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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

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Fourth Advanced Operational Aviation Medicine Course

**Royal Air Force Institute of Aviation Medicine
Farnborough, Hampshire**

17-26 June 1975

NORTH ATLANTIC TREATY ORGANIZATION

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FOURTH ADVANCED OPERATIONAL AVIATION MEDICINE COURSE

held at ROYAL AIR FORCE INSTITUTE OF AVIATION MEDICINE
FARNBOROUGH, HAMPSHIRE

17–26 JUNE 1975.

Edited by

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PREFACE

During June 1975 the Fourth Advanced Operational Aviation Medicine Course was held at the Royal Air Force Institute of Aviation Medicine, Farnborough. Representatives from nine NATO countries attended the course, and they included doctors from sea, land and air forces.

The course covered in depth some aspects of aviation medicine which are of current concern to the effectiveness of NATO air forces. The topics included the training of aircrew in aviation medicine, medical aspects of naval helicopter operations on the northern flank of NATO, developments in personal equipment with special reference to helmet developments, high speed escape and thermal problems, and the use of hypnotics in air operations. These topics were of special interest to the Royal Navy and Royal Air Force.

Representatives visited the Royal Naval Air Medical School where they observed current techniques used in training for rescue from helicopters, and the Martin Baker Aircraft Company Limited for demonstrations of their current equipment and development work.

In this publication the lecturers have prepared papers which it is hoped will provide useful material for the application of current work to the needs of operational aircrew.

I would like to acknowledge the considerable help I received from the staff of the Royal Air Force Institute of Aviation Medicine and the Royal Naval Air Medical School, and in particular to my assistant Miss Carol Bryant for help with the organisation of the course and in the preparation of many of the manuscripts.

A N NICHOLSON
Wing Commander
Course Director

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HELICOPTER OPERATIONS ON THE NORTHERN
FLANK OF NATO

by

Surgeon Lieutenant Commander A P Steele-Perkins RN

INTRODUCTION

The general requirement of the helicopter support of the British Naval committment to the northern flank of NATO is the protection of sea forces. This involves anti-submarine operations, and in this role the helicopter has proved highly efficient. It has a fast operational reaction, and with sonar and radar it possesses a good capability for the location of submarines. Usually, several helicopters are operational at any one time, and they form a protective screen around the force. In the Royal Navy the Sea King helicopter is used in this role. An additional role for the helicopter is in commando assault operations. Helicopters ferry troops and equipment to and from ships, and provide field support. The Wessex Mk 5 is used in this role. It can carry about 10 fully equipped soldiers.

The Helicopter Environment. The usefulness and efficiency of the Sea King helicopter is such that it is used to its full potential. A sortie is usually of 4 hours, and many factors contribute to the fatigue of aircrew. The most important are noise, vibration and general discomfort. Vibration is a problem in all helicopter operations, but rotor blades worn by the salty atmosphere increase the problem. The aircraft is noisy because the gear box intrudes into the cabin and there is very little sound proofing, and, though helmets are used by aircrew, throat microphones tend to transmit some of the noise. With radios, inter-communications and sonar, noise may be a particularly important factor in aircrew fatigue.

The crews of helicopters often operate in a cold environment. Electrical heating of the extremities tends to combat serious discomfort, but the crew member most at risk is the sonar operator who sits directly behind the hole in the floor through which the sonar transducer travels.

Operations. During operations rests between sorties are usually reduced by briefing, changing and eating while sleep may be impaired by the pitching and rolling of the ship and by the high noise levels. These factors are important and contribute significantly to the fatigue of all crews.

Military support operations often involve mountainous country, and demand high levels of concentration. Such operations are hazardous because of turbulence and draughts. With down draughts the helicopter may descend with full power being applied, and knowledge and practice of the techniques of mountain flying are important. There is also a danger of disorientation. It is easy to misinterpret apparently horizontal cues and to misjudge heights. The "break-off" phenomenon can be experienced in helicopter flying over mountainous country. Operations over snow covered land can be particularly hazardous, as it is difficult to judge height, and a radar altimeter is essential. The re-circulation of snow through rotor blades when close to the ground reduces vision (white-out) and safe handling of the helicopter is a skilled operation.

Survival. An additional hazard is survival in the event of a crash. In the Arctic survival can be a matter of minutes unless the crew is suitably protected. All crews have a survival pack, and this contains a single-man life raft and survival aids. With a crash into the sea a helicopter may turn over, and partially sink before the crew are free. Immersion is a serious complication, and it is important that the dinghy is used as soon as possible. A life raft with an inflatable floor and a canopy provides good protection against chill. Frequent practice drills and experience of the behaviour of a sinking helicopter are necessary for aircrew operating over the sea.

MEDICAL ASPECTS OF OPERATING ON
THE NORTHERN FLANK OF NATO

by

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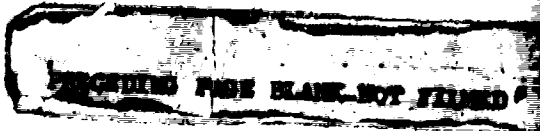
INTRODUCTION

The arctic environment has been described as a dynamic force with a powerful and often violent influence on the ignorant or unwary. Man has learnt to live and work in the Arctic by developing clothing and equipment that will protect him from the cold; but military experience has shown that success in such adverse conditions depends far more upon the knowledge of how to behave and use the protective equipment available, than it does upon the equipment itself. To survive successfully in the Arctic man must have a working knowledge of the climatic conditions and environmental characteristics. Without such knowledge it is unlikely that he would survive should he ever be stranded, in the open, with limited resources. Such knowledge is also essential for aircrew and groundcrew who will be either flying, or servicing aircraft and ground equipment, under conditions not normally encountered when operating in more temperate climates.

