvée rompue au-delà de la position de serrage, mais il n'a pu être déterminé si celle retrouvée était la gauche ou la droite). La jambe gauche est alors projetée vers l'arrière et vers le haut à hauteur du "connector" et heurte au niveau du fémur le montant latéral gauche du dossier du siège. En effet on retrouve la chenille d'oxygène écrasée et en partie sectionnée par le montant gauche et la plaquette de fixation du "connector". Les radiographies montrent l'aspect particulier de la fracture avec rotation en dedans du fragment inférieur.

L'amplitude de ce mouvement de la jambe vers l'extérieur a été rendu possible par la dislocation lombo-sacro-iliaque et la jambe gauche qui n'est plus retenue que par les tissus musculaires est arrachée par l'effet du souffle qui est alors suffisant.

La similitude de fracture du fémur droit implique un processus identique et fait penser que si la jarretière droite a rempli son office de rappel de la jambe en début d'éjection (empreintes dans les logements des embouts coniques) sa tenue ultérieure reste indéterminée, mais laisse supposer une rupture des deux jarretières sous l'effet du souffle.

Il est intéressant d'évaluer les efforts subis par le membre inférieur du pilote au moment de la sortie du siège de la cabine.

Le calcul théorique a permis de préciser que dans ces conditions le membre inférieur du pilote avait été soumis à une force de 855 Kg, ce qui permet d'expliquer les déformations subies par le système de retenue des jambes, les fractures et arrachement des membres.

CONCLUSION -

Les effets du souffle au cours des éjections à grande vitesse provoquent des dégâts importants aussi bien aux personnels qu'au matériel. Les blessures rencontrées en dehors des lésions classiques sont plus spécifiques et proviennent soit de l'effet direct soit de l'effet indirect de la force aérodynamique exercée sur le corps humain. Au-delà de 400 noeuds elle peut atteindre plusieurs tonnes et permet ainsi d'expliquer l'arrachement de l'équipement de tête, les lésions de la face, les traumatismes graves des membres supérieurs et inférieurs (luxations-fractures), les disjonctions articulaires et même parfois l'arrachement d'un membre.

La mise à feu du siège éjectable par la poignée haute assure dans la majorité des cas non seulement une protection efficace du visage par le rideau-masque mais également une position correcte qui offre une moindre prise au vent relatif. L'utilisation d'un système efficace de rappel et de maintien des jambes contre le baquet du siège s'avère indispensable.

Cependant comme nous le montre l'observation N° 3 au-delà de 600 noeuds, le domaine d'utilisation du siège est dépassé et les systèmes de protection deviennent inefficaces. Ainsi se trouve posé le problème de la conception et de la fabrication des systèmes efficaces de maintien de la tête, du buste, des bras et des jambes de l'utilisateur. L'amélioration des performances du siège assurant une stabilisation sur trajectoire évitant les basculements et les rotations intempestives, telle que le réalise le siège à fusée est indispensable.

Enfin la corrélation des données des témoignages, des études et calculs théoriques, des examens cliniques des lésions, des radiographies, et de l'examen des équipements permet de reconstituer les circonstances de l'accident et d'en expliquer les mécanismes pathogéniques des lésions observées.

Nous ne serions suffisamment insister non seulement sur l'intérêt de l'emploi systématique de l'autopsie mais encore de la radiographie post-mortem qui ne se contente pas de visualiser les lésions mais qui joue un rôle non négligeable dans l'explication de leur mécanisme pathogénique.

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WIND BLAST: PROTECTION FOR THE HEAD BY MEANS OF A FABRIC HOOD

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SUMMARY

It appears that in wartime operations there is a high probability of aircrew having to eject at low level and at transonic speed and there may be little chance of creating more favourable conditions for escape by exchanging forward speed for altitude.

Wind tunnel experiments and operational[1] experience show that current helmets are usually lost on exposure to airspeeds from 350 to 500 kt.

This paper gives an account of experiments that have been done to prove the feasibility of protecting the head from exposure to blast by means of an automatically erected fabric hood.

These experiments show that such a hood placed over the face of a dummy test subject drapes the head effectively on exposure to blast, and prevents the loss of even simple helmet assemblies at least up to mach 1.

INTRODUCTION

There are a number of ways of protecting aircrew from the effects of exposure to blast during escape at air speeds up to Mach 1. One of these attempts full protection for aircrew, and in its developed form is to be found as an ejectable nose or crew compartment in the USAF F111 strike-aircraft. The device is extremely complex and expensive so one is naturally drawn towards the development of simpler concepts. Typical of such ideas is the rigid helmet with an automatically closing and sealing visor as in the Mk 5 helmet now under development for the Royal Air Force. However, it is suggested that the use of a strong fabric face-screen or hood might well provide a yet simpler and cheaper solution to the problem. The idea of using a fabric cover[2] to protect the face from exposure to blast is not new, and a version has been encorporated in Martin Baker seats for many years. Unfortunately at very high air speeds the Martin Baker face-blind is unusable because the hands are likely to be torn from the firing handle and the arms subjected to serious flailing. It is now the practice to use the seat pan handle rather than the blind for ejection.

It appears that the effectiveness of the face-blind depends on its being held down. Unfortunately failure to keep a grip on the firing handle allows the wind to strip the blind exposing the face to blast and allowing the loss of the protective helmet.

This paper discusses the development of a fabric hood designed to overcome these difficulties in that it is automatically erected into position and firmly fastened at its lower end, so that on exposure to the airstream it drapes the head.

DISCUSSION:

EARLY HISTORY[3]

Some years ago a full pressure suit for high altitude operations was developed at the RAE. The head enclosure was quite unauthodox (see Figure 1) in that it was made from rubberised silk, terylene cloth and melinex and was operable after the fashion of a clam shell or handbag. The helmet was given shape by a pair of hinged metal hoops which carried a gas pressure seal and mechanical locking device. In the open condition the fabric hood folded up and the hoops rested on the back and chest of the wearer. The clam shell helmet could be erected and closed automatically within < 160 ms by means of a pair of inflatable tubes attached to the hinges.

The form of this helmet suggested that it might in principle make the basis of a device for protecting the head from exposure to blast. Clearly, in these circumstances only the front half of the clam shell would be needed, but the metal hoop would be an unacceptable hazard during ejection, so it would have to be replaced by a stiff non rigid device such as a shaped tubular pneumatic frame.

STOWAGE AND ERECTION

Stowage and erection of the proposed anti blast hood are secondary to its protective function, but because of interaction with other aspects of man/equipment assemblies a great deal of the available effort was devoted to the development of the pneumatic system. However, because the development of a rigid anti-blast helmet had already started, work on the fabric hood could only be carried out on a low priority basis spread over several years.

After several unsuccessful experiments with inflated tubes in various different configurations, it was decided to try the effect of a straight rubber tube constrained to the shape of the hood frame by a terylene fabric envelope of somewhat smaller diameter. Although an improvement on earlier configurations, the resulting structure was not immediately stiff enough, but by triangulating the limbs of the frame with pneumatic struts a satisfactory arrangement was achieved as shown in Figure 2.

A sketch of the inner rubber tube dipping with its bifurcated struts is shown in Figure 3. The terylene cover was cut and made up in such a way that it controlled the shape of the whole system, and a very promising structure was achieved with an inflation pressure of about 3 atm.

Having achieved an acceptably stiff pneumatic frame for the fabric hood a means of stowing the device on the crewman's body garment was sought. Eventually a satisfactory method of packing the hood was found and put into operation as follows:-

a. The inflation tube is joggle folded as shown in Figure 4.

b. The loose fabric of the face hood is folded concertina fashion on top of this.

c. The last of the hood fabric with attached velcro patches is rolled over and pressed down on to a velcro U shaped base forming a neat horse collar which is finally dutch laced to the body garment. See Figure 5. The hood can be released from the body garment during descent by pulling a toggle which allows the dutch lacing to run.

It was found that the manner in which the high pressure gas was admitted to the erection tubes was important in that the force available for correct positioning was adequate in the early stages of the operation but not towards the end of the cycle.

In practice it was found necessary to ensure that the front of the hood burst out of its package first and was thrown forward so that the maximum effort was available for clearing the head-gear. See Figure 6. This was achieved by porting the high pressure gas into each rear strut above the packing kink so that the limbs of the hood were inflated immediately as far forward as the joggle folds.

In a number of successful erections made in still air, the leverage applied by the pneumatic system at 3 atm was found to be enough to overcome fouling of the head-gear with the head in any natural position and wearing current RAF protective helmets. It was found however, that the hoops tended to narrow at the base at higher residual pressures, apparently due to stretching of the terylene cloth in the struts. This could cause fouling with wider head-gear assemblies.

Two blast exposures were made (facing into wind) at 350 kt. In one of these a completely successful erection was made, but in the other the hood fouled the side of a Mk 2 RAF helmet but did free itself. It should be noted, however, that in practice the hood will be erected before exposure to air blast.

SPEED OF ERECTION

As already indicated the fabric hood must be erected before exposure to the blast and it is desirable to achieve as high a speed as possible in order to anticipate the jettisoning of the canopy by a useful margin. For instance, in modern aircraft the time available may be as short as 0.06 seconds.

A bread-board gas supply system (nitrogen) was made up to test the speed of erection. It consisted essentially of a small pressure vessel of about 18 cc water capacity connected to the erection tubes via a quick release cock and 3 mm bore high pressure rubber tubing. The initial gas pressure in the pressure vessel was about 136 atm and the residual pressure in the erection tubes was about 3 atm after operation. An electronic clock was used to measure the time of erection both from the instant of break out and from the operation of the quick acting cock.

Figure 6 shows the time history of a typical erection from the break out of the stowage, the erecting time was 0.11 seconds while from the gas trip it was 0.28 seconds. The increased time was apparently due to the resistance of the gas delivery pipe. It was found however that the speed of the gas delivery had apparently reached its optimum value for this hood design since any increase in the rate of flow tended to upset the sequence of the break out cycle making fouling the head-gear more likely.

EXPOSURE TO BLAST

Preliminary blast tests were made on the anti-blast hood in a blower tunnel where the maximum attainable air speed was 350 kt and where the duration of exposure could not be closely controlled. The head-gear worn was the RAF Mk 1 protective helmet, G type cloth flying helmet and P type oxygen mask.

Some 15 exposures were made with the dummy man set up at various angles to the air stream and the results of the tests are summarised in Table 1. In view of the damage done to the fabric structure it is clear that neither the sail cloth used in the hood nor the stitching were strong enough for the very severe conditions expected at transonic air speeds. The fabric used in the tests was a terylene material weighing about 136 g/m^2 and having a strength of 262 N per cm run. Later models of the anti-blast hood were made up in a heavier sailcloth (M26) which has a weight of about 190 g/m^2 and a strength of 445 to 462 N per cm run.

It was observed during the tests, that the face hood seemed to be less stable in some circumstances when the erection tubes were pumped hard than when they were not. This is believed to have been caused by stretching of the sailcloth when under pressure and indeed the use of heavier material in later models seemed to overcome the difficulty.

Two ejections from a Canberra aircraft at speeds between 400 and 450 kt were disappointing. In one case, in spite of very turbulent air conditions in the open rear cockpit, the hood was erected successfully, but for reasons unconnected with the test, the seat was not fired. In a second case the turbulence caused the anti-blast hood to deploy wrongly and so the hood and the head-gear were lost during ejection. Ejection tests from the Canberra had to be discontinued owing to the withdrawal of the aircraft but hood erection tests were continued in a 7 m wind tunnel at low air speeds. These show the maximum air speed from various directions at which successful deployment can be expected. They are as follows:

Angle to Air Stream 0°	Slight Deployment Fault at x m/s Air Speed		Satisfactory Erection at x m/s Air Speed
0	-		36 (70 kt)
45	21 (41 kt)	Below	21
90	26 (50 kt)		21

EJECTION FROM A ROCKET PROPELLED SLED

Following the loss of the Canberra as a test facility, other possibilities had to be considered. Fortunately the Pendine high speed rocket track became available at this time and two experiments were set up to test the behaviour of the anti-blast hood on exposure to transonic air speeds.

The vehicle offered was an expendible sled and the other conditions of test were as follows:-

i	Dummy:	RAE type with stiff neck, padded hips and wearing a normal overall.
ii	Special Clothing:	Torso garment with anti-blast hood attached (see Figure 5).
iii	Head-gear:	G type cloth flying helmet, Mk 1 protective helmet and P type oxygen mask with chain suspension harness.
iv	Head Restraint:	None - stiff neck dummy.
v	Leg Restraint:	Garters and legs tied at knee.
vi	Arm Restraint	Arms held to body under parachute harness.
vii	Blast Protection:	Anti-blast hood erected prior to test. Inflation tubes blown up to about 3 atm and sealed.
viii	Seat:	Mk 3 seat, 2 harnesses, type Z parachute, 1.25 seconds time delay.

The first experiment failed for reasons unconnected with the test, but it did show that the heavy terylene sailcloth used in the fabrication of the hood was strong enough for exposure at sonic air speed.

The test was repeated using a new anti-blast hood. The speed of the vehicle at the moment of ejection was about 650 kt and Figure 7 shows an extract from the film record of the flight of the seat; the frame intervals being 40 ms each except for the last one which is 80 ms. The film shows the white anti-blast hood firmly draping the dummy head throughout this period and on retrieving the test specimen it was clear that the oxygen mask and protective helmet had remained in place. They were found close to the dummy head which had separated from the body on impact with the ground. The anti-blast hood suffered little damage (Figure 8) in spite of the severe blast to which it had been exposed. Clearly then, the M26 terylene sailcloth gave reasonable protection from exposure to air blast at about 650 kt.

Two further tests were made using this time the blast test facility[4] at RAE Bedford. The dummy man was dressed in a normal overall, a Mk 14 life preserver, a Mk 2 protective helmet and a P type oxygen mask with a chain suspension harness; the anti-blast hood being pre-erected.

At 650 kt air speed with the dummy seated facing into wind, the oxygen mask and protective helmet showed no sign of disturbance, although the erection tubes and their attachment to the periphery of the hood were badly torn. In spite of this damage the dummy face was effectively covered throughout exposure.

After essential repairs, the same hood was used in a further test at 750 kt. While adequate cover for the face was given, the visor bar and visor transparency were forced up over the crown of the helmet. The oxygen mask came off the face when one of the suspension chains and the breathing tube broke. Both were trapped inside the hood which was still covering the face and the helmet itself remained on the head. Figure 9 shows the extent of the damage suffered by the fabric face hood.

CONCLUSIONS

Different ways of protecting aircrew from exposure to blast during ejection have been under consideration by various authorities for many years. In the United Kingdom the chosen device is a rigid helmet with an automatically closing and sealing visor. However, we are encouraging workers to seek other solutions to the problem, and the experiments described in this paper set out to prove the feasibility of one such concept : a fabric hood which is used to protect the head from exposure to blast in ejections from aircraft up to transonic air speed.

Work on this concept has proceeded at low priority over a period of about 10 years, but the accumulated results of our experiments are certainly encouraging. For instance, ejection from the high speed rocket sled and tests in the Bedford blast tunnel show that even the simple protective helmet assemblies can be kept on the head during exposure to blast up to sonic air speeds.

The Canberra experiments, in spite of their lack of success, show the importance of erecting the hood before jettisoning the canopy. The development of means of stowing and erecting the anti-blast hood has been successful in principle, although the speed of erection (100 ms) is too low for modern requirements and work is still required to cut this time by at least 50%. This of course is bound up with the development of a man mounted miniature gas supply unit. Up to the present time only working bread-board models have been made.

Clearly, the experimental work on this project has not gone far enough but the results so far obtained show that rigid totally encapsulating helmets as a protection against exposure to blast, could probably be replaced by the much simpler and cheaper fabric hood and standard type of protective helmet.

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DISCUSSION

In reply to questions from Glaister, Thorne stated that the dummy head seen in the high speed films (RAE Bedford blast testing) had been as free to move as would be expected from a normally articulated dummy when restrained by a 5-point harness. They had not attempted to simulate human head and neck response. Thorne also stated that helmet lift forces had not been determined and would probably prove impossible to measure within the short time available - especially with a decaying turbulent velocity profile. Payne (U.S.) considered that the jet size would have been inadequate for accurate measurement, and asked whether the helmet was weakened in any way, and what was the strength of the chin strap. He mentioned that two kinds of helmet strap were in use in the U.S., with break strengths of some 400 - 500 lbs and 4 - 5 lbs respectively, and wondered in which category the test helmet came. Thorne replied that it was the standard RAF Mk 2 helmet with conventional strap. (This was originally fitted with shear pins designed to break at 130 - 150 lb, but four years ago the strength of these pins was doubled to reduce the frequent occurrence of helmet loss, and they have since been eliminated. The current neck strap breaks at about 350 - 400 lb - Ed.)

TABLE 1

Test No	Air Speed Kts	Angle of Inclination to Slip Stream	Angle of Twist to Slip Stream	Conditions of Erection Tubes	Remarks
1	350	0	0	Pumped Hard	Fabric torn and frayed over oxygen mask - caused by mic switch - 2 inches long. Very small tear in brow ½" long - cause not known.
2	"	+45	0	Hard	Threads broken and gusset seam lifted on L.H. side of brow.
3	"	+80	0	Medium	Screen flapping a lot. Initially lifted off face for very short time - no damage.
4	"	-45	0		No anti-blast screen - sun visor torn off. Protective helmet blown away. O_2 mask toggled down tight - not disturbed.
5	"	-45	0	Medium	Patches and seams sewn over with zig-zag stitching - no damage.
6	"	-80	0	Medium	Patch over L.H. brow gusset lifted. Otherwise no damage.
7	"	0	90	Medium	Wind got into back of screen. Velcro peeled off overall and torn from bottom of screen.
8	"	0	45	Medium	Rather long exposure - 15 sec above 100 mph - down stream flutter caused L.H. brow gusset to break and some stitching attaching erection tube to screen broken - about 3" long.
9	"	+45	45	Hard	New screen with transparent PVC goggles sewn into face-piece - no damage.
10	"	-45	45	Hard	Old screen again. L.H. brow patch broken and frayed. Zig-zag stitching along top of mask reinforcing patch broken - velcro and press studs stripped down stream round to centre.
11	"	+45	45	Hard	Velcro and press studs stripped round to R.H. shoulder. Sun visor on protective helmet blown away. Mask harness left loose - not disturbed.
12	"	+45	45	Slack	No damage - a lot of down stream flutter. New screen used.
13	"	+45	45	Hard	Velcro and press studs stripped half way.
14	"	+45	45	Slack	Large gap at nape of dummy head blocked up - no damage fastenings intact.
15	"	+45	45	Hard	Gap at nape of neck blocked - no damage.

<u>NOTE 1</u>

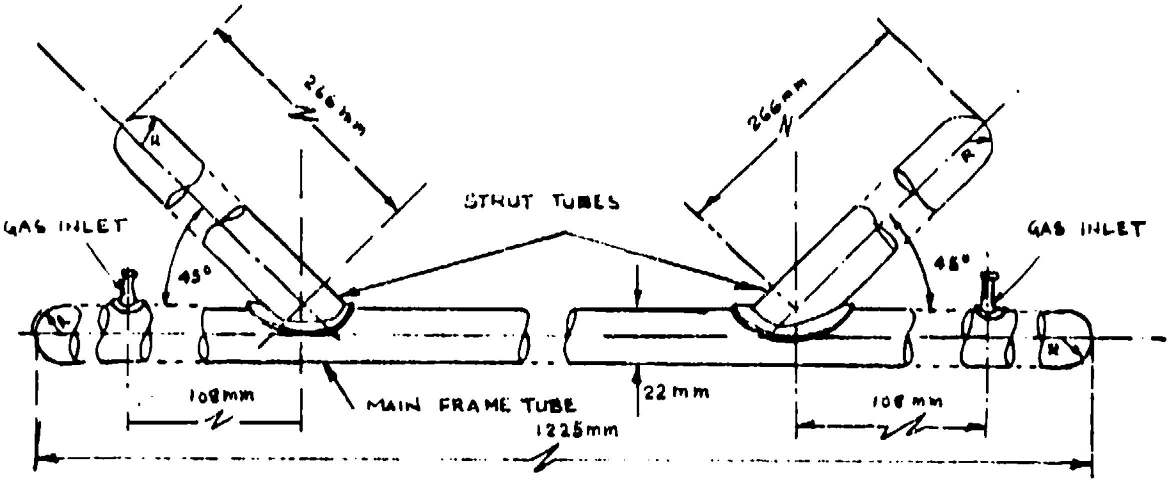
+ Indicates inclination of dummy away from } Slip Stream
- Indicates inclination of dummy towards } Slip Stream

<u>NOTE 2</u>

Only in the case of test 7 was the face exposed to the blast. In the other tests the damage was relatively slight and would not have occurred if it had been possible to limit the exposure to 3 or 4 seconds total. In tests 10 to 13 air was deflected round the back of the head causing the screen to parachute.