Environment

Winter in Northern Norway lasts from October to April, the long hours of darkness, heavy arctic clothing, the cold, and heavy snow conditions all contribute to the difficulties and markedly lower work achievement. There is a reduction in mental performance and a deterioration in the ability to perform manual skills to the extent that the majority of tasks will take up to two or three times as long as 'normal'. The ability to fight and survive under such extreme conditions comes mainly from experience and training in that particular environment and improvements in mental and manual performance will also come with the knowledge of how to live in that environment, rather than by attempting to fight it.

From mid November to the end of January there is a period of almost complete darkness gradually changing to twilight, until in February the sun creeps slowly above the horizon. The climate and topography differs greatly from area to area, and each presents their own particular problems. Only 4% of Norway is arable land, the remainder being 24% forest and 70% mountains and lakes. The coastline is long with deep fjords and the interior mountainous and slashed with deep valleys. The north of the country lies in the Arctic and Subarctic zone whilst the remainder of the country is in the so-called Temperate zone.

In the North, winter temperatures can be expected to fluctuate from +6°C to -40°C and are a strange mixture of Cold/Wet and Cold/Dry conditions. One of the most striking features, and very difficult to deal with, is the sharp rise and fall of temperature that is sometimes encountered. Variations of 15°C - 20°C in a twelve-hour period are not uncommon. Cold/Wet conditions are demoralizing at the best of times but when followed a few hours later by freezing conditions they are almost impossible.

The cooling power of the environment is significantly increased by air movement, and windchill and its effects are of particular interest to groundcrew, as a great deal of their work has to be carried out under the downwash of the rotor blades. This downwash creates wind-speeds of up to 40 knots which in turn causes swirling clouds of re-circulating snow to penetrate even the smallest opening in a man's outer garments. Additionally, ambient wind speeds of 5 - 20 knots are typical for the area. The winds from the North and East bring very dry weather, while from the South they bring subarctic conditions. The South Westerlies generally herald a rise in temperature and frequently bring heavier snow falls.

The 'Windchill Index' devised by Siple[1] has proven to be a very useful means of determining the extent to which man can be exposed to cold. As you know, the 'index' is read from a nomogram of the variables, namely, the ambient temperature and the wind speed, such as that illustrated at Figure 1. The cooling rate is expressed as Kcal/m²/hr for various temperatures and wind speeds, with the cooling rate based upon the naked body at a neutral skin temperature of 33°C.

To many, the "equivalent chill temperature"[2] will be more meaningful than the 'wind-chill index'. The graph translates the combined effects of wind and temperature to the equivalent temperature that would cause the same rate of cooling of human flesh, under calm conditions. Whilst there should be little danger, for Arctic trained personnel, down to equivalent temperatures of -29°C, it can be seen from Figure 2 that groundcrew teams working under the rotor downwash will be working in extremely stressful conditions.

Groundcrew Tasks

The tolerance of man to the cold is largely determined by the parts of his body which are usually unprotected, such as face and hands. To use the words of Buxton and Edholm, "no really satisfactory face-mask for the functioning soldier has been available and gloves have often to be removed for fine work"[3]. The position has not greatly changed as far as groundcrews are concerned, and a careful assessment of the work involved in each task is necessary to decide not only what tools are required, but also what shelter and heating may be necessary. Basically groundcrew tasks can be divided into four main categories.

  a. Work which can be completed by personnel dressed in cold weather clothing and handwear. This includes flight maintenance, anti-icing, de-icing and replenishment of fuel and oils which, although straightforward tasks, take longer than would be required under more temperate conditions. The insulative qualities of cold weather clothing will be adversely affected by fuel, oil, grease, anti-icing and de-icing fluids and an outer layer of suitable protective clothing is required for these tasks.

  b. Work which entails the removal of handwear. This will be necessary because of inaccessability of the small size of some parts and two men will be required where one would usually suffice; one working and one directing warm air onto the metal and hands of the operator. Under severe conditions regular rest periods will also be needed.

  c. Major repairs, such as engine change, will need to be carried out under a shelter, provided with a heat supply. Work in a shelter takes somewhat longer than usual, but personnel can work for longer periods without regular 'rest and rewarm' breaks.

  d. Domestic duties, such as tent erection, camp consolidation and snow clearing.

The nature of these tasks are such that they require concentration and, in some cases, strenuous physical effort. In extreme weather conditions continuous and strenuous physical effort can, and does, adversely affect morale and there is a further risk that the untrained may become victims of exhaustion. In my opinion, it is questionable whether United Kingdom medical standards are sufficient for men who are destined for land based service in the Arctic or Subarctic environment.

Medical Selection Examination

The combat soldier or the Royal Marine undergoes hard training in preparation for arctic service, but modern warfare demands technical support on most military operations, unlike the infantry the supporting technicians are frequently physically unfit and ill prepared for the rigours of the cold. In my opinion it is doubtful if the medical category of P2 is sufficient for men who are to be drafted to an arctic environment. Certainly it has been my experience that personnel with a history of the following should be excluded:

  a. <u>Respiratory disorders</u>. Upper respiratory tract infections are common and seem to occur around 7-10 days after arrival in an arctic environment. Such infections appear to be precipitated by a combination of; unusually dry air, and increase in smoking, fatigue and dehydration. Usually such cases respond to 24-36 hours bed rest, extra fluids and aspirin. Cases with a past history of chest complaints are most difficult to clear up and relapse is common; in fact, their usefulness as members of a team is questionable.

  b. <u>Cardiovascular dysfunction</u>. Any man with a previous history, such as cardiac arrhythmia, is a potential casualty as his condition will be exacerbated by the cold. Men who show any signs of poor circulation in temperate climates should also be disqualified.

  c. <u>Renal disorder</u>. Specifically colic or renal stone. Dehydration is a very real problem in the Arctic and Canadian experience in various exercises indicate that dehydration appears to be the main contributing cause of casualties and loss of effectiveness[4]. Dehydration arises because of:

  i. the relative unavailability of potable water

  ii. increased loss of body water through sweating

  iii. increased respiratory loss of water

  iv. cold-induced diuresis.

Without doubt the main cause is the difficulty in obtaining sufficient water to counteract fluid loss. An arbitory figure of some five pints a day has been suggested as the amount required to replace fluid losses. To melt sufficient snow to produce five pints of water per man takes considerable effort, and often, men are just too tired to gather the amounts required.

  d. <u>Skingrafts to hands</u>. Experience has shown that after a few weeks of working under field conditions even established skingrafts tend to break down.

  e. <u>Psychiatric history</u>. Personal adjustments are required to operate effectively in low temperatures, men with good service records and stable personalities seem to adapt to the situation very well indeed. Boredom, however, tends to be a problem and what may, in other environments be considered minor problems, can grow out of all proportion and lead to bouts of depression, resulting in men withdrawing and being isolated from a group. A man with a poor record or a psychiatric history does not usually adapt well to this type of situation and his performance is likely to be adversely affected.

Time does not permit me to go into detailed case histories, but may I just say that in the Commando Air Squadrons we now exclude anyone, falling into the above categories, from Arctic land based service; on earlier occasions when men have been permitted to go despite adverse histories they have invariably "fallen over". Even with a simple condition like haemorrhoids perhaps one should think twice, as the constipation produced by dehydration coupled with the lack of desire to bare one's nether regions to the cold, can cause extreme discomfort and agony to the unfortunate sufferer!

To achieve the higher standard of physical fitness required for Arctic service it is essential that a screening process, along the lines described is adopted. The problem is then one of maintaining a healthy state which will depend largely upon the individual protecting himself from the hazards of the environment.

Pre-Arctic and Survival Training

The lack of success in dealing with cold can also be related to lack of supervision or lack of self-discipline. For instance cold injury should not occur under normal circumstances and, accidents apart, can be avoided if the individual is taught how to use his protective clothing to best advantage and maintain thermal balance. Useful training can be given to all, including technicians, who may be suddenly faced with Arctic operations, but such training should commence at the man's home base. We have found a two tier system of training very useful in training personnel for Arctic service and men are now required to undergo a period of pre-Arctic training prior to deployment to Northern Europe, this is then followed by survival training on arrival.

During pre-Arctic training emphasis is placed on protection and the problems of operating in cold environments. Among the main topics discussed are:

a. environmental effects

b. use of protective clothing

c. use of shelter

d. life style

e. cold injuries

f. survival techniques.

Once the basic details have been covered, confidence and knowledge of the environment will only come from actual practical experience. This can be achieved by placing men, at short notice and with minimum kit, in a simulated survival situation where their every effort is centred on living. The stress of a real survival situation cannot be simulated but initially the 'survivors' become surprisingly anxious, despite the fact that they know their situation is only temporary. After a few days one can begin to detect a newfound confidence and awareness of the new environment among those under training and with correct supervision the trainees soon learn the required lessons, such as learning how to maintain a normal body temperature and take care of clothing, as well as moving through snow, preparing food and looking after each other. The time and effort put into this type of training is amply rewarded and men quickly learn to respect, but not to fear, the cold environment.