Fig.1 Fabric head enclosure for full pressure suit

Fig.2 Erected hood showing triangulating struts



MATL: BLACK RUBBER LATEX DIPPING 0·75 mm THICK.

Fig.3 Anti-blast hood:inner tube for pneumatic erection frame

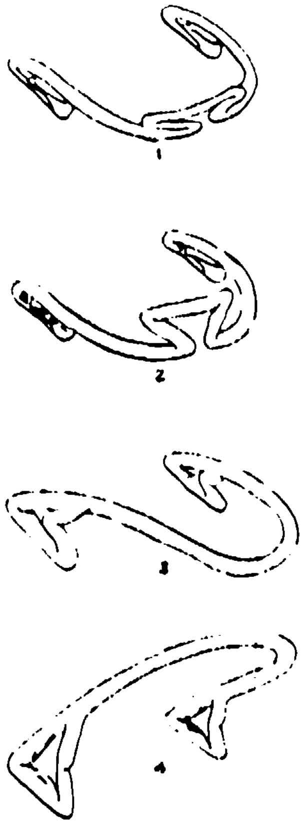


Fig.4 Diagram showing joggle fold stowage, four stages in erection of tubular frame

Fig.5. Horse collar hood stowage within life preserver

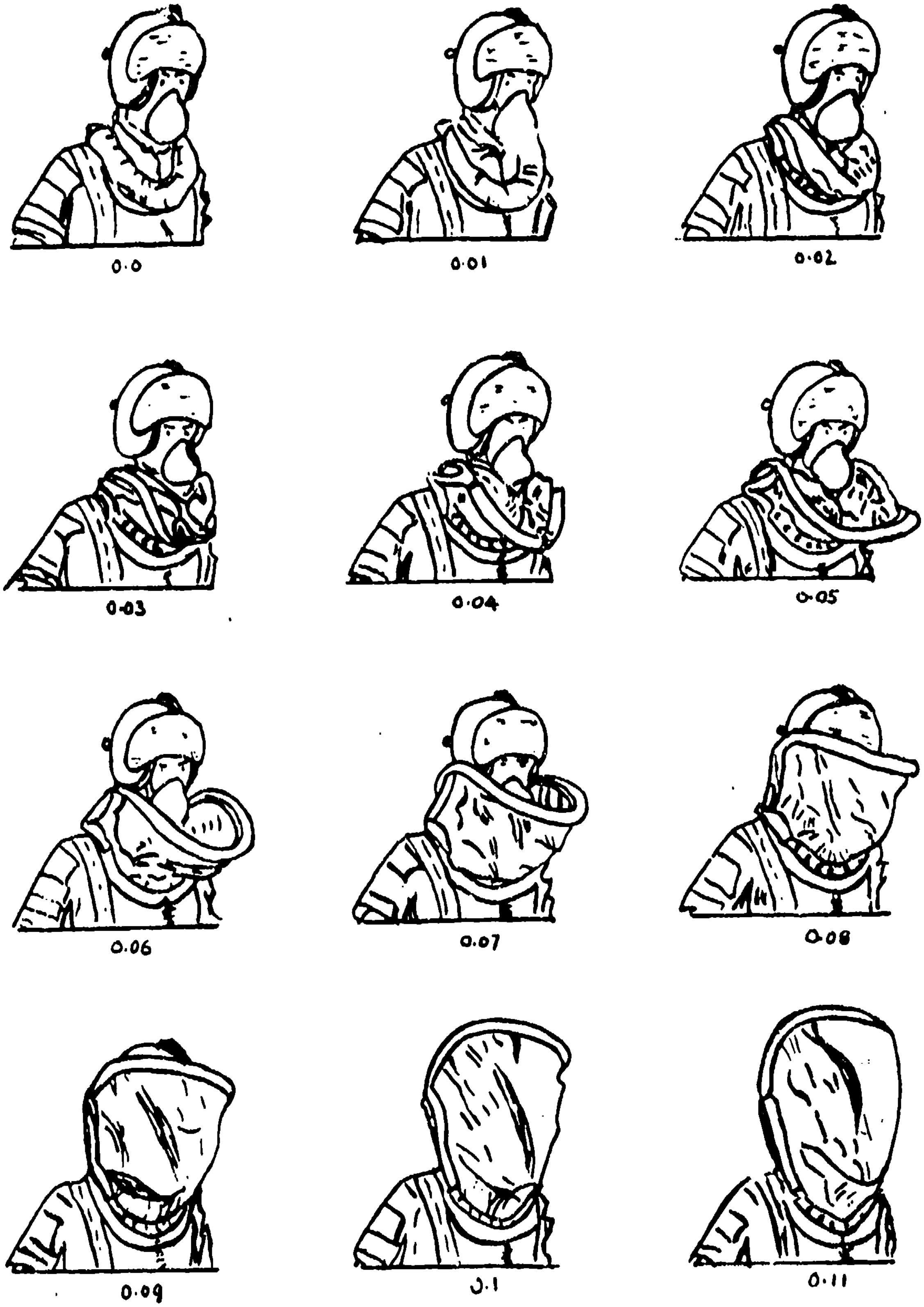


Fig.6 Erection of anti-blast hood Vs time (sec)

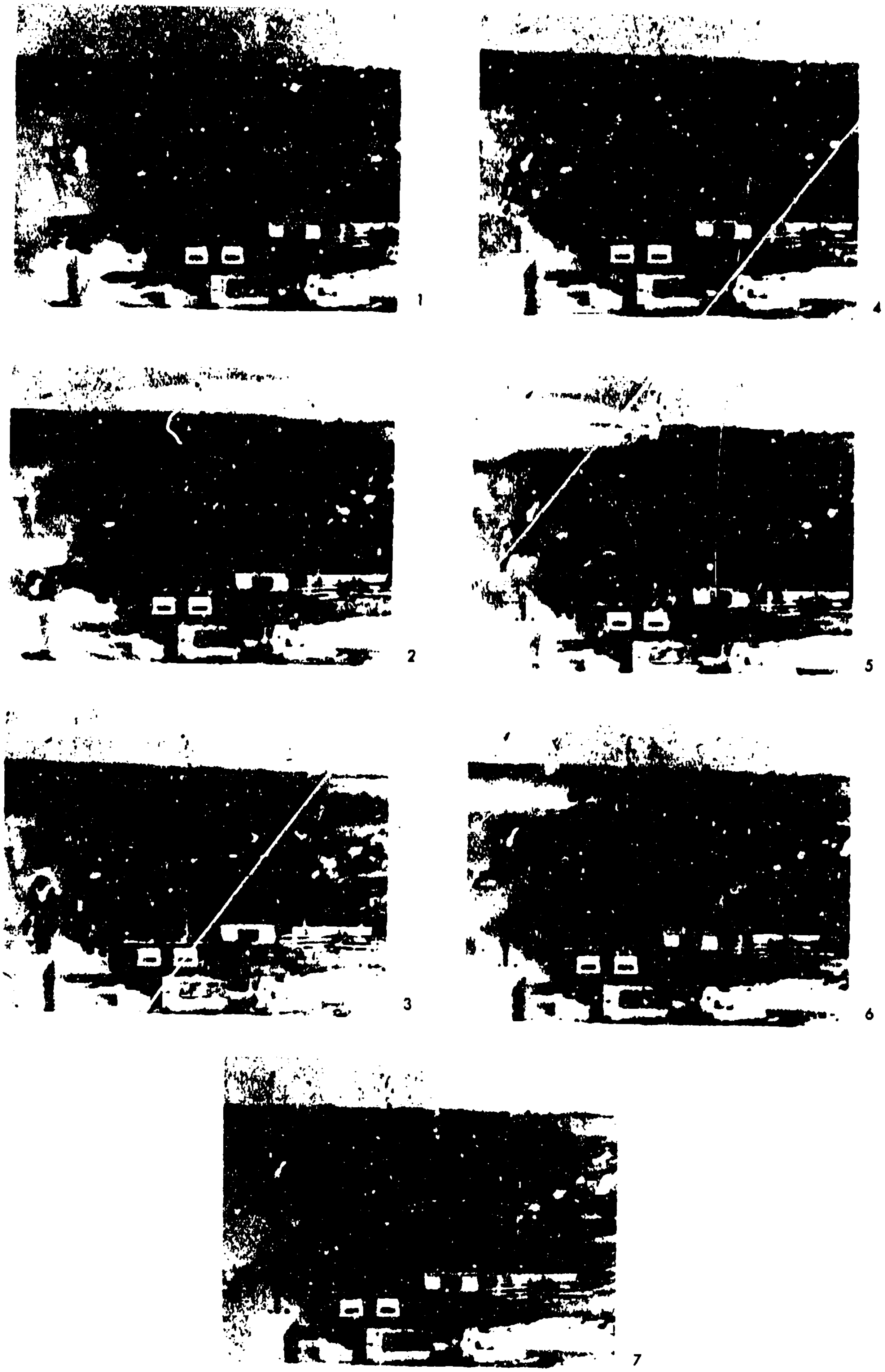


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Fig.7 Ejection from rocket sled at 650 kt: test dummy wearing anti-blast hood

Fig.8 Anti-blast hood after ejection at 650kt

Fig.9 Damaged anti-blast hood after exposure at 750kt

AN ARM RESTRAINT SYSTEM FOR EJECTION SEATS IN HIGH PERFORMANCE AIRCRAFT

By

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SUMMARY

Current high performance aircraft, such as the Multi-Role Combat Aircraft (MRCA) from which ejection at high speeds (up to 650 knots) is likely, require an arm restraint system. This paper describes the restraint system that has been designed by the Martin Baker Aircraft Co for the MRCA. The system evolved comprises a seat portion consisting of two fixed length tapes, and a man portion incorporated into a sleeved life preserver. Each seat tape is enclosed in a fabric tube which allows automatic disconnection of the two portions during emergency ground egress. The system functions on ejection by retracting the arms in a similar manner to MBA leg restraint systems. The development, testing and performance of the system is described. Limited studies to date have demonstrated that the proposed rate of arm retraction is physiologically acceptable both with the hands on the firing handle and under simulated commanded ejection. The arm restraint tapes can be routed unobtrusively to prevent interaction upon routine cockpit movement during normal flight. The performance of the arm restraint system during ejection tests using dummies is also described.

INTRODUCTION

On ejection from an aircraft, aircrew are immediately exposed to the air blast which results in forces acting on the body strapped in the ejection seat. Deceleration of the man-seat combination will depend on the drag forces produced by aerodynamic pressure and the body weight. As the ratios of drag force to weight for the torso and the limbs are dissimilar, and because the torso is better restrained, there will be relative motion between the torso and the limbs which may result in flail injury. The nature and severity of the injury are obviously dependent on the amount of energy to be dissipated. Thus at relatively high indicated air speeds, an arm for instance may either strike the seat structure producing long bone fractures, or the extreme limit of movement of the arm may be exceeded resulting in dislocation or fracture dislocation of the shoulder joint.

Analysis of over 1000 non-combat ejections in the USAF (References 1 and 2) has shown that aircrew ejecting at 600 KIAS or above will have a 100% probability of sustaining flail injury. With ejection in the region of 450-475 KIAS the probability of injury is 50%, whilst it is less than 10% at speeds of 300 KIAS or less. Previous experience has shown that most aircrew ejecting at speeds up to 450 KIAS can retain a grip on the firing handle sufficient to restrain the arms and prevent flail injury. During ejections at speeds in excess of 450 KIAS however, the forces involved may pull the arms away from the firing handle so that they are free to flail with subsequent high probability of injury.

As long ago as the early 1950's, the risk of flail injury was recognised by the Martin Baker Aircraft Co and in March 1953 the first British ejection seat appeared fitted with a system to restrain the lower limbs. Although an arm restraint system was provided on the Martin Baker type 8 ejection seat (designed for the TSR 2 aircraft) no seat currently used in the RAF or RN is fitted with arm restraint.

THE ARM RESTRAINT SYSTEM FOR THE TYPE 10A EJECTION SEAT

With the advent of current high performance aircraft such as the MRCA, the specification requires that aircrew shall be able to eject safely at airspeeds up to 625 KIAS at ground level. At that airspeed the forces acting on the arms would exceed that which aircrew could counter by retaining a grip on the firing handle and the probability of arm flail injury would be very high.

The development of an arm restraint system for this aircraft has been undertaken by the Martin Baker Aircraft Co in conjunction with RAF IAM. The original design requirements included the following points:-

a. That when the crew member ejects with his hands on the seat pan firing handle between his legs, his arms should be restrained in that position.

b. That after ejection of the seat from the aircraft there shall only be just sufficient slack in the system to enable him to move his right hand over the right thigh to reach the Manual Override Handle which enables the crew member to separate from the seat if the normal seat automatic system should fail.

c. That in the case of a command ejection, where one crew member initiates the ejection of both seats from the aircraft, the commanded crew member might have his arms at any position in the cockpit. The restraint system is required in this instance to retract and restrain the subject's arms towards and against the side of the seat and prevent subsequent flailing.

d. It is also required in the MRCA that in the event of a ground emergency the aircrew member must have no more than three actions to perform to free himself from the seat and harness in order to exit the aircraft rapidly. The addition of any connections between the seat and the man for the arm restraint system must not increase this number of emergency actions.

e. The arm restraint system must be unobtrusive and not interfere with normal operation of the aircraft and must, of course, integrate satisfactorily with the other items of flying clothing.

The current design, now being evaluated in the escape system test firing programme of the MRCA, is in two main portions, one mounted on the man and the other mounted on the ejection seat. The essential principles and features of the system are illustrated in Figure 1.

The crew member wears a life preserver incorporating thin meshed sleeves. Each sleeve carries a restraint tape held to the sleeve by Velcro. Each sleeve restraint tape is continued up around the shoulders and across the back of the life preserver waistcoat to provide counter-restraint when arm retraction occurs. The tape is looped around two fixed webbing rings, one around the lower forearm and the other around the upper arm. Each arm tape carries the ring (male) portion of a barrel connector which is normally held in position at the upper end of the tape by a thin tie-thread.

The seat portion consists of two restraint tapes, one end of which is attached to the underside of the seat. Each tape passes down to a pulley (attached to the aircraft floor by a sheer rivet which breaks at 900 lbf) and then up through a 'snubber unit' on the front of the ejection seat. This configuration allows a 2:1 ratio of seat restraint tape 'reel-in' movement compared to seat movement. The snubber units allow the tapes to travel in one direction only, ie downwards. Each seat tape passes upwards to the man, stowed for convenience under the lap and shoulder straps of the seat harness. Each tape terminates in the female portion of the barrel connector, the union of the connector being effected on the upper arm. Each tape is enclosed in a low friction fabric sleeve. independent of the seat tape. Each tube terminates in a metal collar at its lower end, resting on top of the snubber unit and tie-threaded to the seat tape. At its upper end each tube is fastened to the retracting barrel of the connector. It is this tube which effects the automatic disconnection of the man and seat portions of the system in the ground emergency situation, and is described later. The length of the enclosed seat tape system is the same for all seats and all subjects.

The system works in the following manner; as the seat starts to move upwards at the commencement of the ejection sequence, the seat tapes (still anchored to the aircraft floor at the pulley) are pulled through the snubber units, breaking the tie-threads to the outer tubes. When tension is transferred to the barrel connectors, the tie-threads on the ring portion are broken, each ring is pulled down the arm, separating the sleeve tapes from their Velcro fastening. At a point determined by the inclusion of a metal ball 'stop' in each seat tape, the lines cannot be pulled through the snubber units any further, the load is transferred to the sheer rivets on the aircraft floor; these break, separating the seat entirely from the aircraft. Thus as the seat leaves the aircraft, the ejectee's arms are restrained towards either the firing handle or the sides of the seat. The fabric sleeve enclosing each seat tape merely crumples down on itself and plays no part in the restraint system during ejection.

Figure 1 also illustrates the configuration of the retracted arm restraint system as it would be shortly after the initiation of ejection; the outer tube is concertinaed down and the arm is being restrained towards the seat firing handle. When the crew member separates from the seat later in the ejection sequence, the seat tapes are automatically cut through, just above the snubber units, thus releasing the man's arms.

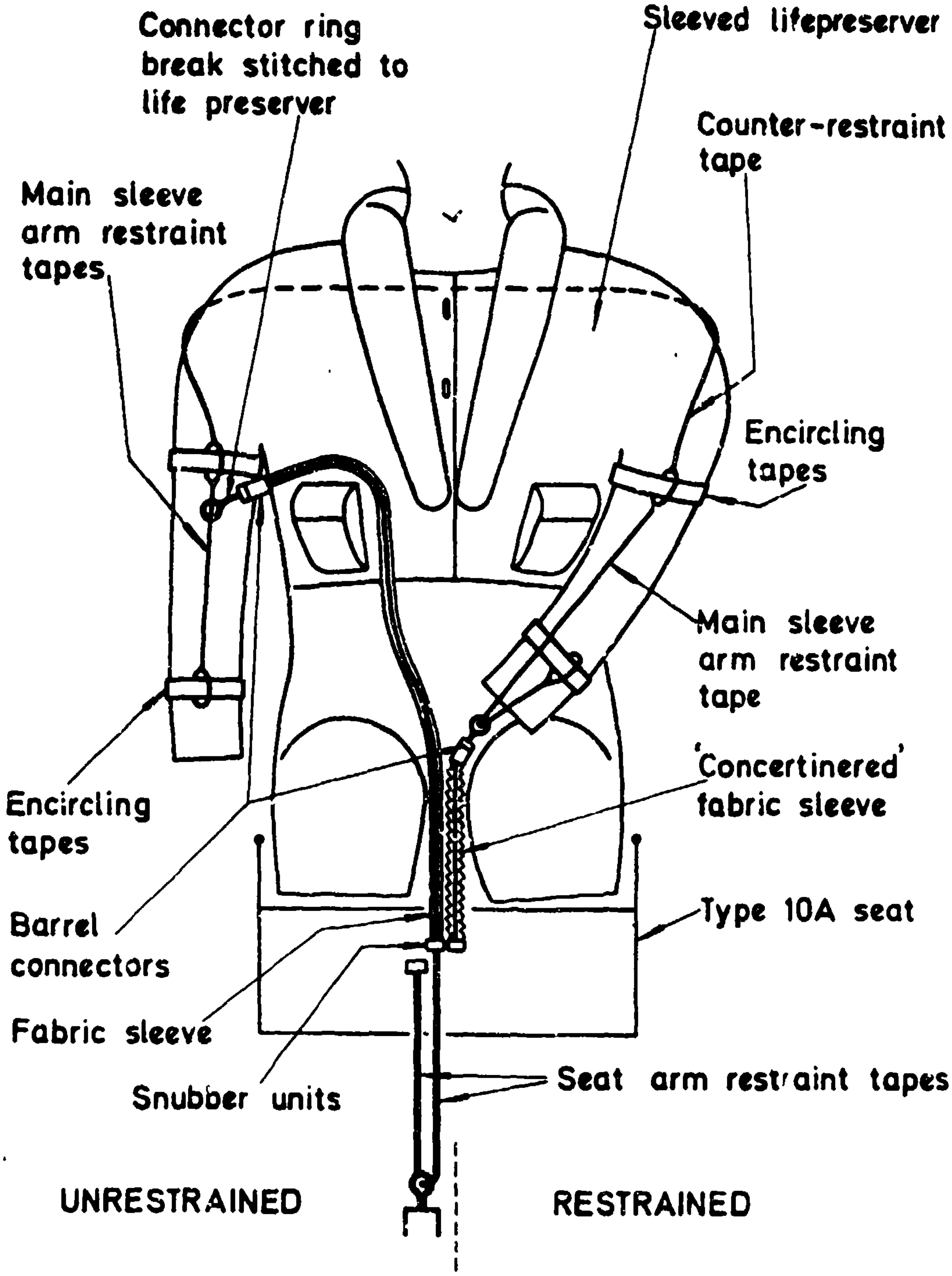
As stated earlier, the function of the outer tubes is to effect automatic release of the seat portion from the man portion on rapid egress from the seat on the ground. The outer tube is slightly shorter than the enclosed tape so that as the crew member, having released the other connections between himself and the seat (ie disengage the harness Quick Release Fitting, disconnect the Personal Survival Pack lanyard, manually disconnect the man portion Personal Equipment Connector from the seat portion PEC), stands up in the cockpit the tube becomes taut and retracts the barrel of the connector. The latter releases the male portion on the sleeve of the life preserver.