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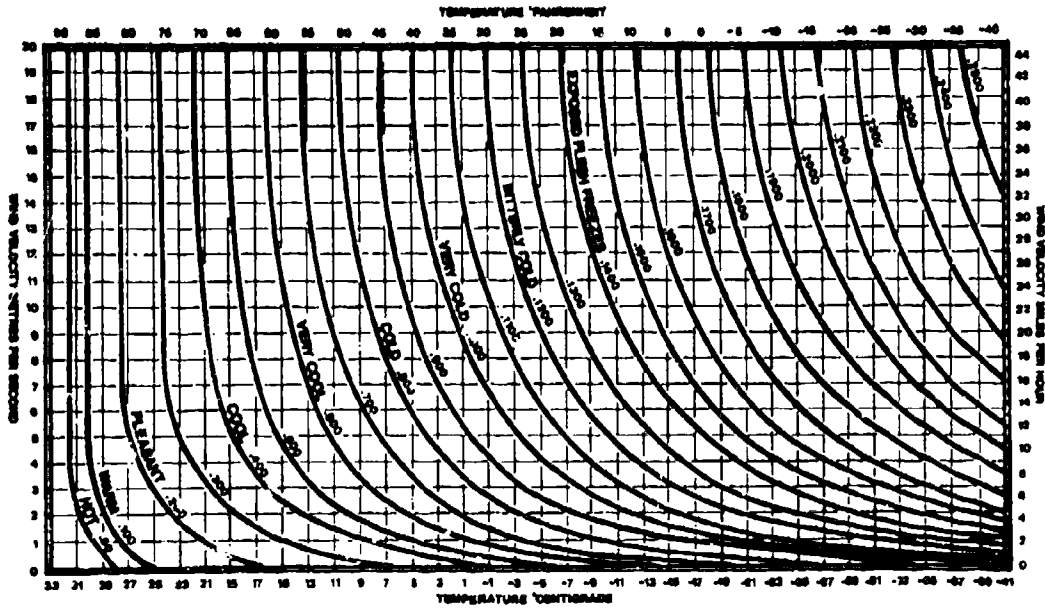
Figure 1

Wind Speed Knots	Temperature (°C)																
Calm	5	2	-1	-4	-7	-10	-13	-14	-18	-21	-24	-26	-29	-32	-35	-37	-40
EQUIVALENT CHILL TEMPERATURE																	
3 - 6	2	-1	-4	-7	-10	-13	-15	-18	-21	-24	-26	-29	-32	-35	-37	-40	-43
7 - 10	-1	-7	-10	-13	-15	-18	-23	-26	-29	-32	-37	-40	-43	-46	-51	-54	-57
11 - 15	-4	-10	-13	-18	-20	-23	-29	-32	-35	-40	-43	-46	-51	-54	-57	-62	-65
16 - 19	-7	-13	-18	-20	-23	-29	-32	-35	-37	-43	-46	-51	-54	-59	-62	-65	-70
20 - 23	-10	-13	-18	-21	-26	-29	-35	-37	-43	-46	-51	-54	-59	-62	-68	-70	-76
24 - 28	-13	-15	-18	-24	-29	-32	-35	-40	-46	-49	-54	-57	-62	-65	-70	-73	-79
29 - 32	-13	-15	-21	-24	-29	-35	-37	-40	-46	-51	-54	-59	-62	-68	-73	-76	-81
33 - 36	-13	-18	-21	-26	-29	-35	-37	-43	-49	-51	-55	-59	-65	-70	-73	-79	-81
	LITTLE DANGER (for Arctic trained troops)					INCREASING DANGER						GREAT DANGER					

Figure 2

Cooling power of wind expressed as 'Equivalent Chill Temperature'

THE OPERATION OF HELICOPTERS FROM SMALL SHIPS

by

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SUMMARY

The operation of the Wasp helicopter from the decks of Tribal Class and Leander Class Frigates of the Royal Navy is described and some of the difficulties involved in such operations, including ship movement and turbulence, are discussed.

The Royal Navy has a number of helicopters operating from a variety of ships and therefore ships' decks. The term operating from small ships would probably be better redefined as operation from small decks for once one excludes the aircraft carrier deck the size of decks available are all relatively small.

The helicopter that this dissertation will be largely concerned with is the Westland Wasp aircraft. It is a small helicopter with four relatively short rotor blades, a gas-turbine engine mounted immediately behind the cabin, a twin-bladed tail rotor and a four-wheel undercarriage, each wheel of which is individually castored. The major role of the Wasp helicopter is that of a torpedo-carrying anti-submarine attack helicopter and it operates from the small flight decks of Leander and Tribal Class Frigates of the Royal Navy. The Wasp is fully instrumented for night flying but is not sufficiently well equipped to be brought to the hover in the dark without considerable difficulty. Noise and vibration are a constant and inescapable element of any helicopter flight. They vary in intensity from aircraft type to aircraft type and even from aircraft to aircraft. Attempts are made to tune out severe vibrations during the test flying of each aircraft at the factory before its delivery to the Service and luckily the Wasp is not a particularly bad helicopter from this aspect even though much of the time it has to be flown with the cabin doors removed.

The Wasp's main task is to deliver homing torpedoes to a position predetermined by the mother ship and other A/S ships (or helicopters) operating in the vicinity. Once airborne and with good radar direction this task is not normally particularly difficult, nor is the return to the immediate vicinity of the mother ship. The main problems tend to arise during initial take-off, final approach and landing, and to understand these difficulties we need to look at some of the basic factors involved. The Westland Wasp was developed from the Saunders Roe P531 Scout, and has a special four-wheel undercarriage and an extra low minimum value of collective pitch to improve its deck operating capability. But apart from this the pilots have had to take the helicopter as it was designed and have had to develop their own techniques and skills to suit the task of operating from ships. How does this task differ from other types of operation? The vessel and its superstructure will create a region of turbulent air which the helicopter must negotiate during the take-off and landing manoeuvres. However, much turbulence can be experienced ashore around buildings or in mountainous localities. Similarly, although the flight deck of a ship is dimensionally very small this type of helicopter frequently operates from confined areas ashore, for example out of jungle clearings. The main difference in the shipborne situation is that the turbulence and the constricted space almost always occur simultaneously. In addition, because calm conditions at sea are rare and because a relative wind can arise from the speed of the ship, the manoeuvres are normally made in the equivalent of high winds not often encountered on land. A third factor, one that is unique to shipborne operations, is deck motion. A ship's deck has 6 degrees of freedom of which the angular motions of roll and pitch and the vertical heave are the more important when considering the operation of helicopters. The deck and ship movements can present the pilot with a moving set of references which could lead to disorientation when on the approach in poor visibility or at night, or when over the deck close to any superstructure. Deck motion can also increase the difficulty of judging the rate of descent of the helicopter and of the slope of the "ground" on which one is about to land. The technique adopted where possible is usually to hover (during landing) or to wait on the deck (during take-off) until a quiescent period of motion occurs before making the final manoeuvre.

This then is the shipborne situation. The pilot has to manoeuvre his aircraft through moderate to severe turbulence onto or from a landing platform that is very restricted in size and which, together with the visual references, can be rolling, pitching and heaving.

Flying in such limited and turbulent conditions can require a considerable degree of manoeuvring close to the deck. Such manoeuvres inherently mean changes in the power demanded from the engine by the main and the tail rotors. The yaw control is provided by the tail rotor which is often working in conditions near the regime of blade stall. Therefore, quite modest increases in yawing moment applied by the pilot in dealing with turbulence can create a demand for a large increase of power. In fact the amount of control available to the pilot is often considered in terms of the Wasp's power limitations and certainly when manoeuvring onto a ship's deck the engine torque indicator is an instrument that is constantly monitored by the pilot.

The Ships

The Tribal and Leander Class Frigates have their flight decks placed at or near the stern of the vessel. This has the advantage of giving the pilot an approach path that is usually free from obstructions. However, it has the disadvantage that the vertical displacement of the deck associated with the pitching motion will be at its maximum at this position. The Leander Class has the forward end of its flight deck obstructed by superstructure, mainly the hangar, extending the full width of the ship. The Tribal Class on the other hand has its smaller deck relatively free from immediate obstruction. Both the Tribal and the Leander Class have stabilisers that limit the amplitude of their rolling motion although

at a ship's speed of less than about 10 kts this stabilisation becomes ineffective. According to the pilots the stabilisers also have the disadvantage that although they may limit the amplitude of the roll they tend to increase the rates of change of acceleration of the ship's deck.

Landing and Take-Off Procedures

In principle it is preferable to take-off and land the helicopter while it is facing into the relative wind and, although it is possible to approach and land on or take-off from virtually any azimuth direction relative to the ship, it is usual to follow a common pattern for all approaches in which the helicopter comes in to land from the port astern sector. He then hovers the aircraft alongside the flight deck on the port side and lands from that position under the control of the flight deck officer. As the pilot usually sits in the right-hand seat of the cockpit the above approaches give him the best view of the flight deck and is the one that can be best used at night.

The operating routine for landing can best be described if it is considered in four phases:

1. The approach to the "gate" which is the position from which final approach is commenced.

2. The final approach.

3. The land-on (or take-off).

4. The handling on the deck.

1. The Approach to the Gate

This is accomplished normally under radar control from the ship which brings the helicopter to the position in space where it can best commence its approach down the glide slope. There are various set manoeuvres in case of radar or other control failures in which the helicopter is brought overhead the ship and then flies a set circuit pattern to bring it onto the glide slope. These are quite complex and require a great deal of accuracy and skill in the flying of them. As is stated above the point of all the approaches is to intercept the glide slope leading to the ship's flight deck.

2. The Final Approach

The radar approach intercepts the glide slope at 2 miles and the initial descent is commenced under radar control. At approximately ½ of a mile from the ship the pilot is looking up to try and identify the deck and the glide path indicator. The latter is a projector site fashioned such that it projects three beams of light as shown in Fig. 1. The upper band of light is amber and indicates the aircraft to be above the glide path; the glide path band itself is green and can be seen ½ of a degree above and below the 3 degree glide path. The red band shows below the green and indicates the aircraft to be below the glide path. The glide path indicator (GPI) has two problems. The lateral limits of the projected beam are approximately 6 degrees either side of the centre line, beyond that the glide path indicator is not seen as a series of beams of light but may be seen as a "ghost" amber at all heights. This may give rise to a false sense of security in that the pilot thinks that he is high on the beam for his approach. The second problem is that at the interface between the red and the green bands another "false" amber may be perceived, particularly in hazy conditions. It is hoped to overcome this latter problem in the near future by exchanging the colour of the green and amber beams, ie the amber becomes the glide path and the green becomes the high beam. Other and better GPI's are under development and are being tested at RAE Bedford.

To re-cap, the helicopter is brought onto the approach about 2 miles astern of the ship, the airspeed is reduced to 60 kts and the descent commenced down a 3 degree glide slope at approximately 15 degrees relative to the ship's course. Overall command of the situation is retained by the ship's commander, first of all through the helicopter controller if the ship is fitted with radar and then by the flight deck officer who must be in visual contact with the helicopter. Transfer of control at visual contact takes place at a range of not less than ½ of a mile and normally at approximately ¼ a mile. When in close proximity to the ship the pilot brings the helicopter alongside the port beam about 15-18 metres above sea-level. He can then adjust his position and speed relative to the vessel without fear of overshooting into the superstructure. Finally he manoeuvres the helicopter sideways under the direction of the flight deck officer to bring it to the required position over the flight deck.