PERFORMANCE OF THE SYSTEM

Following the initial development of the system and a trial to evolve a practical strapping in drill for the aircrew, several laboratory exercises have been carried out as part of the general evaluation of the ejection seat for the MRCA. One trial involved several hundred simulated emergency ground egresses from a mock-up cockpit to investigate the behaviour of the automatic disconnect system. On every occasion the seat arm restraint tapes separated cleanly from the sleeve portions of the system, thus ensuring very rapid egress from the cockpit (egress times were in the order of 3-4 seconds). A further exercise showed that for any one aircrewman, the quality of restraint was satisfactory irrespective of the bulk of his flying clothing. Following on from that, and using subjects spanning the anthropometric range of aircrew size, the length of the tube system on the seat was defined, and similarly the position of the ball 'stop' in the seat tape. More recently a sizing trial has been performed to determine the number of sizes of sleeved life preservers required to cover the full size range of aircrew, taking into account the different bulks of the various clothing assemblies to be worn. It was concluded that only two sizes of the basic garment will be required.

The optimal length of the restraint tape on each sleeve of the life preserver has yet to be determined. The object of any future work would be to define how many sizes are needed and secondly, to analyse the quality of restraint when only two sizes of sleeve tapes (one for each size of life preserver) are used. Any compromise on the sizing of the man mounted portion of the arm restraint system will have to be weighed against ideal restraint.

Simulating ejection in the laboratory, extensive studies have been carried out to evaluate the problems of arm retraction and then restraint during self-initiated, and commanded ejection. In this latter instance the arms will be positioned outside the thighs due to inertial forces, and then held against the side of the seat by the restraint system. The arm restraint system was operated at realistically high speeds (ie 80-110 milliseconds) to determine the possibility of injury to a subject whose hands were either on the extracted firing handle or outside the seat pan. Only minimal injury to the hands occurred and was of little significance. It was concluded that the rapid application of arm



SCHEMATIC REPRESENTATION SHOWING TYPE 10A EJECTION SEAT ARM RESTRAINT SYSTEM

FIGURE 1

retraction and restraint within 100 milliseconds is unlikely to inconvenience aircrew in an ejection situation. During this work, the degree of flexion of the spine and angular rotation of the head that occurred as a result of high speed arm retraction was assessed as satisfactory.

Dynamic operation of the arm restraint system has shown that the shape of any ancillary pockets (eg Personal Locator Beacon) on the life preserver waistcoat is important to ensure snag free reel-in of the seat arm restraint tapes. Square edged pockets cause snagging of the seat tapes which becomes progressively more severe the larger the aircrew size, and the further back the arms are pre-positioned outside the seat pan. Snagging is prevented by adding a wedge shaped fillet to the top edge of any pockets on the front and side of the life preserver waistcoat.

The early prototype seat and sleeve arm restraint tapes were associated with poor quality of restraint which was shown to be due, in part, to excessive stretch (up to 36% in length at 1000 lbf) under load of the material of which the tapes were constructed. The current arm restraint system is constructed from tapes which have been pre-stretched and heat set during manufacture, and which exhibit only a small amount (less than 7% at 1000 lbf) of stretch under load.

The Martin Baker Aircraft Co and the airframe manufacturers are currently carrying out a complete test programme of the escape system for the MRCA. To summarise, the results to date have shown that the arm restraint system has functioned adequately in principle, but the degree of arm restraint has proved to be less than was anticipated. Various theories have been put forward to explain this apparent anomaly. It has been suggested that the load required to retract the arms against the windblast forces as the seat emerges from the cockpit is greater than the strength of the sheer rivet on the aircraft floor, and thus premature separation of this rivet is occurring with subsequent reduction in the quality of arm retraction and restraint. Evidence exists to support another suggestion that, full arm retraction and restraint having been applied early in the ejection sequence, the windblast forces later in the ejection sequence pull the seat arm restraint tapes back through the snubber units with resultant reduction in the quality of arm restraint. This latter observation is being overcome by the Martin Baker Aircraft Co redesigning the mechanism of the snubber unit. These problems could possibly be overcome in the future by devising a powered 'inertia reel' system to retract the arms prior to seat movement. The upper limbs would then be fully retracted and more easily restrained before the man-seat complex entered the windblast.

However, the test programme to date has demonstrated that safe ejection at high air speeds is possible, and that the current arm restraint system for the ejection seat in the MRCA will prevent a large proportion of those major flail injuries that would otherwise occur during high speed ejection without any restraint system whatsoever.

The various studies undertaken by RAF IAM during the evaluation of the arm restraint system for the Type 10A ejection seat for the MRCA are detailed at References 3-6.

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DISCUSSION

The Chairman commented upon the rebound of the retracted arms which was apparent in the high-speed films. Gill replied that this was an experimental artefact and would not occur in a real life ejection. It was occasioned by the need to make a single set of arm restraint tapes last for some 160 tests. The snubber units had been unlocked and the actuating force (a falling weight) was discontinued just before the ball stop reached the snubber unit.

ON PUSHING BACK THE FRONTIERS OF FLAIL INJURY

by
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SUMMARY

Under combat conditions, limb flail injury in U.S. open ejection seats has proven to be a severe problem. Very roughly, about half of all combat ejectees suffer flail injury or death, according to the estimates in this paper.

The problem can be avoided by providing (and using) active limb retention cuffs and garters, or passive limb entrapment devices, although the latter require that the seat fly stably after leaving its rails.

Adequate passive entrapment devices have been demonstrated in the wind tunnel, using volunteer subjects. More than adequate seat stabilizing devices have also been demonstrated in full-scale wind tunnel testing, and by air drops, as part of an unconnected but analagous U.S. Army program. Both limb entrapment and seat stabilization systems can be readily and inexpensively retrofitted to most existing escape systems. Thus, there is no technical reason, it is suggested, for accepting a high incidence of flail injury in the future.

The paper concludes with a description of a new kind of "extraction escape system" which offers hope, not only of avoiding the high speed problems of existing tractor rocket escape systems, but also of substantially reducing system volume, cost and weight, as well as simplifying the flail injury problem.

FLAIL INJURY INCIDENCE AS A FUNCTION OF SPEED

Although ejection seats have been in service for over thirty years, it has only recently been possible to audit the performance of some U.S. escape systems under the combat conditions for which they were conceived. It is the thesis of this paper that many U.S. escape systems have performed rather poorly under these conditions. Necessarily, the evidence on which this thesis is based, is not as simple and downright as one would like to see.

Until recently it was fashionable to aver that flail injury was not a problem, "because its overall incidence was only a few percent". Miraculous injury free escapes at 600 knots were widely quoted as evidence that speed was not a factor.

In early 1971, James W. Brinkley* asked us to quantify the relationship between flail injury and escape speed in probablistic terms. After a considerable struggle (reported in Reference 1) we found that there was not only a strong dependence, but a unique dependence on speed, for flail injury in USAF non-combat experience, and that this was confirmed by USN[2] and early RAF[3] experience. The result, slightly modified by more recent data, is plotted in Figure 1. Experimental measurements[4] of grip retention force, and a simple mathematical model of arm flail dynamics[4] provided an adequate explanation of the observed phenomenon for arm flail, and by inference, for leg flail as well. The equation for Figure 1 is

$$\text{P of F} = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{v^2} e^{-(v^2-\mu)^2/2\sigma^2}\, d(v^2) \qquad (1)$$

Where $\mu = 245{,}000$ (knots²), $\sigma = 103{,}000$ (knots²) For all Flail Injury

$\mu = 276{,}000$ (knots²), $\sigma = 103{,}000$ (knots²) For Major Flail Injury

Flail injury occurs because, after the arm(s) or leg(s) have broken away from their "stowed" or initial position, they build up a substantial velocity relative to the torso and seat, before reaching a "stop". This "stop" may be part of the seat structure, the limit of travel of a joint, or a combination of both. At high speeds the "stop" is encountered with such force that bone or joint fracture results.

Figure 1 is necessarily a rather gross relationship for "all seats". Because of differences in system design, leg support, stabilization, and so on, we should expect different curves for different seat designs. Unfortunately, if we limit the analysis to a particular seat, the number of data points is so much reduced that the probability of flail (P of F) estimate is very inaccurate. For the time being, therefore, it would seem that "better" and "worse" seats must be judged on the basis of engineering common sense, rather than statistical performance analysis.

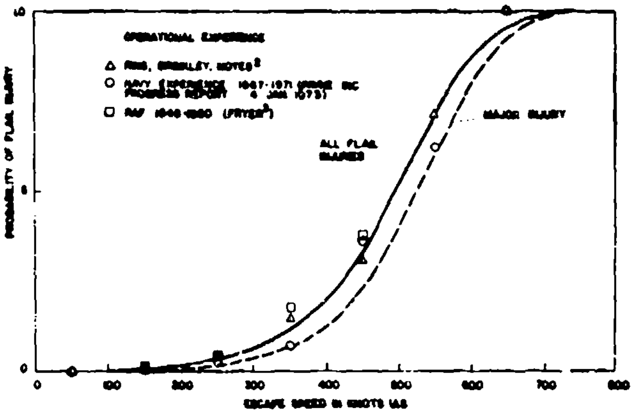

Figure 1 — Probability of flail injury as a function of escape speed. The curves are given by equation (1).

THE ESCAPE SPEED PROBABILITY DISTRIBUTION AND ITS USE IN PREDICTING FLAIL INJURY

Knowing the P of F variation with speed, we can determine the overall magnitude of the flail problem if we know the speeds at which pilots eject. This should be another probability curve, of course. In fact, it turns out that, under non-combat conditions, the escape speed distribution, with astonishing accuracy, is a "gamma distribution", given by

$$\text{CP of E} = \frac{1}{\beta^{\alpha+1}\,\Gamma(\alpha+1)} \int_0^{V} V^{\alpha} e^{-V/\beta}\, dV \qquad (2)$$

Where $\alpha = \mu^2/\sigma^2 - 1$

$\beta = \sigma^2/\mu$

$\Gamma(\alpha+1)$ is the gamma function of argument $(\alpha+1)$

For non-combat USAF escapes[1]

μ = 240.1 knots

σ = 95.1 knots

The astonishing thing about this function — at least to an engineer who is not a wholehearted believer in statistical theory — is that one merely computes μ and σ from the raw data, and equation (2) then describes a curve which comes very close to all the data points; as Figure 2 shows. In non-dimensional form, equation (2) becomes[1]

$$\text{CP of E} = \frac{\Phi^{\Phi}}{\Gamma(\Phi)} \int_0^{\chi} \chi^{\Phi-1}\, e^{-\Phi\chi}\, d\chi \qquad (3)$$

Where $\Phi = (\mu/\sigma)^2$, as index of precision

$\chi = v/\mu$, the normalized speed

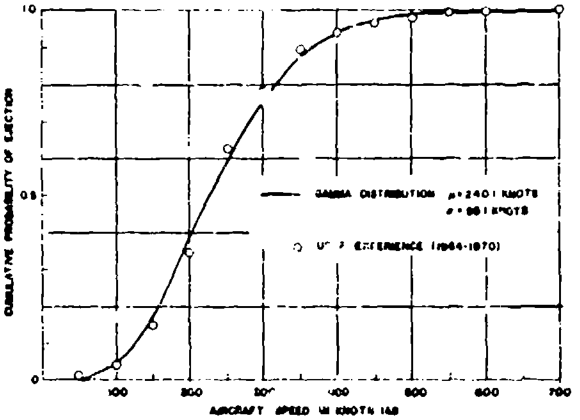

Figure 2 USAF non-combat probability of ejecting, as a function of speed, from Payne & Hawker[1]

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Mathematicians will recognize that equation (3) is explicitly integratable for integer values of χ; another surprising attribute of the gamma distribution!

the differential of (2), gives the distribution function

$$\text{P of E} = \frac{v^{a} e^{-v/\beta}}{\beta^{a+1}\,\Gamma(a+1)} \tag{4}$$

Which is the probability of ejecting, per knot of speed. Its integral is unity. If we multiply equations (1) and (4), and integrate the product we get the total flail incidence (T.F.I.)

$$\text{i.e., T.F.I.} = \int_0^\infty (\text{P of F.}) \times (\text{P of E})\, dv \tag{5}$$

For the data in Figures 1 and 2 the result of such a calculation is as follows

	Equation (5)	USAF Non-Combat Experience	
		Payne & Hawker[1]	Ring, Brinkley & Noyes[2]
Total Flail Incidence	5.14%	5.20%	6.88%
Total Major Flail Incidence	3.43%	—	4.41%

(It should be noted that the Figure 2 speed distribution is not based on the same population as the Figure 1 data, and that this probability explains the discrepancies between predicted and calculated flail incidence. Payne and Hawker[1], using consistent populations, obtained 5.63% theoretical, against 5.70% observed.)

If we know the escape speed distribution, therefore, it would seem that we can deduce the flail incidence from this rather simple calculation. This is useful, because in combat situations the ejection speed may be the most precisely known data available.

For one reason and another, the direct assessment of flail injury incidence in combat escapes is not very precise. If the crew member is recovered, the examining Medical Officer is not necessarily looking for injury cause, and may not correctly identify the cause. P.O.W. data is even less precise, requiring, as it does, a certain degree of self-diagnosis by essentially unqualified personnel. Also, we are asking the P.O.W. to recall events of several years ago, as part of a very traumatic situation, and upon which other painful and/or injurious experiences may have been directly imposed. There is no M.I.A. data at all. Thus estimates based on equation (5) must be given substantial weight, in the absence of better data.

COMBAT ESCAPE SPEED DISTRIBUTIONS

Escape speed distributions for USN recovered and P.O.W. aviators are given by Every[4,5], and USAF P.O.W. escape speeds by Kittenger[3]. USAF recovered crew member data are unfortunately not yet in the open literature.

The corresponding distributions are shown (non-dimensionally) in Figures 3-5. The USAF P.O.W. data is a poor fit; this may be real, or it may represent errors in the data processing, a possible fruitful question for someone to investigate.

When all the distributions are plotted together, as in Figure 6, it is obvious that they are all rather similar in non-dimensional form. That is to say, their variances are very similar, and only the absolute means differ.

These mean speeds are as follows

USAF Non-Combat[1]	240 Knots
USN Non-Combat*	211 Knots (1967-71)
USN Recovered Crew Members[4]	321 Knots
USN P.O.W. Crew Members[5]	438 Knots
USAF P.O.W. Crew Members[3]	388 Knots
Average of all P.O.W.'s	413 Knots

These numbers are clearly very significant. On the average, recovered pilots punched out at speeds 110 knots faster than in a peacetime; P.O.W. pilots at much higher speeds still. Is there yet a fourth and still higher mean speed for M.I.A. pilots? If so, perhaps major flail injury is a major cause of M.I.A. Or perhaps, for the same reason, the M.I.A. pilots are the upper end of a more comprehensive speed distribution, the P.O.W.'s representing the lower end. It might be possible to test such hypotheses by compiling a speed distribution for M.I.A. escapees, based on observations of their companions in the air at the time they escaped.

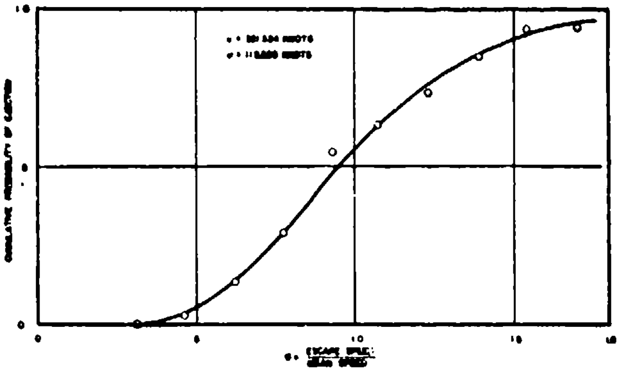

Figure 3 — Cumulative probability of ejection as a function of normalized ejection speed for recovered Navy pilots[4].

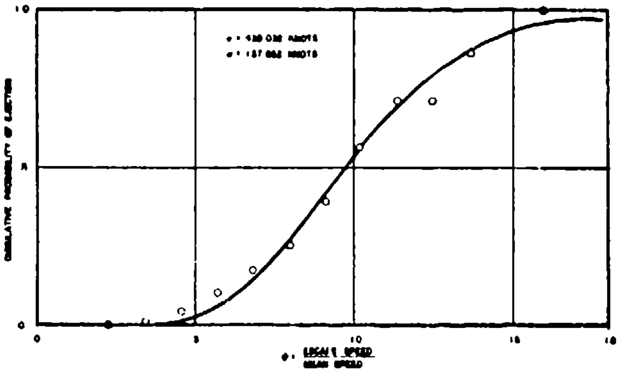

Figure 4 — Cumulative probability of ejection as a function of normalized ejection speed for Navy POW pilots[5].

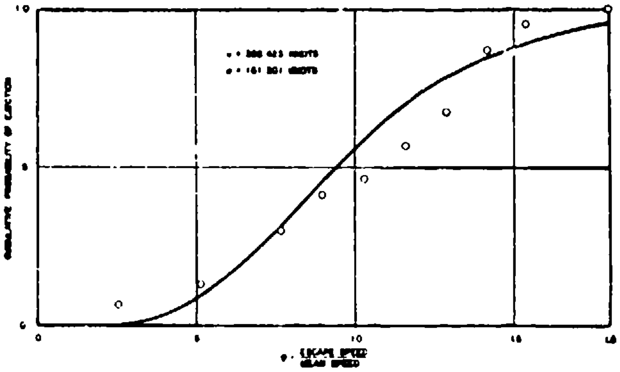

Figure 5 - Cumulative probability of ejection as a function of normalized ejection speed for USAF POW pilots[3]

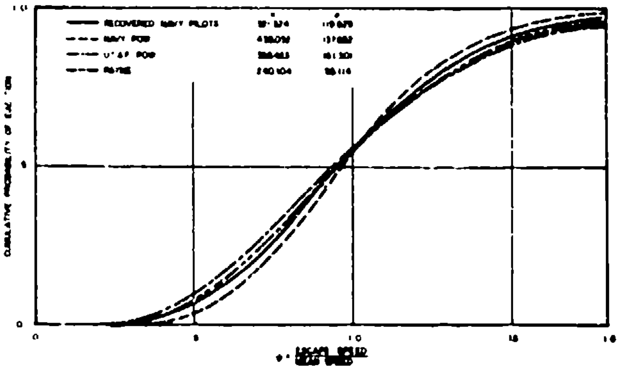

Figure 6 -- Cumulative probability of ejection as a function of normalized ejection speed

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*Approximately; from Naval Safety Center data analyzed in Reference 5.

COMBAT FLAIL INJURY ESTIMATES

The dimensional speed distributions are given in Figures 7 and 8. Using equation (5) in conjunction with Figures 1 and 8 we obtain the following estimates

	% All Flail Injury	% Major Flail Injury
USAF Non-Combat	5.14%	3.43%
USN Recovered Crew Members	15.78%	12.06%
USN P.O.W.'s	40.30%	33.79%
USAF P.O.W.'s	29.51%	24.60%

Now these figures are based on the evidence of those who came back to tell us about it, so they represent the lower bound (Fl_L) of our estimate. An upper bound (Fl_u) is obtained by assuming that all dead and M.I.A. crew members suffered flail injury. Then if m is the number missing (M.I.A. plus known killed) and p is the number of P.O.W.'s, the upper bound flail incidence is

$$Fl_u = \frac{(Fl_L)\,p + m}{p + m} \qquad (6)$$

$$\simeq 72.60\% \text{ for Navy data } (p/m \simeq 0.85,\ Fl_L = .403)$$

The refinement of these estimates, and filling in the many blanks will have to be left to others, since the writer does not have access to all the relevant data. But we might tentatively conclude that safety systems which kill, maim, or injure about half the people who use them cannot be regarded as fully developed.