3. The Land-On (or Take-Off)

In the third phase over the deck an attempt is made to establish a hover relative to the ship with the wheels about 2 metres above the deck. Control of this operation is still under the direction of the flight deck officer who would normally be in radio communication with both the ship's command and the pilot but who also has hand-held flags (or at night illuminated wands). When in the flight deck officer's opinion the helicopter is correctly positioned, and at an appropriate time with regard to ship motion, the helicopter is put firmly onto the deck. Take-off is similarly under the flight deck officer's control and he chooses the most appropriate moment for lift-off. The helicopter becomes airborne in a comparatively very short time and usually there are no problems provided that the pilot does not translate into forward flight until he is clear of the ship in order to avoid impact between the main rotor and various aerials, masts, or other parts of the superstructure of the ship. Difficulties on take-off are only likely to arise when a combination of adverse effects such as hot ambient conditions, ingestion of hot funnel gases devoid of oxygen, light winds, and maximum take-off weight, all occur together.

4. Handling on the Deck

In the fourth phase, that is on the flight deck, the helicopter must be "flown" by the pilot as long as the rotors are turning; for, even though the wheels are on the deck, the rotors will still retain their faculty for exerting lift forces and control moments. Therefore once the touch-down has been established

the pilot will select the minimum collective pitch of the main rotor blades that is available to him and, as has been stated, on the Wasp helicopter an extra low collective position is provided. The Wasp replacement, the Lynx, has a capability of producing reverse thrust pushing the helicopter onto the deck to counteract the increase in lift that can occur as the rolling motion of the ship causes the rotor disc to change its incidence.

The Wasp is normally flown with its auto-stabiliser equipment operative. It is necessary therefore for the pilot to switch off the auto-stabiliser as soon as possible after touch-down and similarly it is only switched on immediately before take-off. If this is not done the auto-stabiliser will attempt to counteract the roll or pitch of the aircraft that is being impressed upon it by deck motion. If this is considerable it may cause damage to the rotor blades.

Turbulence

In relative winds anywhere from ahead of the ship the airflow around the flight deck is both variable and complex in character. Vertical downdraughts can occur which contain funnel gases and the helicopter rotor may then pull these gases into the engine and into the cockpit of the helicopter leading to discomfort of the aircrew and detriment of engine performance. The masts, the funnels, the boats, of the Frigate forward of the flight deck give rise to eddy shedding and vortices can roll up between the junction of the deck and the side of the hull. These can combine to give a band of greater turbulence along the edge of the flight deck. As the relative wind moves around to the side this turbulence can spread out over the whole of the flight deck and a downdraught can occur on the leeward side of the vessel. In a beam wind this curl-over becomes more pronounced and should a helicopter move out to the leeward side or attempt to land from the leeward side a lot of power could be required to deal with this downdraught.

The helicopter pilot becomes aware of the turbulence as he approaches alongside the stern of the vessel. In light winds there will be little influence but above 15-20 kts of wind over the flight deck it will become increasingly significant. Winds from ahead are probably the least troublesome. When out on the port beam in such conditions the helicopter will be flying in the undisturbed free airstream; there will then be a short transient period as it moves through the band of turbulence at the deck edge to hover (relatively) in the low wind velocities over the flight deck. The worst situation from a landing point of view occurs when the relative wind is 30-40 degrees on the starboard bow. In such a case all the hovering and movement onto the flight deck would be carried out with the aircraft completely immersed in the turbulent wake. The full range of power and control of the Wasp helicopter may be required to land in such a situation especially if the pilot allows the helicopter to get into the downdraught on the leeward side mentioned previously. There are obvious benefits to be gained by allowing the helicopter to approach facing into wind if this is possible. However, this is not always so especially during exercises when the mother ship may be constrained in the direction of its movement.

Ship Motion

The degree of movement of the ship's flight deck depends upon the sea state and the direction of the ship's head into the waves. In practice wave motion is irregular and the amplitude of flight deck motion is not constant and therefore short intervals of time occur when the movement of the flight deck is relatively small. It is then that the helicopter can land-on or take-off even in rough seas since the moment of touchdown or lift-off can be chosen by the pilot and the flight deck officer and the duration of the action is only a matter of a few seconds. Limits are laid down as to the degree of flight deck motion. However, as the limits in fact apply to this moment of landing only the helicopter will usually fly in any weather in which it would be possible to launch the seaboat to rescue the pilot should the Wasp ditch. Apart from the actual landing, the helicopter will be standing on deck with its rotors running for one or two minutes both before take-off and after landing. The ship's motion during this period, in which the pilot is 'flying' the helicopter on the deck, may be considerable especially if the ship is turning onto or off a flying course. For this reason a central strop which can be released by the pilot, and lashings for each of the wheels which are released by flight deck crew, are provided. When the wheel lashings have been removed the central strop can be used to allow the pilot to turn the helicopter around on the spot to the direction selected for take-off. The strop is then released as take-off power is applied. When returning to the deck, unlike landing on a static sloping ground ashore, the pilot cannot be certain beforehand in which direction the deck will be inclined at the instant of touchdown. He is unable therefore to anticipate the control movements that will be needed. His requirements are for a control system that will give him the ability to move his helicopter rapidly and precisely without unduly large control movements and this on the whole the Wasp helicopter gives him. However, in spite of the 'controllability' the best technique is for the pilot to keep his "wings" as level as possible and not to attempt to follow the motion of the deck otherwise there is a distinct chance that he will become disorientated, particularly at night. Also in contrast to landings ashore, the rate of descent of the helicopter is a combination of the aircraft and the deck vertical velocities. It could be expected that the pilot would thus have greater difficulty in judging his landing, leading to heavy loads in the undercarriage. That this is rare is both attributable to the pilot's skill and an indication that the collective control on the Wasp is sufficient for the deck landing manoeuvres required. The pilot's experienced technique and skill have a large influence on his ability to land on a small deck. The more experienced he gets the better his landings tend to be. Attempts to compare the degree of heavy landing with deck movement and with relative wind speed over the deck has shown that high rates of descent onto the deck tend to occur more often in light winds and when the deck is level (ie in good flying conditions). This probably reflects the greater caution exercised by pilots on the landing task as the sea state increases but it undoubtedly means an increased workload in the cockpit in such circumstances.