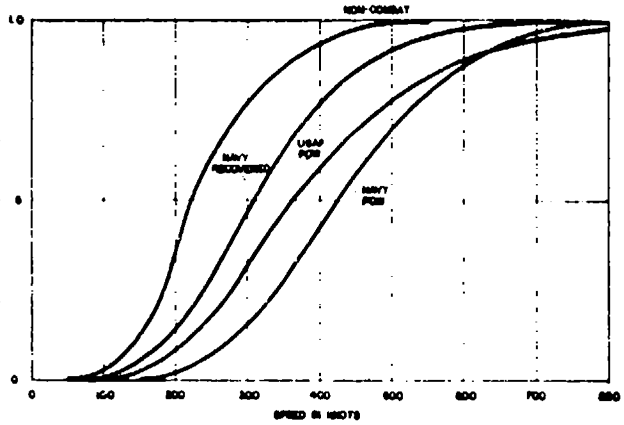

Figure 7 Summary of cumulative probability of ejection

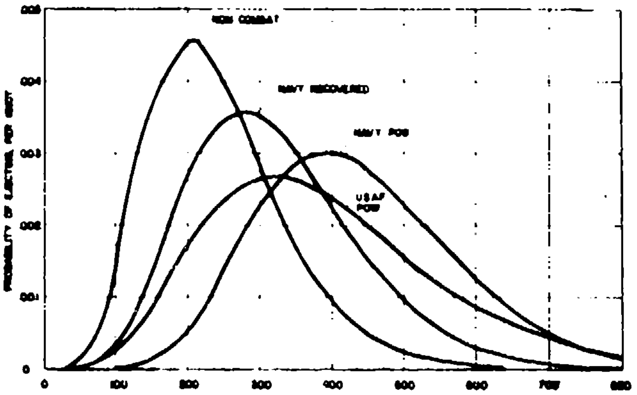

Figure 8 Summary of escape speed distribution

WHY ARE COMBAT ESCAPE SPEEDS SO HIGH?

This is a large subject with many ramifications, and there is not space to attempt a detailed analysis here. The writer would merely like to suggest that combat speeds are the "real" speeds for which seats should have been designed. In peacetime, after flail injury was first tentatively recognized, we urged pilots to slow down before ejecting, and the "slow down" indoctrinizations worked pretty well — in peacetime*. What we *should* have done was to fix the seats.

AVOIDING FLAIL INJURY IN THE FUTURE

Appendix A is a little exercise in elementary hydrodynamics which suggests that there is nothing inherently dangerous about the ram air pressures associated with 600 knots I.A.S., or indeed with twice that speed. Several other examples could be cited. In a rather bizarre incident[10] the writer's wife inverted an experimental boat at 41.6 mph, in such a way that both she and the writer were "ejected downward" from rather narrow cockpits, at dynamic pressures in excess of 3,000 lb/ft^2 without injury. Fryer[11] subjected himself to 1,000 lb/ft^2 for nearly half a minute, without serious injury. And the list could be continued. This admittedly indirect evidence would seem to indicate that the only serious impediment to the use of open ejection seats at high speed is flail injury.

Flail injury can be avoided in two ways:

- By active restraint with garters and cuffs
- By passive "limb entrapment" devices

Garters and cuffs may be the best solution, so long as crew members are willing to wear them, and they can safely support against limb side loads which may be as high as half a ton[4, 11]. The alternative of passive entrapment[12], such as the nets shown in Figure 9 requires that the seat also fly stably, pointing in the direction in which it is going. But is this wholly bad? Excessive spin rate is another cause of injury at high speed, albeit not as well documented as flail. References 12 and 13 report on so-called "in-plane stabilizer plates" which can probably stabilize any new or existing open ejection seat and eliminate the need for a drogue chute. Such in-plane stabilizers are illustrated conceptually in Figure 10, and reduced to practice, for a different application, in Figure 11.

Figure 9 — Passive restraint nets originally proposed by Brinkley, under wind tunnel evaluation[12].

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*With a mean escape speed of 240 knots, it is arguable whether non-combat, non-carrier pilots need ejection seats. The speeds are quite low by World War II standards.

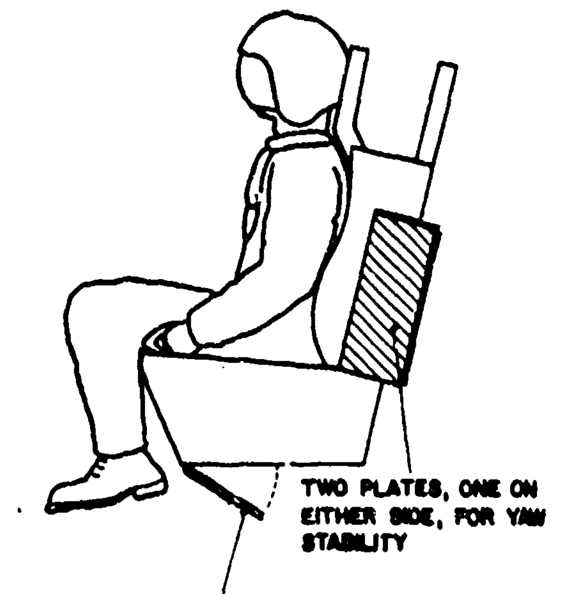
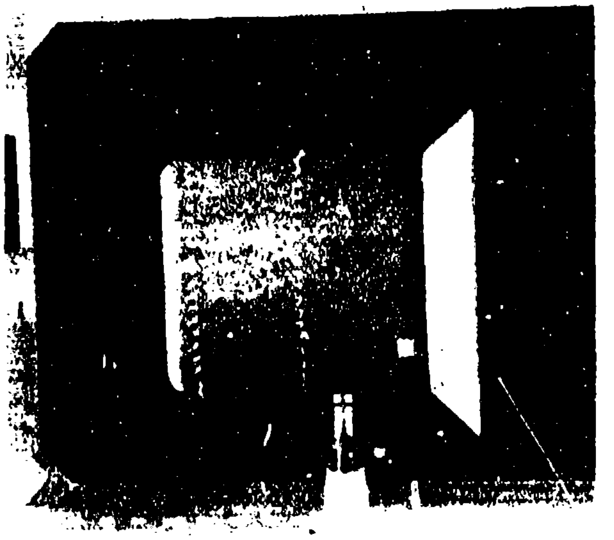


Figure 10 — "In-plane stabilizer" plates[12] have been shown to stabilize a seat satisfactorily in full-scale wind tunnel tests

Figure 11 — "In-plane stabilizer" plates have proven very successful in stabilizing these air dropped containers. The photograph is of a half-scale model under wind tunnel test for U.S. Army Natick.



AN ALTERNATIVE APPROACH

Perhaps the time has come to consider alternatives to ejecting the crew member in a seat. If we look at the basic problem of getting a man away from his aircraft, we see that it is necessary to accelerate him in a direction roughly normal to the aircraft trajectory; up, down or sideways. We can accomplish this acceleration by pushing or pulling, and a little calculation shows that we need between 10g and 20g, if the man is to be sure of clearing the aircraft structure.

In practice, all current escape systems eject upwards, despite the fact that this usually means a fin must be cleared. Sideways ejection would present severe wing clearance problems with many aircraft (although it is feasible from helicopters), and downwards ejection is unfeasible at the low altitudes at which many escapes occur. An additional advantage to upwards ejection is that it enables the so-called "zero-zero" capability to be achieved.

Having established the direction, the next question is whether to push or pull the man out. Because of his jointed deformable structure, man is not well adapted for pushing unless an auxiliary supporting structure — a bucket — is provided. Fortunately, the chair which man invented to ease the structural rigors of the earth's one g acceleration still works well at the higher accelerations needed for aircraft escape, so long as the torso and back muscles are supplemented by a shoulder harness and seat back to prevent the spine from buckling over. The acceleration force is directly applied to the seat pan, which directly accelerates the upper legs and lower torso. The supported spine "pushes" the upper torso and head, and the lower legs are "pulled" by the knee joints.

It is unfortunate that the acceleration needed to clear the aircraft induces loads in the spine which are high enough to cause a significant probability of vertebral fracture. We may be forced to "live with" a vertebral fracture rate of 5% or so because the alternative is a higher death rate due to fin impact. (Vertebral injury rates as high as 40% have been experienced with new or modified escape systems, but this has usually been traced to engineering mistakes in configuration, cushion dynamics and so on. Subsequent modifications have usually brought these "high" rates down to "acceptable" levels.)

The alternative to pushing a seat out is pulling out either the man alone, or the seat/man combination, as in the tractor rocket system. The reader may object that this is playing with semantics, so far as physiological problems are concerned, because most of the force is still applied in the region of the pelvic girdle. But a properly designed harness can also support the man under the arms so that the compressive force in the spine is reduced. It seems possible that with a proper balance of harness resiliency, spinal loads could be reduced to an apparent DRI* design value of say, 5g, with the expectation that operationally, the figure would vary from 0 to 10 g because of variations in fit, body dynamics and materials.

Even if this balance of forces is unfeasible, extraction by means of a harness (perhaps with auxiliary torso support) is a viable alternative to seat ejection: as the many successful low speed escapes with the Stanley YANKEE system attest. Robert M. Stanley and his team have clearly achieved, in the YANKEE Tractor Rocket Extraction System, a notably different and innovative solution to the escape problem, and one which appears to be very effective at low and medium air speeds. At high escape air speeds, present indications are that, in its present form, the tractor rocket is likely to be less successful, for detailed engineering reasons, some of which are discussed in Reference 14. In particular, flail injury is likely to be severe. But this is not inherent in the concept of extraction itself; rather the reverse is true, as the divers at Acapulco (Appendix A) are trying to tell us. The high speed flail potential of present extraction systems is due to the fact that they do not extract the man in the proper way, so that he can more or less dive headfirst into the relative airflow.

The development of a tractor rocket suitable for high speed escape is clearly a considerable undertaking, and has yet to be achieved. Existing (spin stabilized) tractor rockets seem to have the following defects at high speeds:

(a) They are not aerodynamically stabilized, so that the pitchup aerodynamic moments cause them to precess in roll.

(b) Because of high drag and/or insufficient forward inclination of their trajectory, they do not fly in the right position to pull the crew member out "head first into the flow" (Figure 12), even if the pendant line(s) had *zero* aerodynamic drag. (As shown in Reference 14, the crew member has an inherent tendency to "back-somersault" out of the cockpit and end up feet first. This is ***highly*** undesirable from a flail injury point of view, and must be countered by a powerful "forward and up" pull on the pendant(s) if the crew member is to successfully "dive" into the flow, as in Figure 12.)

(c) Since rocket development is inherently expensive, rectification of defects (a) and (b) is likely to be expensive.

(d) The crew member acceleration does not start until line stretch, which may be as long a 0.16 seconds after the rocket has left its mortar.

These considerations led us to the conception of an "inertial escape system" which employs a simple high velocity mass instead of a rocket. A pendant, connected to this mass, extracts the crew member. The high velocity kinetic energy of the mortared mass or ball is "transformed" to a physiologically tolerable acceleration on the man, either by pendant resiliency or by a slipping clutch. These two alternative versions are illustrated in Figures 13 and 14.

Conceptually, the resilient lanyard system is the easiest to understand. It suffers from the disadvantage that it can only be used effectively at lower speeds (less than 350 knots say) and in situations where the aircraft roll rate is less than about 50-100 degrees/second during the escape; figures which can be improved to some extent by

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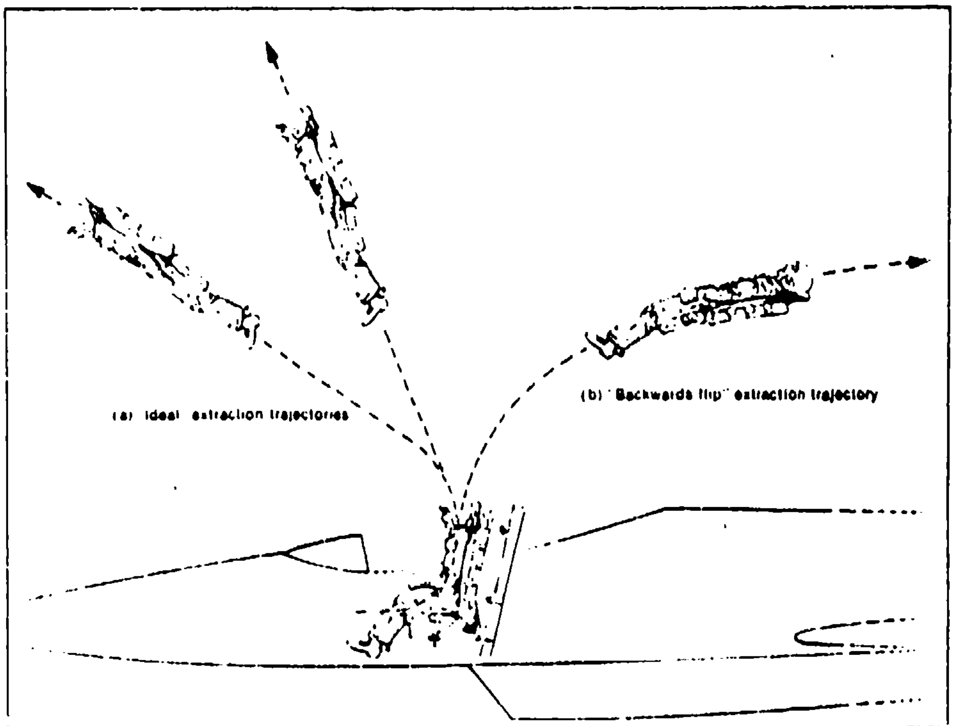
*DRI – Dynamic Response Index as defined in Reference 15.

Figure 12 — Good & poor (lethal) extraction trajectories



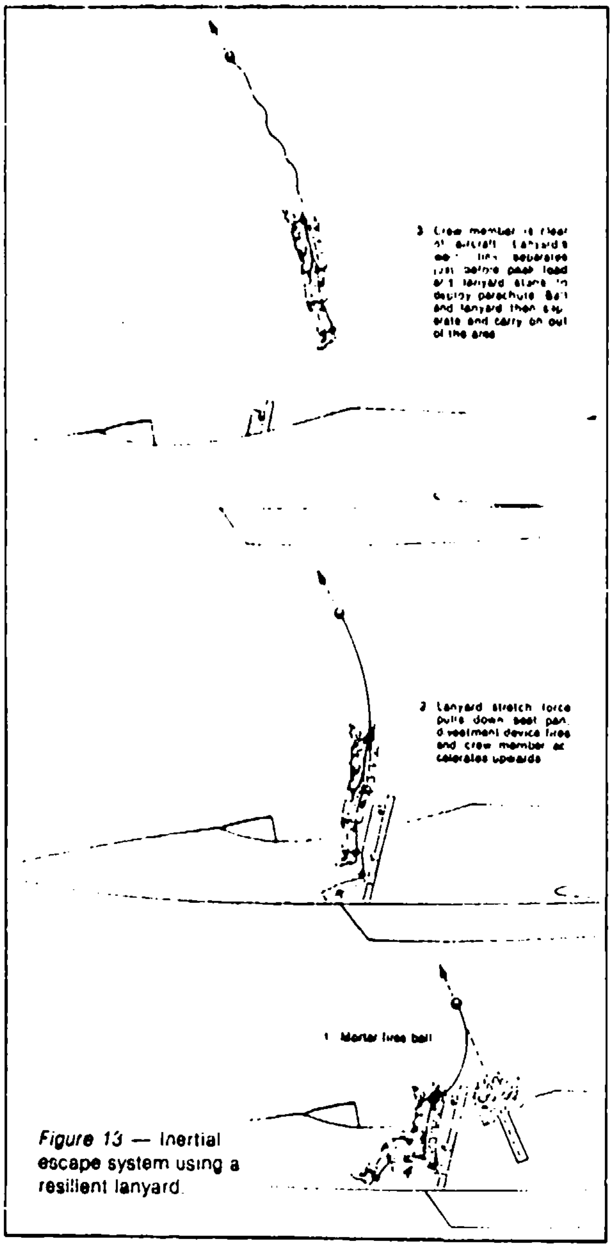


Figure 13 — Inertial escape system using a resilient lanyard.

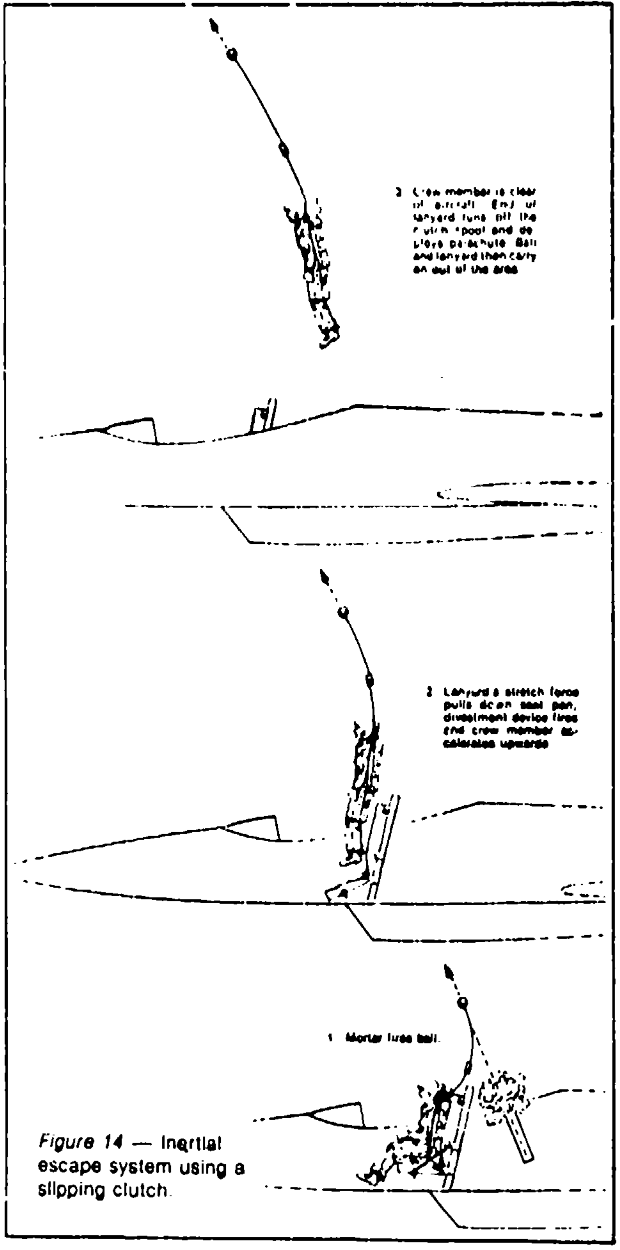


Figure 14 — Inertial escape system using a slipping clutch.

giving the crew member lateral support (smooth seat side panels, for example) or by arranging for the seat to move part way with him, moving upwards on rails; or by running the pendant through a fairlead above the cockpit, but braced to the fuselage structure.

In contrast, the slipping clutch system transmits the full upward acceleration to the crew member almost instantly (about one millisecond) and removes him so rapidly that roll rates of over 300 degrees/second may be tolerable without special lateral support provision. Present indications[14] are that it may be used safely (up to at least 600 knots EAS) without danger of serious limb flail injury, because the man "dives" into the airflow, and because the ballistic coefficients of his various segments are similar, in the absence of a seat mass attached to his torso.

Either system could represent a substantial cost and weight savings, relative to a rocket extraction system. Development costs should be much lower because gun development is inherently low cost, compared with rocket development. In the clutch system, the adverse lanyard aerodynamic effects are expected to be minimized because the lanyard will always be in tension. Additionally, the lanyard diameter may be an order of magnitude less than the 11mm used on the existing systems, if a material such as Kevlar or S-glass is employed.

Reference 14 indicates that, in addition to being potentially low cost, the ballistic escape system may be very lightweight as well. For a helicopter escape system, a total weight penalty of only 35 pounds is suggested.

This reference also includes calculations of system performance when escaping from a fixed wing aircraft at 600 knots.

CONCLUSIONS

It is suggested that, under combat conditions, roughly half of all open ejection seat escapees suffer flail injury or death, and that this should be regarded as unacceptable for the future. Such injuries may be almost entirely avoided by properly designed active limb restraint, or by passive limb entrapment. But positive seat stability is desirable in the first case, and mandatory when passive entrapment is used. "Inplane stabilizer" plates are one way of aerodynamically stabilizing a seat from the moment it leaves the rails, and have been thoroughly proven in full scale wind tunnel testing. They can be retrofitted to most existing escape systems.

As a longer range, alternative solution to the problem, a state of the art extraction system may avoid existing flail problems, extend the safe escape envelope, be cheaper to develop and buy, and impose smaller weight and volume penalties. A candidate system has been described in the paper.

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APPENDIX A

SOME HYDRODYNAMIC OBSERVATIONS ON THE SPORT OF DIVING

A study and understanding of the wind blast and limb flailing injury problem must necessarily be approached indirectly, using anthropometric analogs of the human body, theoretical calculations, and any other sources of data which may be available. An interesting example of the latter is to be found in the sport of diving, where athletes repeatedly subject themselves to dynamic pressures hitherto regarded as lethal in escape system technology.

Perhaps the best known venue for such high diving is at La Quebrada near Acapulco where contestants dive from a cliff 100 feet above sea level. Target diving is also growing in popularity, however, and it is fairly normal for contestants to dive from an 80 ft. tower, the object being to execute maneuvers in mid-air and then to impact in the center of a "target" roughly 6 ft. by 6 ft. square.

In diving from 100 ft., the diver impacts the surface of the water at about 80 ft. a second, which corresponds to an initial dynamic pressure of about 6,440 lbs. per square foot. Because the "added mass" or "virtual mass" associated with longitudinal motion through the water is only about five percent of the diver's mass, we may neglect it in calculating his motion when fully immersed, together with gravity forces, which are cancelled out by bouyancy terms. The equation of motion after full immersion is then very simple, namely

$$du/dt = -C_D S \tfrac{1}{2} \rho_w u^2/m = -K_w u^2$$

where

$K_w = C_D S \rho_w / 2m$
$C_D S$ = "drag area" of the diver
ρ_w = mass density of water
m = mass of the diver
u = velocity

Upon integration between the initial entry velocity u_1 and u, we obtain

$$u/u_1 = 1/(1 + K_w u_1 t)$$

A second integration gives the distance travelled in time t as

$$y = (1/K_w) \log (1 + K u_1 t) = (1/K_w) \log u_1/u$$

The initial impact and penetration of the water may be treated as follows. Let m' be the virtual water mass associated with a cross-section of the diver, and u his velocity. Then

$$\text{Impact Force} = F = d(m'u)/dt$$

$$\text{Impact Impulse} = I = \int F dt = \int d(m'u) = m'_1 u_1$$

where m'_1 is the virtual mass corresponding to his greatest cross-section passing through the water plane, and u_1 the corresponding velocity.

But

$$du/dt = F/m$$

where m is the mass of the diver. If u_0 is the initial velocity, therefore

$$u_0 - u_1 = \int F dt/m = I/m = m'_1 u_1/m$$

Thus

$u_1/u_0 = 1/(1 + m'/m) \approx 1/(1 + 1.5/5.3) = 0.78$, say, from round numbers.

Impacting at 80 ft/sec., therefore, implies a velocity change of 80 x (1 − 0.78) = 17.6 ft/sec. In passing through the water surface feet first, this takes about .042 seconds, corresponding to a mean deceleration of 13.0 g for a feet first entry. When the diver enters head first, the maximum impact force is reached much sooner — roughly when his shoulders enter — and the velocity change of 17.6 ft./sec. is considerably larger than we had previously thought to be tolerable for impact type $-G_z$ acceleration.

Variations of the significant parameters after impact from a 100 ft. dive are plotted in Figures A-1 and A-2. Note particularly from Figure A-1 that a velocity change of 60 ft./sec. is achieved in a distance of 7½ feet, despite the fact that the acceleration is $-G_z$. After the first 20 ft./sec. or so, of course, the forces applied to the diver's body are distributed to some extent, and after 40 ft./sec. (3 ft. immersion) they appear more as a suction distribution pulling him back (tending to extend the spine) rather than as pressure forces on his head and shoulders, which would tend to load up the spine in compression.

In the calculation of impact velocity for Figures A-1 and A-2, the velocity (u) and distance fallen (y) were taken as

$u = \sqrt{g/K} \tanh (\sqrt{gK}\, t)$
$y = (1/K) \log \cosh (\sqrt{gK}\, t)$
$K = C_D S \rho/2m$
$C_D S$ drag area
≈ 1.2 ft.² for a clean diving position
≈ 3.0 ft.² for a swallow dive
ρ air density
m mass of the diver
g = acceleration due to gravity

For dives from 100 ft., it was found that the effect of air drag was very small, so that

$u \approx gt$
$y \approx gt^2/2$

Specially significant about these results for high diving are the following points:

- The diver's legs do not split open in a feet first entry, presumably because favorable "added mass" pressures act on his tapered legs as they pass through the free-surface, to keep them together. This would not be true of motion in air.
- The diver can hold his arms in position in a head first entry, presumably because they are "swept" towards each other.
- Serious "limb flailing" does not generally occur with entry in either direction.
- Dynamic pressures of 2,000-4,000 lb./ft.² do not cause injury.

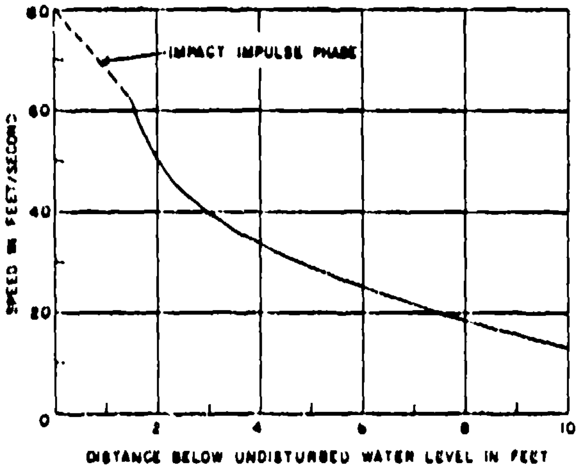

Figure A-1 — Variation of velocity with depth after a head-first impact from a 100 ft. dive

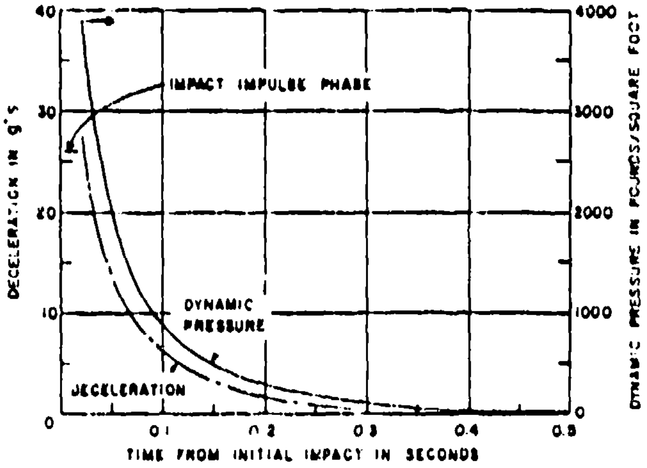

Figure A-2 — Acceleration and dynamic pressure after head-first impact from a 100 ft. dive

EXPERIMENTAL EVALUATION OF LIMB FLAIL INITIATION AND EJECTION SEAT STABILITY

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INTRODUCTION

For flail injury to occur it is necessary for the limb to acquire a considerable angular velocity relative to the body in order that there may be sufficient relative kinetic energy to cause the damage. This energy, it is supposed, is accumulated over the length of stroke from the initial lodgement to the position of arrest. Static forces are generally not sufficient to dislocate the shoulder or hip joint or to cause bone fractures. The question arises as to what causes the initial dislodgement. Is it inertial force due to seat motion or aerodynamic force due to pressure on the limb? Are these forces of irresistibly large magnitude or is the occupant caught unawares and compelled to let go at force levels which he normally could resist? This uncertainty led the Aerospace Medical Research Laboratory at Wright-Patterson Air Force Base, through the Office of Biodynamics and Bionics, under James W. Brinkley, to initiate a full-scale wind tunnel study to measure the limb loads on volunteer subjects in different ejection seats. The static stability of the ejection seat is also an integral part of the flail problem. It was therefore decided to measure the forces and moments of the candidate seats, as part of the same program.

DESCRIPTION OF EXPERIMENT

The wind tunnel investigation had two primary goals: (1) the measurement of limb dislodgement forces in free flight simulation of an ejection and (2) the determination of static stability of the seats/occupant combination. We also wanted to compare the forces and moments measured with anthropometric dummies and live subjects in identical ejection seats.

An Advanced Concept Ejection Seat (ACES-II) and the F-105 ejection seat were used during these tests (Figures 1 and 2). A detailed comparison of these two seats is included in Reference 1, but for the purposes of this paper the ACES-II will usually be referred to.

All of the limb force measurements were made by strain gauged beams that were calibrated to measure a particular force. The ejection initiation handles recorded the force on the hands (arms) out from the body and back toward the seat structure (Figure 3). The knees were supported by brackets (Figure 4) and measured the separation (knee out) force. The feet, which normally are not attached to any part of the seat, were fixed to "stirrups" that measured the foot out and back force components (Figure 5). Finally, the helmet was rigidly mounted to the seat structure and instrumented in such a way that lift, drag and side force, pitching and yawing moment could be measured (Figure 6). The pressures both inside and outside the helmet were measured with static pressure taps (Figure 7).

EXPERIMENTAL PROCEDURE

The standard test run was at a set pitch and yaw angle. The dynamic pressure was varied and balance and limb force measurements taken at 20, 30 and 40 lb/ft^2. The limb force measurements were recorded digitally and plots of force area coefficients

$$C_F A = \frac{F}{\frac{1}{2}\rho U^2}$$

F - Force in Pounds
ρ - Air Density in Slugs per Feet^3
U - Free Stream Velocity at ft/sec

versus dynamic pressure were recorded. The seat/man combination forces and moments (ie. lift, drag, side force, pitching moment, yawing moment and rolling moment) were taken with respect to wind and body axes after the stand tares were subtracted. All the figures in this paper are referred to body axes. The reference center of gravity for the seats tested is shown in Figure 10 and the positive directions for the limb force measurements are shown in the schematic of Figure 11.

These tests were conducted in the subsonic wind tunnel facility at the University of Maryland (Glenn L. Martin Institute of Technology) under its Director, Donald S. Gross. The tests of the F-105 seat were in April 1973 and the ACES-II in the following September. The cooperation of the tunnel staff was greatly appreciated during these experiments.

RESULTS AND DISCUSSION

Limb Dislodgement Forces

The force at the knees shows a systematic variation with yaw angle (Figure 12). At the nominal ejection angle (0° pitch, 0° yaw) the knee outward force area equals about 0.2 ft^2. This corresponds to an outward force on the knees of 108 pounds at a speed of 400 knots. As the seat is yawed, the windward knee (right knee if you are yawing to the left) shows a tendency to be forced inward or toward the left knee. The leeward knee (left knee if you are yawing to the left) continues to be forced outward from the nominal position. The effect of pitch was minimal at these low pitch angles. Finally, at a yaw angle of -30° the left knee experiences an outward force area of 0.6 ft^2; this is approximately 325 pounds at 400 knots.

The force outward at the feet shows a similar variation (Figure 13). At the nominal ejection angle the foot out force area is approximately 0.1 ft^2. As the seat is yawed to the left the windward (right) foot is forced inward (toward) the left and the leeward (left) foot is forced outward with a force area equal to 0.4 ft^2 at a yaw angle of -30°. This corresponds to a foot force (outward) of 216 pounds at 400 knots. The effect of pitch is also minimal on the feet. The backward force area on the feet is

Figure 1. A Subject in the ACES-II Seat at -15° Yaw, -15° Pitch.

Figure 2. A Subject in the F-105 Seat, at 15° Incidence and 30° Yaw.

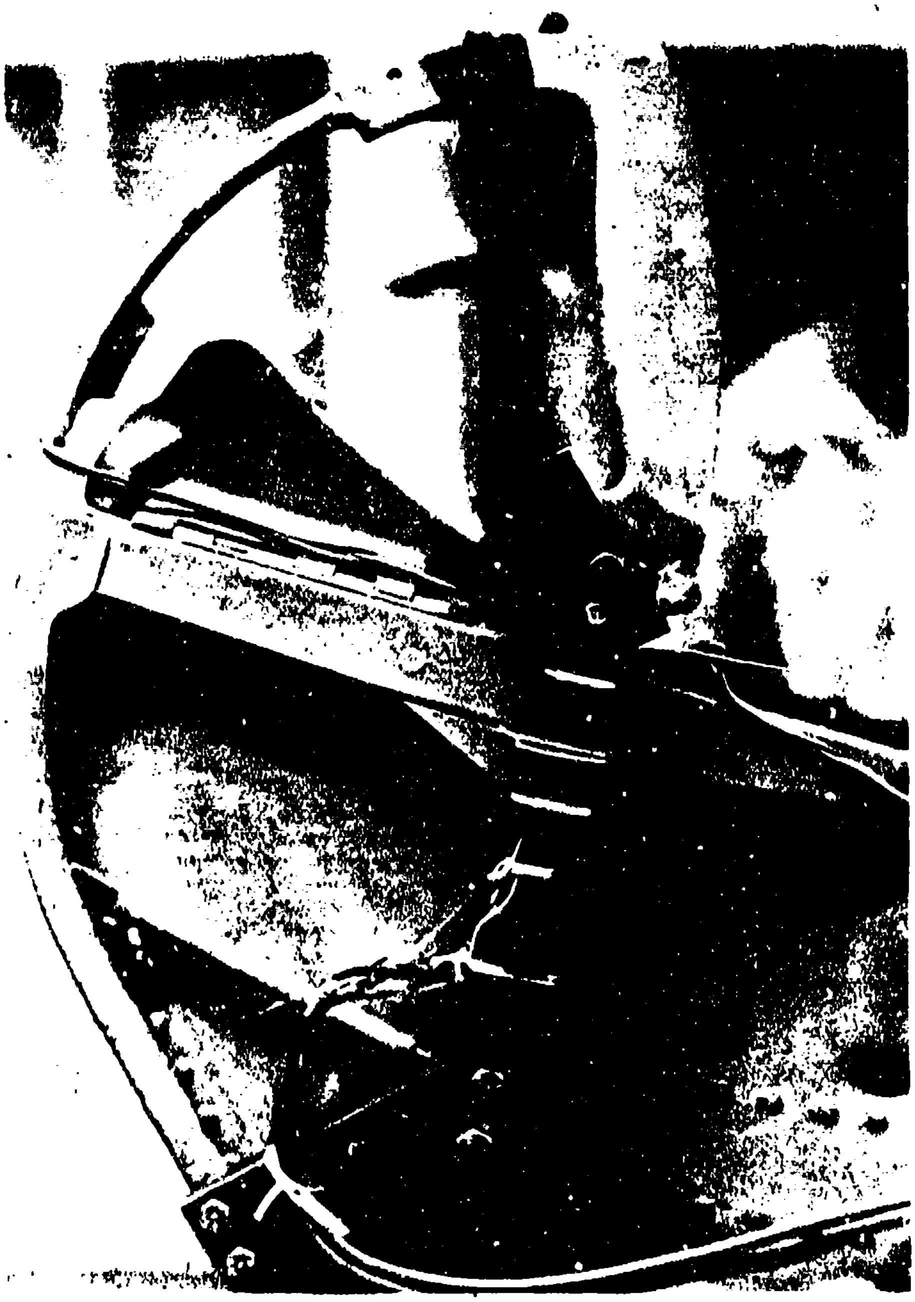


Figure 3. Detail of the ACES-II Ejection Initiation Handle Force Measuring Beam.

Figure 4. The Right Knee "in-out" Force Measuring Beam on the ACES-II Seat.

Figure 5. ACES-II Foot Force ("forward-back" and "in-out") was Measured on the Vertical Beams Supporting the Stirrups to which the Subject's Feet are Strapped.

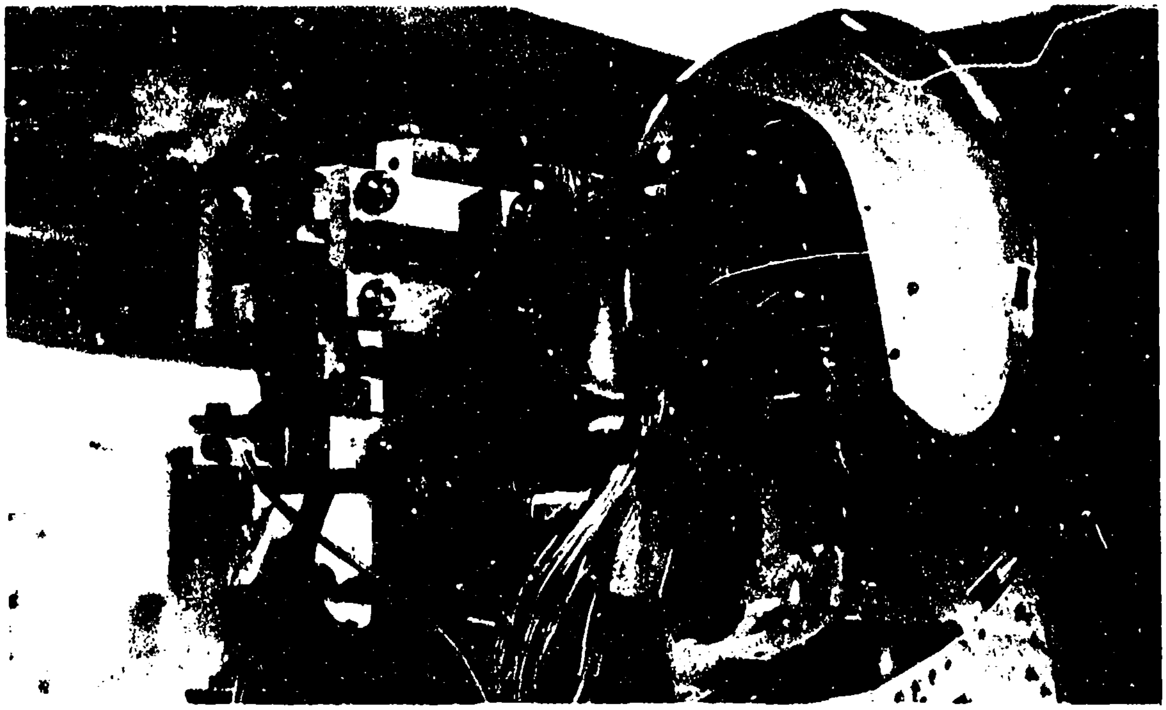


Figure 6. The Helmet Cantilevered on the End of Its Strain Gauged Sting: F-105 Seat.

Figure 7. Inside View of Helmet, Showing Static Pressure Lines to Internal and External Static Pressure Taps.

Figure 8. The "Crested Spoiler" Attached to the Helmet in an Effort to Reduce Helmet Lift.