So far in considering ship's motion we have not considered the effect on the pilot himself. At a state of Alert 2 which means able to launch the helicopter within 2 minutes, the pilot will be strapped into the Wasp on the flight deck, heaving, rolling and turning with the ship. When the wind is anywhere ahead of the ship fumes and smoke from the funnel must add to his discomfort as mentioned before. He may be kept in this condition for 2 hrs by day and up to 1 hr at night. From this condition of alert he may be launched on a sortie right up to the last minute. Wasp pilots have admitted to considerable degrees of

disorientation and even nausea in this situation particularly at night and more than one Wasp has ditched alongside the ship immediately after take-off.

It must now be plain that the workload on the pilot flying from the deck is much greater than when he is operating ashore. The problems mentioned above require even greater than normal concentration and co-ordination from the pilot whilst flying. His reliable external visual cues are limited especially at night and they are usually in motion. Pilots frequently have their own personal visual references to assist accurate landings. However, in poor visibility and at night, on the approach to the ship and in the hover, the pilot is committed to mixed visual and instrument flying which as we know from experience is the worst possible situation and is normally completely contra-indicated in any form of flying. The attention required by the engine torque indicator close to the ship means that even in the best visual conditions much "mixed" flying is required.

Further Areas of Stress

Owing to its extremely fast rate of descent in autorotation, ditching a Wasp is a hazardous business at the best of times. Escape exits when the helicopter is in the water are very limited if the cockpit doors are mounted and closed, and the chances of escape are extremely poor. Therefore at this time the Wasp is only permitted to be flown over water with its cabin doors removed which, of course, includes most of its flying operations. In the tropics this can only be described as an advantage but in total contrast the Wasp is being flown from Frigates on fishery protection patrol off Iceland, ie inside the Arctic Circle and here flying with the doors off can be a considerable disadvantage. With temperatures in the Arctic reaching a mean daily minimum as low as -7°C with occasional drops as low as -17°C and a large wind chill factor through the open door the pilots can become very cold indeed. They are provided with electric gloves and electric boots but the wiring tends to be unreliable and the aircrew have no rheostatic control over this equipment (ie the only control is an on/off switch). Pilots have reported loss of finger tactility such that they have been unable to operate small switches and to pull the circuit breakers by the end of the flight. The doors being off can also result in rain, sleet, snow and even sea-spray entering the cockpit and obscuring instrument visibility. All this and concurrently streaming eyes and nose from the cold do not help the pilot's comfort or concentration whilst flying in these conditions. Fully loaded with weapons (two torpedoes), the Wasp has only a 10 minute flight duration with a little spare fuel for one extra attempt at landing. This strictly limited endurance must always be in the pilot's mind and can do little for his peace of mind during a sortie.

In spite of the short duration of the Wasp sortie and the fact that even during an exercise the pilot must be allowed 8 clear hours under no state of alert from wheels-on of his final sortie of the day, to wheels-off on the first sortie of the next period, life for a Wasp pilot can be quite fatiguing. For instance, during that 8 hours he must get his sleep, get his main meals, and do any necessary Squadron work (which may be considerable). The other 16 hours he will be at a minimum of Alert 8, ie 8 minutes to launch, fully dressed in flying clothing and close to his aircraft. It should be stated here that living in cold weather flying clothing can be very fatiguing in itself. Periods of the 16 hours will be spent strapped into the aircraft at Alert 2 as previously described. Double pilot manning of Wasp carrying Frigates would ease this problem of fatigue but it would also reduce each pilot's flying practice to dangerously low levels. It is probably worth mentioning here that the living conditions on board ship tend to be very cramped. Also when the ship is moving around swiftly in an exercise the noise and vibration in most areas of the ship are not conducive to healthy sleep.

As has been just mentioned the Wasp pilot is usually the only pilot on board; he is the flight commander and he is the captain's adviser on aviation matters such as the local operating conditions in which the ship is sailing. As most of the ships from which he will operate will not carry a Medical Officer, he is also responsible for grounding himself and therefore his aircraft when he is medically unfit, and when he does so he must hold in mind the fact that he thereby renders the ship's major weapon unserviceable. This must be a very stressful decision to have to make, for instance should he have a cold in the middle of an exercise.