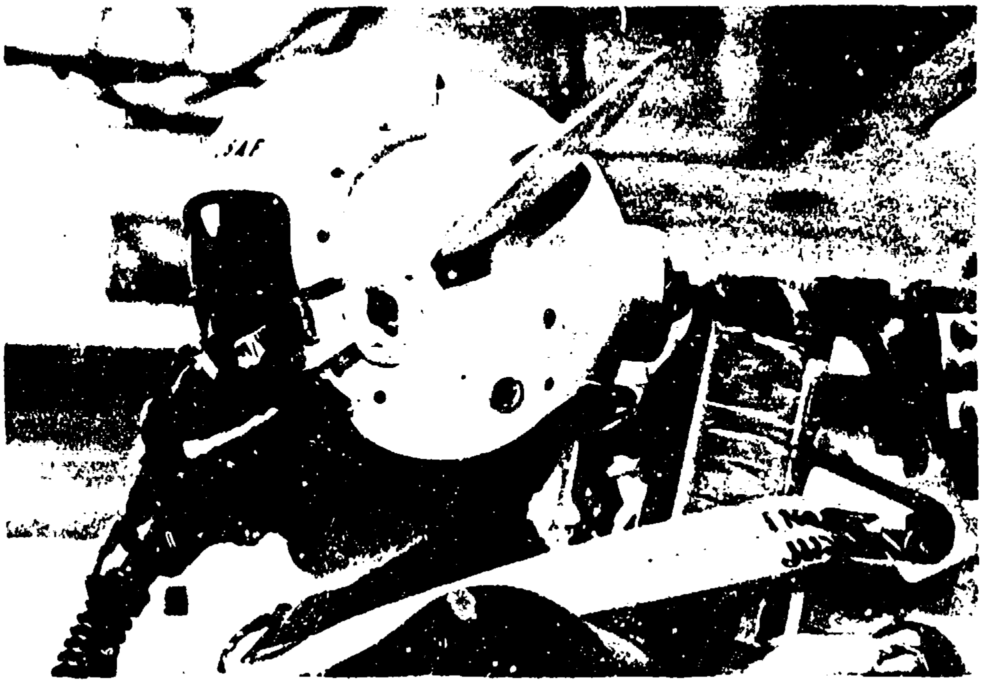
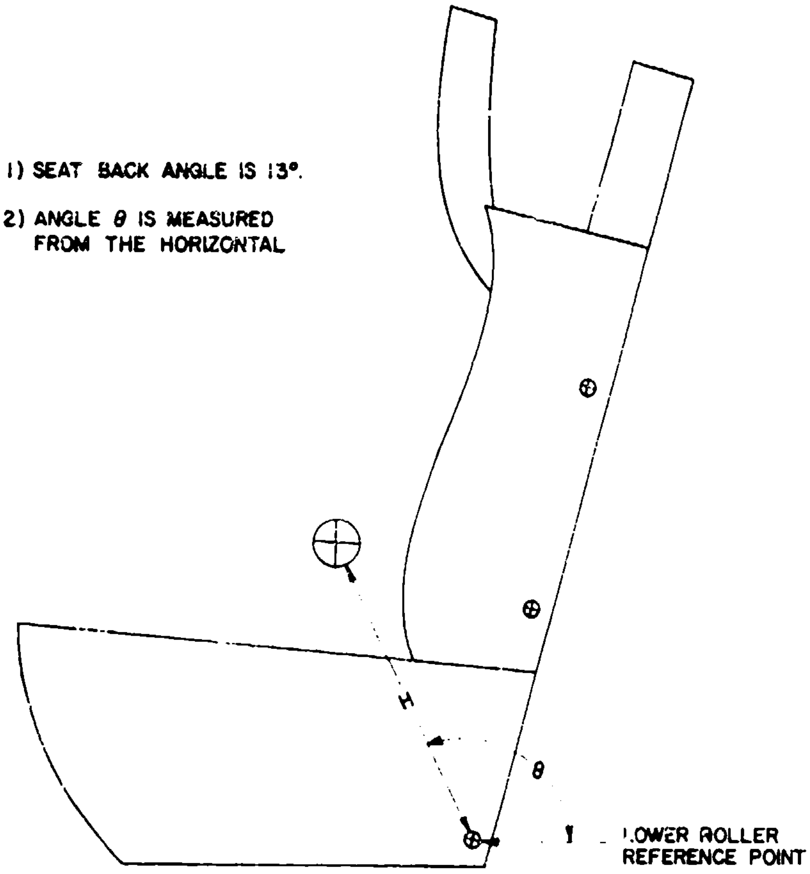


Figure 9. Helmet Fitted with "Wings" to Reduce Lift Forces.



NOTES:

1) SEAT BACK ANGLE IS 13°.

2) ANGLE θ IS MEASURED FROM THE HORIZONTAL

C.G. LOCATIONS IN POLAR COORDINATE FORM FOR SEAT-MAN COMBINATION

SEAT	OCCUPANT	H	θ
ACES II	5%	1.692	110.9
ACES II	50%	1.669	113.1
ACES II	95%	1.649	115.4
F-105	ALL	2.10	109.7

Figure 10. ACES-II and F-105 Center of Gravity Locations Used in Data Reduction.

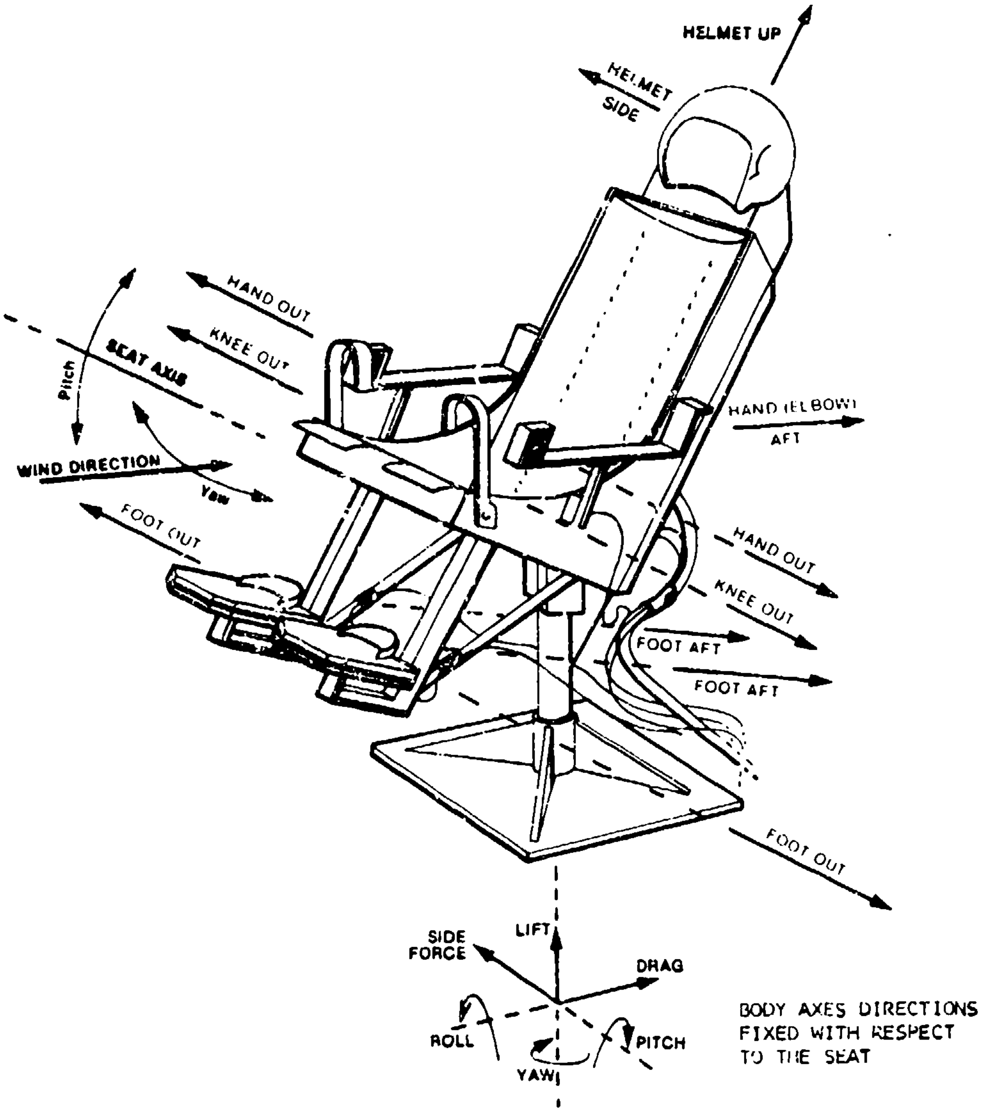


Figure 11. Seat in Wind Tunnel; Axes and Measurements.

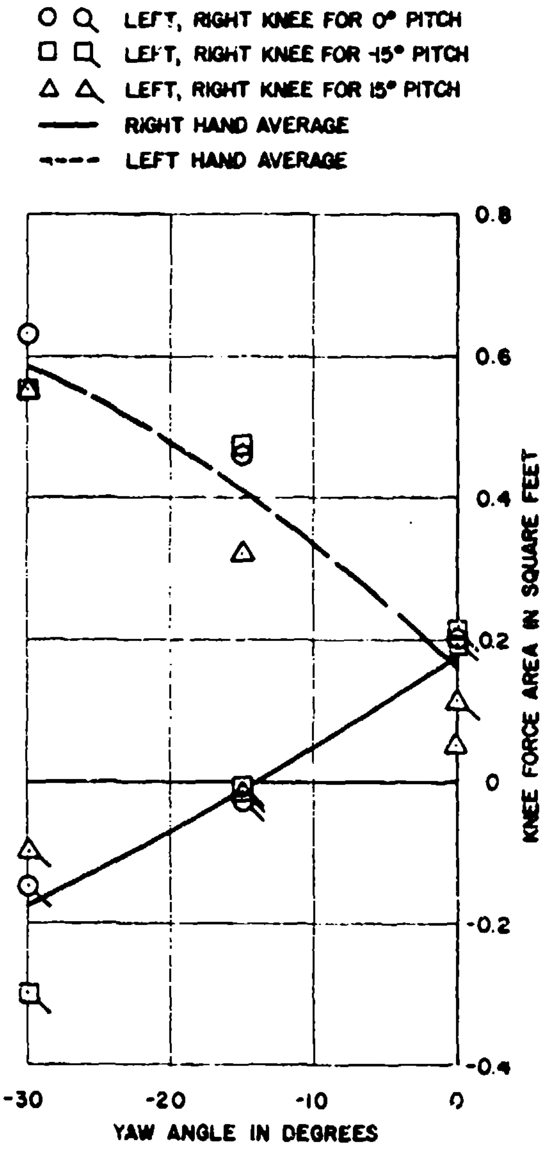


Figure 12. Variation of Knee Out Force Area with Yaw Angle for the Average of the Volunteer Subjects.

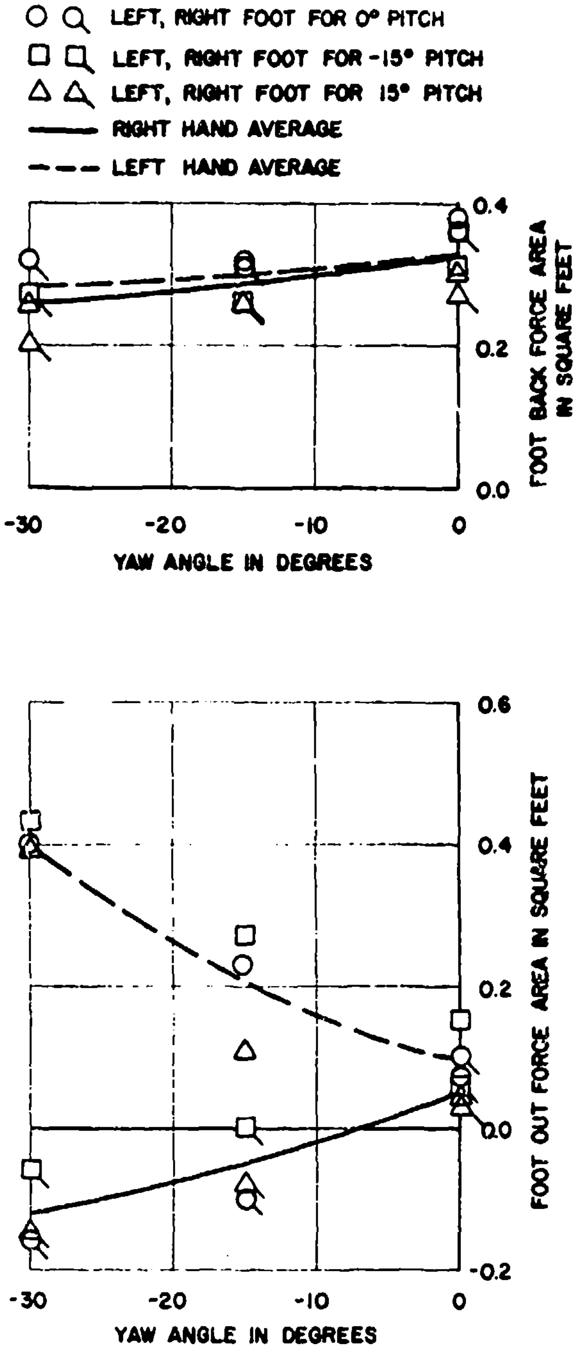


Figure 13. Variation of the Foot Back and Foot Out Force Areas for the Average of the Volunteer Subjects.

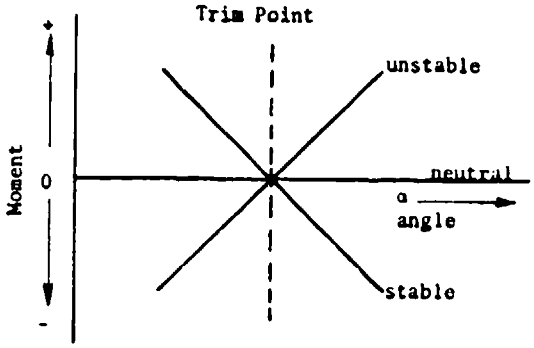
fairly constant with yaw angle up to -30° with a value of 0.3 ft^2. This equals a force of 162 pounds at 400 knots.

The arm outward force area as a function of yaw angle is also similar to the knee and foot out forces (Figure 14). The arm outward force area at the nominal ejection angle is approximately 0.15 ft^2 which would be a force of 81 pounds at 400 knots. The maximum arm out force area equals 0.3 ft^2 and occurs at a yaw angle of -30°. This means that a pilot, if ejected at 400 knots, would experience a force in excess of 150 pounds if his seat yawed to -30°.

The arm back force area as shown in Figure 14 has an average value of about 0.35 ft^2 at the nominal ejection angle. This corresponds to a backward force on the arm of 189 pounds at 400 knots. As the seat yaws the arm back force area falls to about 0.2 ft^2 for both the right and left arms.

Seat Stability

The basic requirement for static stability is summarized in the graph below. A negative slope of moment vs. angle is the criteria for static stability. About the trim point any small positive increase in angle will produce a negative or restoring moment back to trim and vice versa. It is also important that the trim point is near the angle that the seat enters the free-stream after ejection.



If the trim point of the seat is much different from the initial angle of the seat at ejection, then the restoring moments may be such that the seat is driven past the trim point and spinning may occur. Of course, in this simplified explanation we are assuming no passive or active devices to correct for trim point and initial angle offset.

Static Forces and Moments of the Full-Scale ACES-II Seat Plus Occupant

The volunteers for this experiment were military personnel from Wright-Patterson Air Force Base in Ohio. Force areas ($C_DS = D/q$) and moment volumes ($C_mV = M/q$) were used to present the data since we are dealing with a full-scale seat and since a characteristic area is hard to describe on such an irregular body. The lift and drag areas are shown in Figure 15. The effect of pitch angle on the lift area shows that zero lift occurs at an angle of attack of about 10°. At the nominal ejection angle the lift area is -1.0 ft^2. The drag area is approximately 6.5 ft^2 at the nominal ejection angle. The drag area remains about constant at -15° pitch but decreases to about 6.0 ft^2 at 15° pitch.

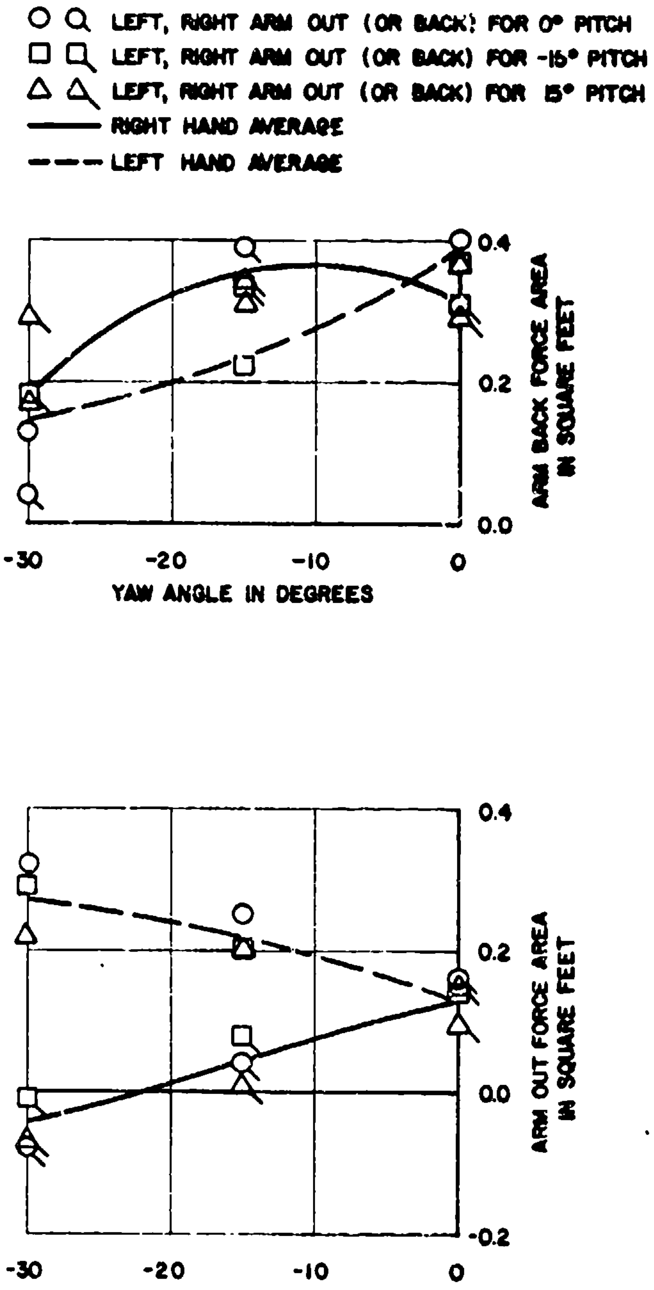


Figure 14. Variation of Arm Back and Arm Out Force Areas for the Average of the Volunteer Subjects.

The pitching moment volume versus pitch angle shows a large negative value at the nominal ejection angle. This implies that the seat will tend to rotate as soon as it is inserted in the free stream. This plot also indicates that the seat does not trim near the nominal angle of ejection. The yawing moment versus yaw angle plot shows a strong unstable tendency. The seat has zero yawing moment near zero but any perturbation will set the seat spinning in the yaw mode. There is very little variation in yawing moment volume with pitch angle.

The ACES-II seat shows a tendency to produce a positive rolling moment with negative yawing angle (Figure 17). The side force also shows a predictable increase with yaw angle.

It should be noted that since the ACES-II seat is actively stabilized by vernier rockets, most of the instabilities noted here are not germane to its performance.

Comparison of Anthropometric Dummies and Volunteer Subjects

It was decided to evaluate and compare the static forces and moments of two anthropometric dummies (5 and 95 percentile) with the average of the volunteer subjects (Figures 18 and 19). The lift and drag area plots show very similar characteristics. The pitching moment was the most variable but the average of the volunteer subjects fell well within the 5 and 95 percent data. The yawing moment versus yaw angle showed good agreement between the dummies and live subjects. In general, the gross aerodynamic seat stability was very similar between anthropometric dummies and the volunteer subjects.

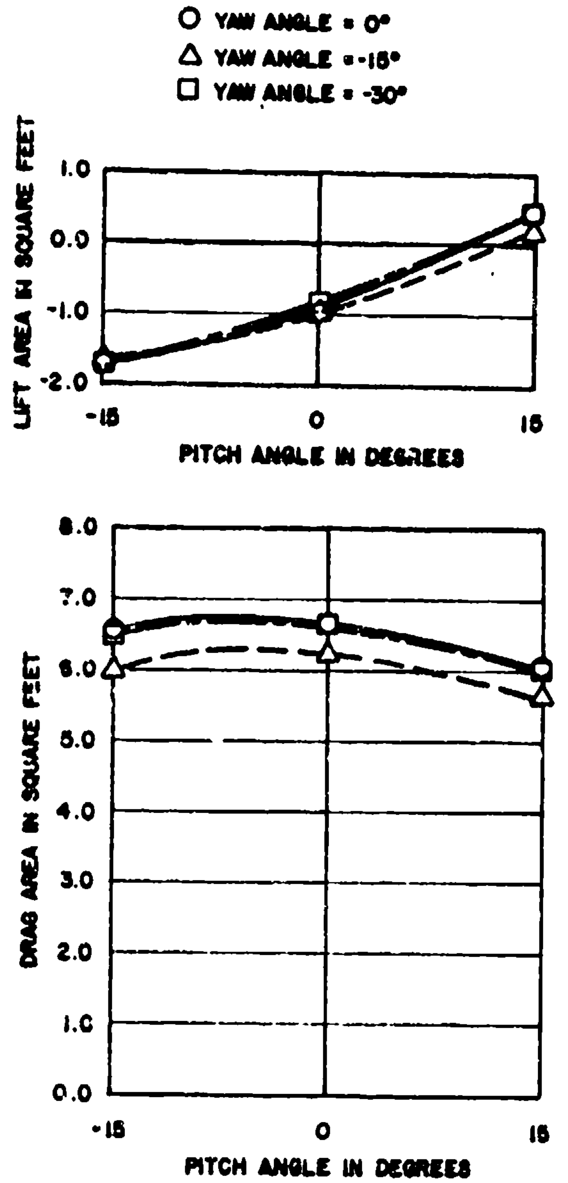


Figure 15. Variation of Lift and Drag Area with Pitch Angle for the ACES-II Ejection Seat.

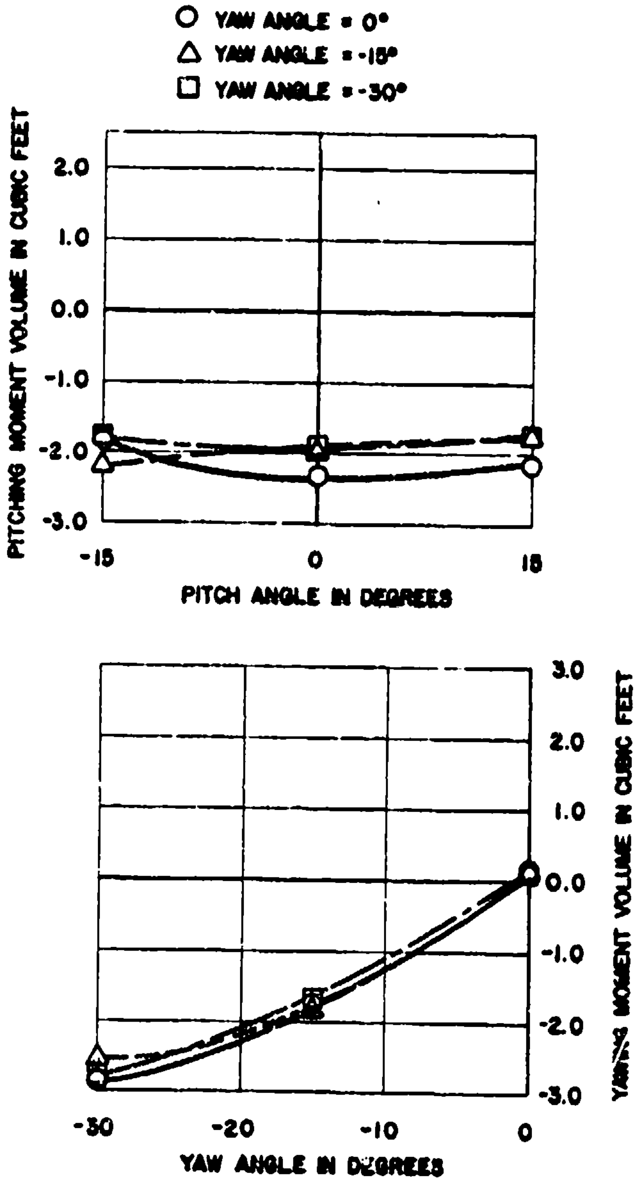


Figure 16. Variation of Pitching and Yawing Moment Volume for the ACES-II Ejection Seat.

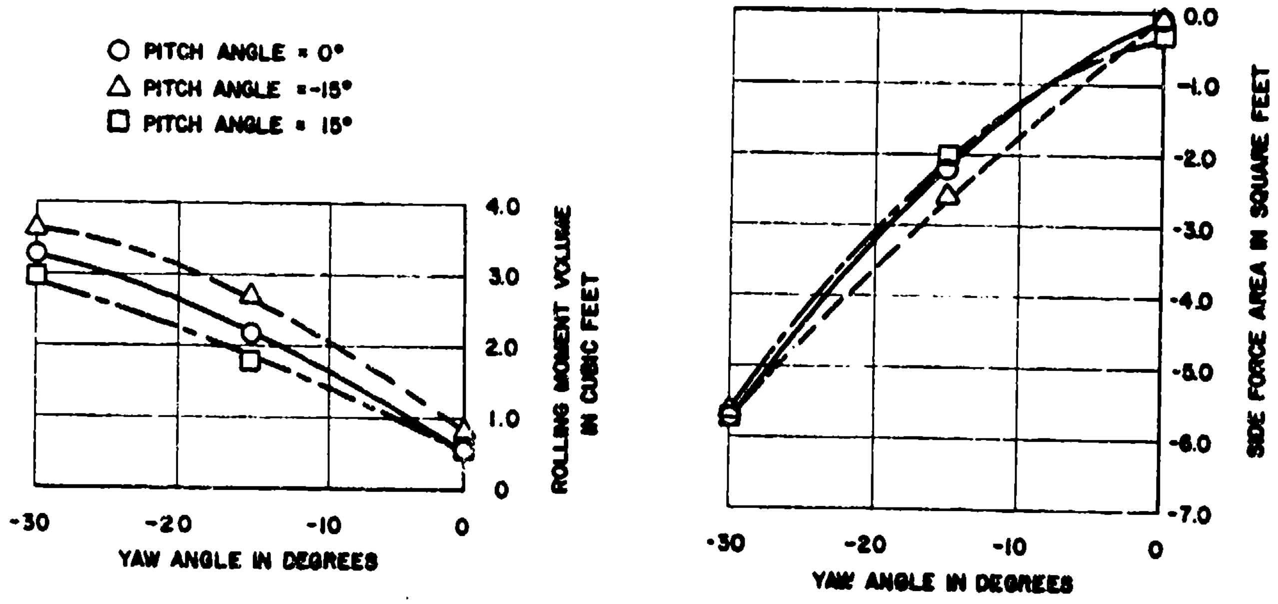


Figure 17. Variation of Rolling Moment Volume and Side Force Area for the ACES-II Ejection Seat.

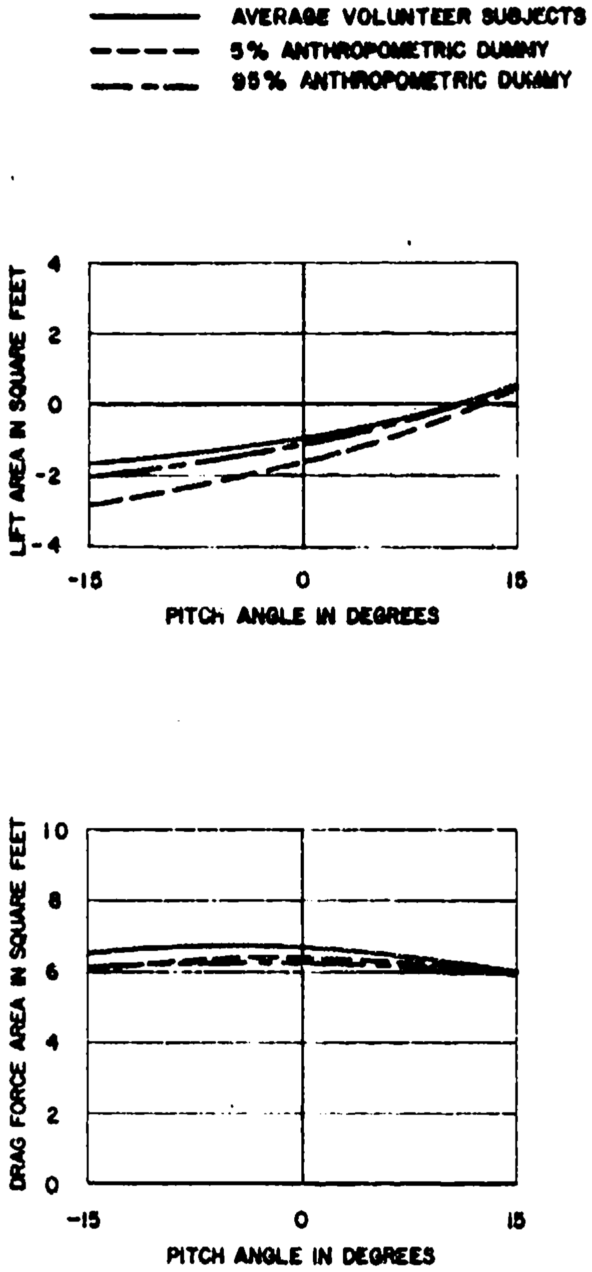


Figure 18. Comparison of Anthropometric Dummies and Volunteer Subjects for Lift and Drag Area.

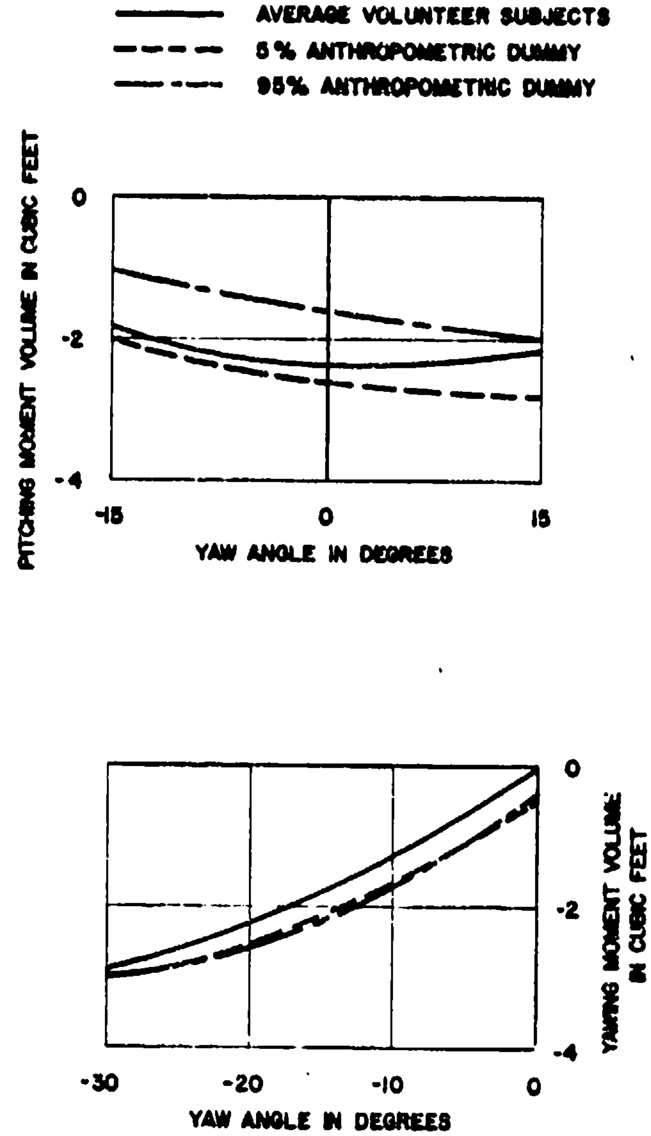


Figure 19. Comparison of Pitching and Yawing Moment Volume Between Anthropometric Dummies and Volunteer Subjects for the ACES-II Ejection Seat.

Comment on Fryer's Earlier Work

The early pioneering experiments in the area of limb force measurements were conducted by the late Squadron Leader D.I. Fryer in the early sixties. His work, which was conducted in water, is compared with our study conducted in a wind tunnel (Figure 20). The results show an excellent correlation between the water tank and the wind tunnel limb force measurements of the arm out force and leg separation force.

Helmet Forces and Pressures

As mentioned in the description of the test set-up, arrangements were made to measure forces and pressures acting on the helmet. This is a separate subject, not necessarily related to the incidence of flail injury, but since, in USAF experience, helmet loss is not uncommon following ejections it seemed appropriate to add these measurements to the program. Also, in Services which do not utilize retention straps with weak links, helmet-induced injury is sometimes suspected during autopsies.

Instead of being attached to the subject's head the helmet was supported by a sting attached to the headrest. The sting was strain-gauged to measure the lift, side and drag forces and the pitching and yawing moments of the helmet. The F-105 seat was used in this series of tests.

Fourteen (14) static pressure taps were fitted to the helmet to obtain evidence of the pressure distribution on the helmet. Ten (10) were used to measure the static pressure outside the helmet and four (4) were used to measure the static pressure inside the helmet. These are shown in Figure 7. The helmet support bracket is seen in Figure 6.

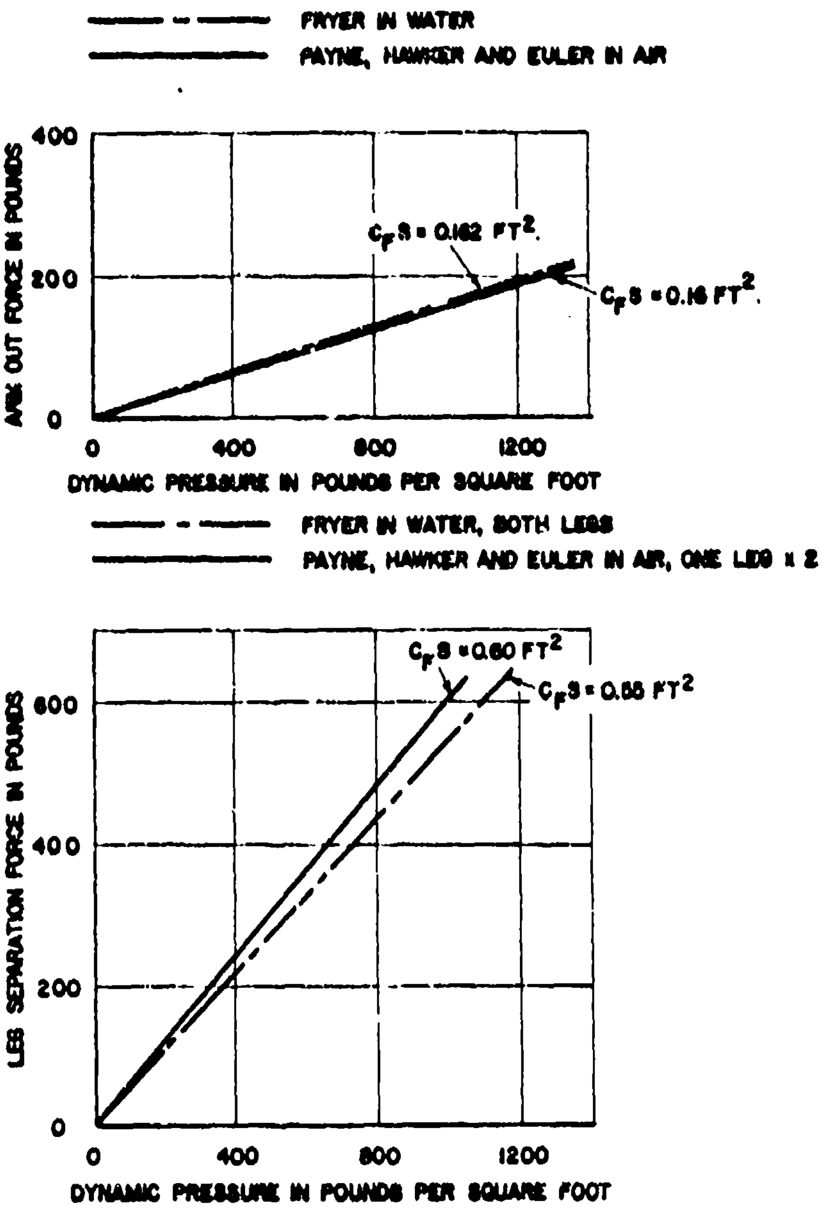


Figure 20. Comparison of Fryer's Water Tank Measurements (Reference 3) and Payne, et al Wind Tunnel Experiments of Limb Force Measurements (Reference 1).

Average values of the three helmet forces are plotted in Figures 21 to 23 and the pitching and yawing moment averages in Figures 24 and 25. The scatter of the individual data points is again considerable, but as for the case of the limb forces, the trend of the means is reasonable. The average lift area of 0.38 ft^2 at zero yaw, zero pitch, is somewhat higher than the figure of 0.28 ft^2 reported in Reference 4*. This lift force is very powerful and makes helmet loss or neck injury inevitable during high speed escape. A force area of 0.38 ft^2 corresponds to a lift of about 460 lb at 600 knots (Figure 26).

The lift force is mainly due to suction on the outside of the helmet, rather than ram pressure inside. The data from the static pressure tap measurements show that the pressure coefficient C_p can be as low as -1.0 on the outside but rarely exceeds 0.2 inside.

The definition of C_p is:

$$C_p = \frac{p - p_\infty}{\frac{1}{2} \rho u_o^2}$$

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* Accuracy of the Reference 4 helmet force measurement was known to be poor.

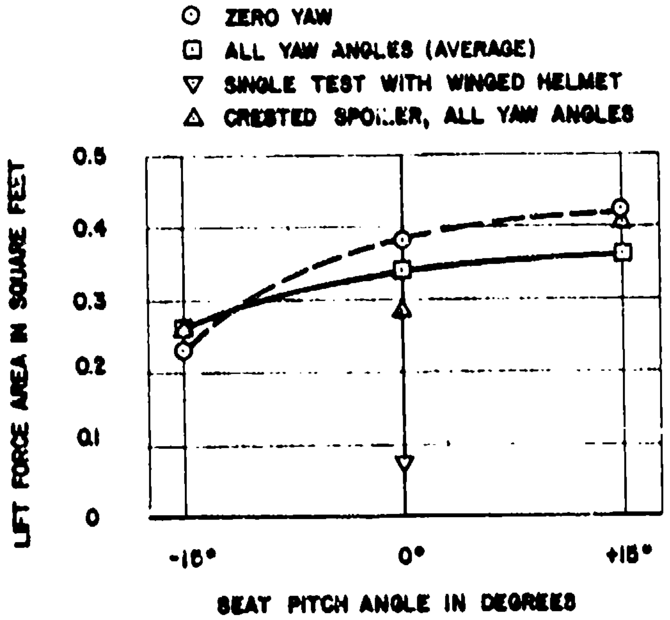

Figure 21. Average Helmet Lift as a Function of Seat Pitch Angle (Helmet Axes).

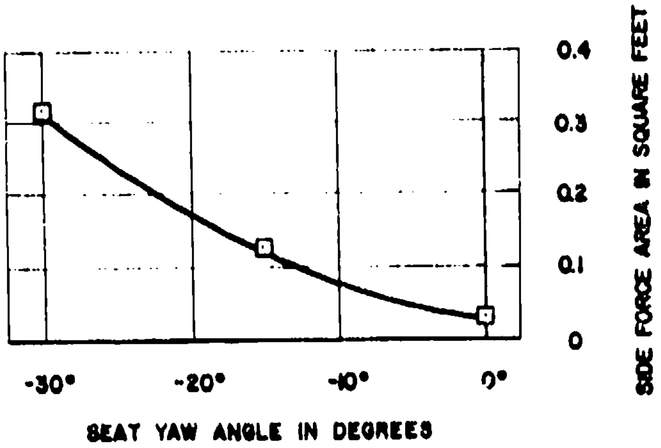

Figure 22. Average Helmet Side Force, For All Pitch Angles as a Function of Seat Yaw Angle (Helmet Axes).

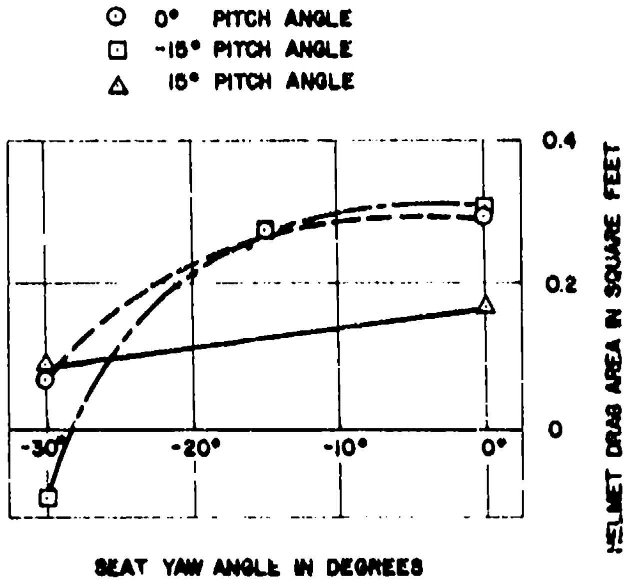

Figure 23. Helmet Drag Area, as a Function of Pitch and Yaw Angle (Helmet Axes).

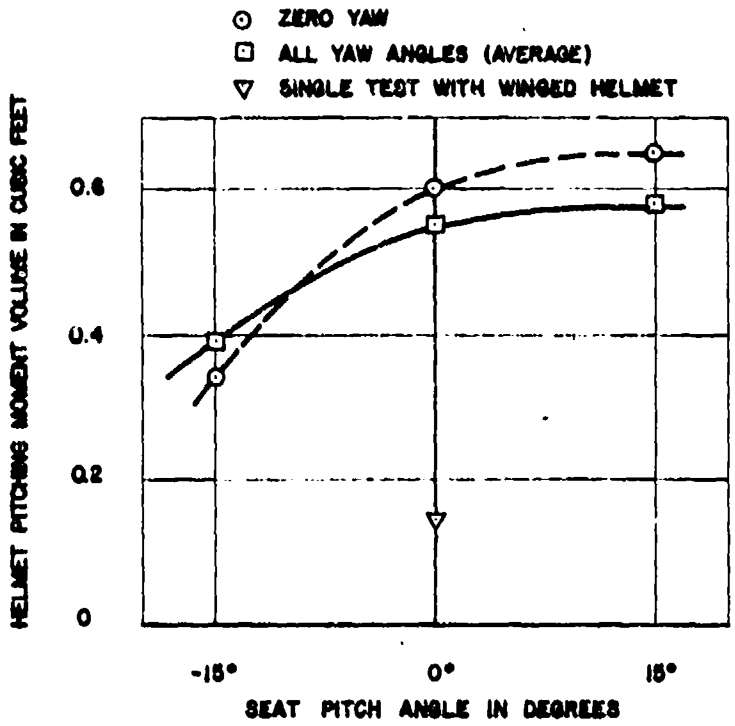

Figure 24. Average Helmet Pitching Moment as a Function of Seat Pitch Angle (Helmet Axes).

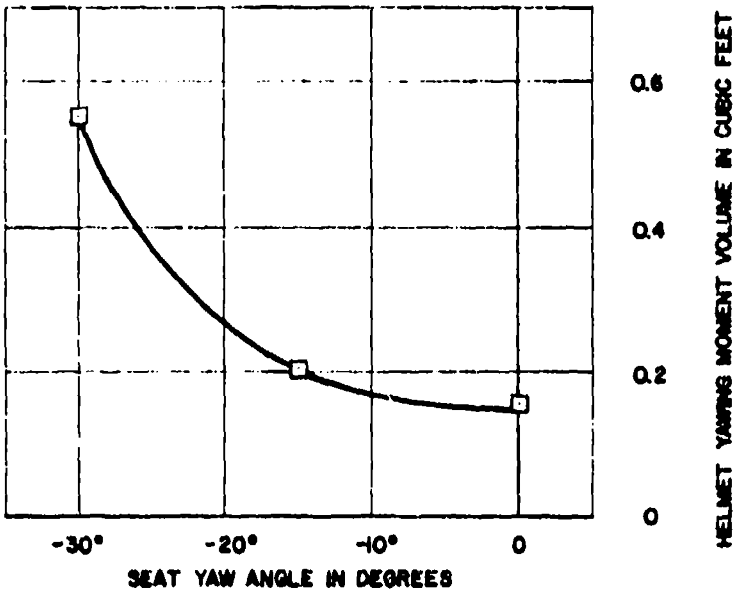

Figure 25. Average Helmet Yawing Moment as a Function of Seat Yaw Angle (Helmet Axes).

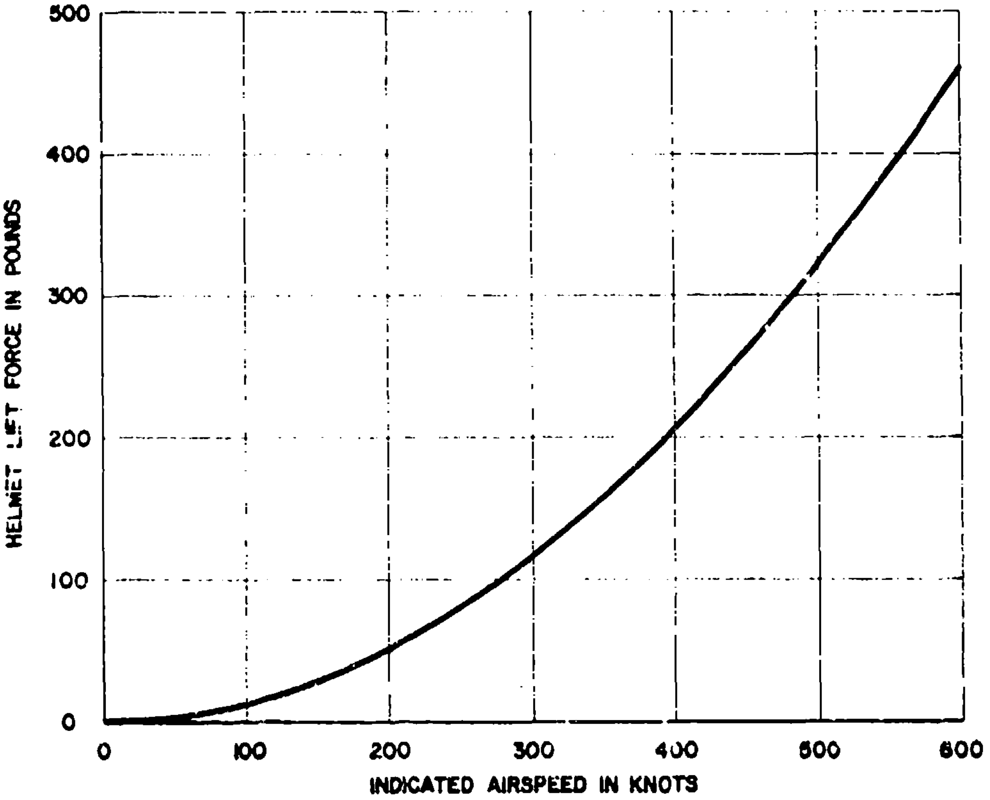

Figure 26. Helmet Lift Force as a Function of Indicated Airspeed Using the Measured Wind Tunnel Lift Coefficient of 0.38.

where

p is the local static pressure

p_∞ and u_0 are the undisturbed pressure and velocity

ρ is the undisturbed air density

From Bernoulli, it follows that, for incompressible flow

$$C_p = 1 - \left(\frac{u}{u_0}\right)^2 \quad \text{or} \quad \frac{u}{u_0} = \sqrt{1 - C_p}$$

Thus $C_p = -1.0$ implies $\frac{u}{u_0} = \sqrt{2}$. Locally, the flow velocity over the helmet is 40% greater than the free-stream flow.

In an effort to reduce lift the "crested spoiler" shown in Figure 8 was tried. As can be seen, the results were disappointing.

The winged helmet configuration of Figure 9 was then evaluated, for zero yaw and pitch. The wings were very successful in reducing both lift and pitching moment, without adverse effect on the other forces. We believe that a "second generation" winged helmet, having small swept back wings at a greater negative angle might achieve zero lift and not impede the helmet wearer significantly. More experimental work in the tunnel is clearly necessary before we can recommend an optimum configuration.

CONCLUSIONS

The primary conclusions of our wind tunnel experiments can be summarized as follows:

1. A sound method for measuring the limb force loads was demonstrated in both the F-105 and ACES-II ejection seats.
2. The loads on the limbs are of such magnitude that initiation of flailing is probable at high ejection speeds.
3. Anthropometric dummies compared well with volunteer subjects in the measurement of gross aerodynamic forces and moments.
4. There was excellent agreement between our wind tunnel investigation and

Fryer's earlier water tank experiments.

5. There is a substantial lift force produced on the standard Air Force helmet which is caused by the suction on the outside of the helmet, not the ram pressure inside the helmet.

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4. Payne, Peter R. — Some Studies Relating to "Limb Flailing" After an Emergency Escape From an Aircraft., AMRL TR 73-24, Wright-Patterson Air Force Base, Ohio 45433 (December 1974)

5. Payne, Peter R. — On the Avoidance of Limb Flail Injury by Ejection Seat Stabilization., AMRL TR 74-9, Wright-Patterson Air Force Base, Ohio 45433 (May 1974)

ACKNOWLEDGEMENTS

We would like to acknowledge the help and advice of James W. Brinkley and the cooperation of Major Ray Ma[illegible]son, Captain John Schaffer and Sergeant Joe Powers whose accurate observations made these tests successful. This work was done under United States Air Force Contract No. F33615-74-C-4015 and followed the first wind tunnel experiments with live subjects (in ejection seats) in Reference 4.

DISCUSSION

In reply to questions from Thorne (U.K.) and Glaister (U.K.), Hawker confirmed that his data had been obtained under static conditions in a wind-tunnel and did not take into consideration possible turbulence of airflow. He did not think it practicable to measure forces on limbs once they had been allowed to move from their initial position, but agreed that these forces would probably increase. Thus, the forces actually measured were those which would tend to initiate movement.

HIGH SPEED EJECTIONS WITH SAAB SEATS

by

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Sweden

Summary

The Swedish development work on devices to protect against wind-blast effects at high speed ejections is surveyed. Examples of past, present and future solutions are given.

The Swedish Air Force experience with high speed ejections is summarized.

Introduction

The combat aircraft of the Swedish Air Force are designed and built by Svenska Aeroplan AB, SAAB, in Linköping, Sweden. There are at present three main types in service:
the attack aircraft 37 (Viggen),
the light attack and trainer 60 (SAAB 105) and
the fighter and reconnaissance 35 (Draken).
SAAB combat aircraft are also in service with the Austrian, Danish and Finnish Air Forces.

The total number of ejections from SAAB aircraft in Sweden is for obvious reasons small. In the development of escape systems it is therefore necessary to gain information to a great extent from flight testing with dummies. This approach was adopted already back in 1940 when the SAAB company started work on ejection seats. The first test was carried out in January 1942 and the first live ejection took place in April 1946, when a pilot made a successful ejection.

The development of faster and more sophisticated aircraft has forced the development of escape systems for which both operational limits and operational dependability have been extended.

The operational speed limit for the escape system of the 60 aircraft is 800 km/h (≅ 430 kts), for the 35 it is 1200 km/h (≅ 650 kts) and for the 37 it exceeds 1150 km/h (≅ 620 kts). The 60 aircraft is equipped with an ejection system of the ballistic type while the 35 and the 37 have rocket seats.

There is no accepted definition of what is meant by high speed in connection with ejections. In this paper the interest will be focused mainly on the prevention of wind-blast effects of ejections at speeds exceeding 1000 km/h (≅ 540 kts).

Deceleration and stabilization

In Sweden it is considered highly desirable that the escape system should have low level capability even if the aircraft is diving. Consequently, the open seat, in which man can sustain higher deceleration than in a capsule, has been favoured. The deceleration of the man sitting in the seat is brought about by a seat-chute which is actively deployed by a gun-powder operated mechanism. Man's best position to stand deceleration is when the force is applied in the sagittal direction. The seat-chute has been designed to counteract turning and tipping movements so that the man is facing the direction of the movement. The stabilization of the seat is also believed to markedly decrease flailing of limbs and head caused by wind-blast.

With increasing speed there is an increasing tendency to a backward tilting movement of the man-seat complex. This is partly due to a momentum given the seat just before it leaves the guide rails. The lower part, still in the rails, acts as a fulcrum around which the wind-exposed parts tend to rotate. The backward tilting is also enhanced if the drag center of man-seat is located headward to the center of gravity. This latter discrepancy can be especially pronounced in the 37 due to the generous seat adjustment range. In order to lower the center of the drag force a metal sheet, similar in action to an air-brake, has been put under the seat. In the 37 the seat adjustment effect is also compensated by automatic adjustments of the direction of the rocket-thrust when the seat position is changed.

One tempting approach to the problem of injuries caused by flailing limbs is to decelerate the seat and torso of the man so violently that the arms and legs should not be bent backwards but rather stretched forward from the sitting man's position. However, this has not been technically possible. It is doubtful if it is physiologically possible. The idea was anyhow dropped, since the injury to the upper extremities are thought to be inflicted already before the seat is disconnected from the aircraft, at the very first moment when the arms are exposed to the aerodynamic forces.

Flailing of limbs and head

Different parts of the body have different masses compared to their aerodynamic properties. Protruding parts like arms, legs and head therefore have, at any speed, a tendency to flail at ejections.

The legs, if not restrained, are generally injured at speeds in excess of 600 km/h (~ 325 kts). In order to prevent the legs from flailing the 35 and the 37 seats have been equipped with leg restraints. The straps are connected to eyes on the pilots' boots by snap-hooks at about half the height of the lower leg. The other end of the strap is connected to the cockpit floor via a friction lock in the seat pan. When the seat is moving at ejection the lower legs are retracted and kept close to supports. The cockpit floor attachment is disrupted.

This one-point restraint of the leg is truly effective, but cannot at higher speeds prevent rotation of the lower leg in the frontal or horizontal plane. In order to improve the fixation in the frontal plane the leg supports in the 37 seat have a V-groove shape.

At high speed ejections injuries are initiated by rotations of the lower leg in the horizontal plane. The harmful abduction of the hipjoint is facilitated by this outward rotation of the foot. Prevention of this rotation is essential. Thus, for the 35 seat a special device has been developed and will soon be introduced into service. The device resembles a pair of tennis rackets located on each side of the seat pan. The frame of the racket rests on the floor of the cockpit and the handle is attached by a spring-load mechanism to the seat pan in such a manner that the racket will be pressed downward at ejection. The surface of the racket will then be positioned lateral to the feet and prevent outward rotation. A modified type of this lateral leg support will probably also be introduced in the 37 seat. The space of the cockpit prevents the use of the same type.

At speeds in excess of 830 km/h (~ 450 kts) it is in general not possible to retain a grip with the hand as e.g. on the firing handle. The Swedish rocket seats are initiated by (one or) both handles on each side of the seat pan. There are at present no arm restraints in any of the SAAB escape systems. However, much work has been and is presently devoted to such projects.

An early approach to the problem was the construction of a "jumping Jack" device. In its first model only the arms were engaged. Cords attached to a reinforced part of the forearm sleeve were guided over the suit in canals, along the upper arm and over the chest to the central strap-lock. The canals could easily be split open by the cords when these were tightned. At the central lock the cords were wound on drums. These drums were in their turn connected with drums on which a second set of cords were wound, the other end of these cords were attached to the cabin floor so that the device was activated early in the ejection sequence. This device was not introduced into service, but lead to a further development in which legs and head were also included. The cords were guided in canals but in addition there were loop-holes fastened to the suit through which the cords were drawn and thus the traction direction was determined. The final common path for the limbs and head cords was a cord on the back of the man which was attached to the cockpit floor. The device has not been introduced into service.

At the moment a different solution is under development. This device consists of two nets, one on each side, which are normally parked on the walls of the cockpit. The cords from the seat running to the net are also parked so as not to interfere with the pilot during normal operation. On ejection the strings will pull the net in such a way that the arms are caught and secured to the lateral side of the body until separation.

In this connection it is appropriate to mention that in aircrafts with tandem position of the crew and with rocket seats it is necessary to get the arms of the man in the rear seat in proper position for ejection also in cases when the ejection is initiated from the front seat. Airbags on the walls of the cockpit are used to provide a funnel through which the man is ejected and by way of which the arms are brought into position.

At present there is no head restraint system in service. The acceleration forces from the gun and the rockets will bend the head forward; the chin may actually hit the sternum. Later, when the head is caught by the wind, it is thrown backwards; the higher the speed the harder the head hits the neckrest. The very thick neckrest is filled with shockabsorbent material to prevent impact injuries to the head. In the 37 the neckrest has, compared to the 35 neckrest, been widened and made slightly concave in order to better catch the head and counteract rotatory movements of the head. For head impact speeds of 106 m/sec (35 ft/sec) the deceleration should not exceed 120 g. A head restraint device should obviously be of value in easing the head impact. Apart from the attempts described above in connection with the "jumping Jack" project some work has been devoted to construction of an inflatable collar, which should help to protect the head and neck from flailing injuries.

Pilot equipment

In the Swedish Air Force a combination of a pressure breathing oxygen mask and a custom fitted helmet with a neckbladder is standard equipment, (cf Larsson and Strömblad 1967). The helmet has no chin protection and the visor runs outside the helmet. It is our experience that the visor is destroyed at high speed ejections. The helmet and oxygen mask have been retained in most of the cases. Further development work on the helmet-visor-mask is obviously needed. The immersion suit has so far generally withstood the strain of high speed ejections.

Swedish Air Force ejections

Through the years 1967 to 1974 there have been 74 ejections in the Swedish Air Force. In one of these cases the speed at ejection is unknown. Neither man nor the aircraft has been recovered. In 8 of the 74 cases the speed was 1000 km/h (~ 540 kts) or higher. At the beginning of the period (1967 and 1968) two ejections with ballistic seats were made at 1150 km/h (~ 630 kts); both attempts were unsuccessful. With rocket seats five out of six cases have survived, two cases at 1000 km/h (~ 540 kts), one case at 1125 km/h (~ 610 kts) and two cases at 1200 km/h (~ 645 kts). Only in one case the outcome was fatal. This was an ejection during steep dive at 1200 km/h (~ 645 kts).

Out of the five who survived, one pilot (ejection at 1200 km/h, ~ 645 kts) sustained only minor injuries, contusion of a knee and facial petechiae, while the other four had major injuries. Among the major injuries encountered are fractures of legs and arms, tearing of big joints and concussion. Four of the five surviving pilots have resumed flying duties. The fifth has not yet been able to do so, his ejection took place as late as middle of October 1974.

The injuries to the pilots encountered in these cases have initiated and guided the development work here summarised. However, the number of high speed ejections is too small to allow a thorough analysis of the effect of the various steps in the development work. In fact, many of the modifications described, even if they are in service, have not yet been put to the test in real situations.

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CONCLUDING REMARKS

by D.H. Glaister

I would like to say a few words in an attempt to summarise the day's programme; but first of all I would like to convey a message from Dr. Walton Jones, the chairman of the Biodynamics Committee of ASMP. He regrets very much that he has not been able to be present today, but has been detained by NASA business in Washington.

This morning, I think that one of the things that struck me, and has perhaps struck me throughout the day, has been the remarkable agreement between the Nations, not only those of NATO, but also Sweden, on the mechanisms of windblast injury and on its frequency of occurrence in relation to windspeed (papers B1, B2, B4, B6 and B11). There was one exception, our host country Canada which appears to suffer fewer injuries, but the numbers of ejections were less than some of the other series so perhaps the signal had been lost in the noise.

We saw this morning that ejections are occurring at increasing speeds with more modern aircraft, particularly in the combat situation, and that injury rates, likewise, are increasing. If one excludes ejections made outside the design envelope of the ejection system, major injuries are now largely due to windblast, especially at the higher end of the speed scale. Injury rates of 40% or more were seen in the combat prisoner of war cases (paper B9) and we were told that at 600 kt the expectation of windblast injury approached 100 percent. These injuries are caused by limb displacement rather than wind pressure per se. We saw several examples of failures in aircrew equipment assemblies - helmets being lost, masks being lost - and again these seemed to occur with equipment from all the countries represented.

Well, by lunch time I think we were getting pretty depressed - the situation seemed poor. It wasn't improved when we came back to some very nice X-ray pictures showing details of very painful looking injuries produced by windblast on limbs free to move (B6).

Fortunately, as the afternoon progressed, things started to get brighter. We saw a number of examples of detailed improvements which have been carried out, and are being worked upon, in order to improve existing systems. Small things like wings attached to helmets to reduce lifting moments (paper B10), net limb restraints (B9), cords giving limb retraction and restraint (B8), 'tennis raquets' doing the same thing (B11), head protection by a fabric hood (B7) and so on. And then we saw some more advanced concepts - aerodynamic techniques for seat stabilisation which in the last test shot shown of the Saab seat (B11) looked very encouraging indeed. We saw that the ejection seat may not be necessary, except perhaps for sitting in, and may not be the ideal ejection platform (B9).

So, looking ahead, we see the possibility of a 750 - 800 kt ejection without a seat, stabilised apparently by shuttlecock feathers and with the limbs restrained by fish netting - it's a nice prospect! On that note I would like to close the session by thanking all the speakers for their excellent papers, and the audience for its attention. Thankyou.

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Advisory Group for Aerospace Research and Development, NATO
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Published July 1975
92 pages

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The special problem of windblast was considered as it affects human tolerance to high-speed ejection.

Injury mechanisms were discussed in several papers and it was shown that most injuries are caused by excessive

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Leg (anatomy)
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Blast effects
Blast injuries
Nuclear explosions
Explosions
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Design
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Wind tunnels

AGARD Conference Proceedings No.170
Advisory Group for Aerospace Research and Development, NATO
BIODYNAMIC RESPONSE TO WINDBLAST
Edited by D.H.Glaister
Published July 1975
92 pages

This volume contains the text, discussion and technical evaluation of papers presented at the AGARD Aerospace Medical Panel Specialists Meeting which was held at Toronto, Canada, 6 May 1975.

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Protection was considered along two lines. The prevention of limb motion by means of restraints was shown to be as practical for the arms as for the legs, and could be extended to provide the arm retraction needed in safe command ejection. It was also shown that the provision of a stable ejection seat would greatly ameliorate the windblast problem.

The problems of head restraint and helmet loss were also considered. Loss was attributed to the aerodynamic lifting moment which had been measured in wind-tunnel tests, and could be reduced by appropriate aerodynamic design.

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