To summarise very briefly, the summation of a combination of the stresses mentioned above can lead to anti-submarine helicopter flying in the Wasp aircraft from Leander and Tribal Class Frigates being a very stressful and fatiguing occupation. Nevertheless it is on the whole approached with great enthusiasm, skill and high morale, and is carried out in an effective and thoroughly professional manner.

STANDARD APPROACH PATH
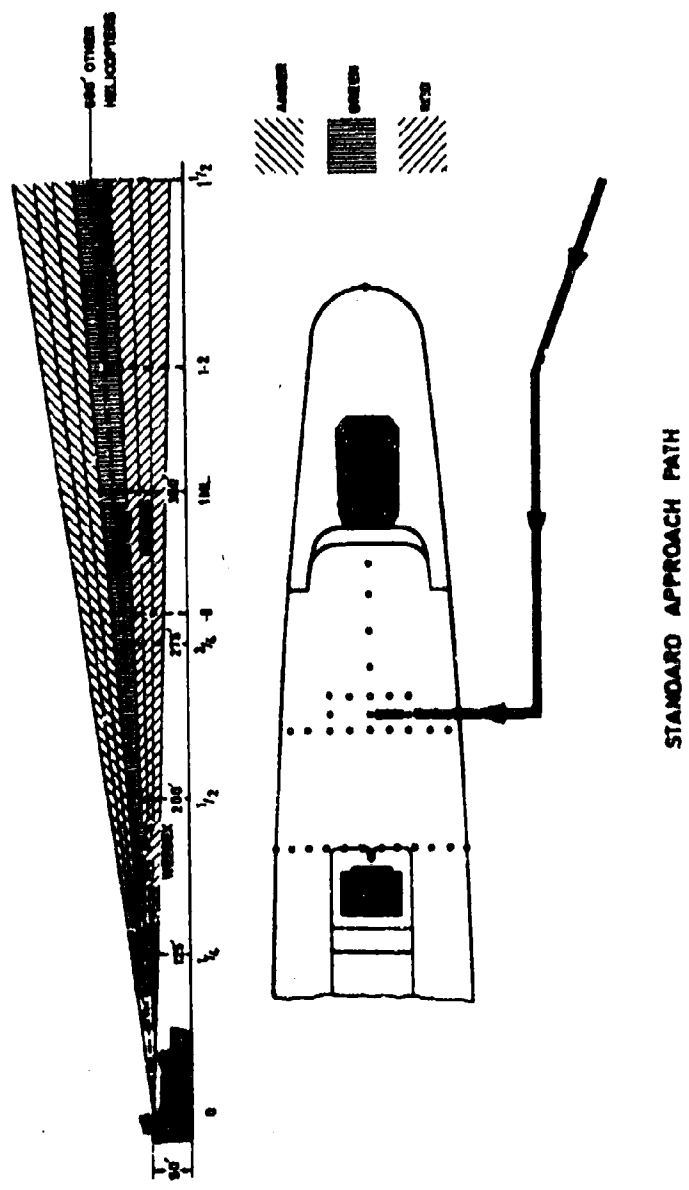
Fig. 1

THE IMMERSION VICTIM

by

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SUMMARY

An aircraft accident may result in the occupants being forced to survive the rigors of an aquatic environment.

In spite of the provision of sophisticated protective clothing and safety equipment, many such victims will suffer the effects of drowning and/or hypothermia.

Those responsible for the training of rescue crews and for the clinical management of such survivors, should be familiar with the treatment of these conditions.

This paper briefly discusses the mechanisms involved in the production of both, and outlines a course of management for the immersion victim.

1. INTRODUCTION

On the 11th July 1965, a U.S.A.F. aircraft ditched in the Atlantic off Cape Cod.[1] Of the 19 crew members, 12 managed to escape from the wreckage, the remaining 7 were presumed killed on impact. Ten and one half hours after abandoning the ditched aircraft, three of the original 12 survivors were rescued alive, the remaining 9 had died of 'exposure/drowning'. All 12 were wearing immersion suits and lifejackets. The water temperature was 11°C. One of the three rescued alive had been unconscious for the last two hours but had been supported by a colleague for that period. The 9 who died were the least protected from the cold from the point of view of body insulation.

Most people involved in Aviation Medicine or in Airsea rescue work have many similar stories to relate. The problem of survival in water following an aircraft accident was well known during the Second World War. [2,3,4] During the war it became increasingly obvious that the problem was just not limited to the immersion phase, as after rescue many of those rescued alive, died. A historical review[5] reveals that this problem was also known in the maritime world among the shipwreck survivors and is still the case today.

Those who are responsible for the survival of aircrew on immersion following "ditching", or on parachuting into an aquous environment, ensure that the equipment and training is adequate to provide the best possible protection for the individual, both from drowning and hypothermia.

Those who are responsible for the training of rescue crews and for the clinical management of such survivors, should be familiar with the treatment of both drowning and hypothermia. Regrettably, the management of both conditions, although adequately dealt with in initial training, are invariably dealt with as two separate entities, the management of either of which does not always lend itself to amalgamation with the other condition. Whereas in practice, both conditions, frequently co-exist.

This paper attempts to clarify the situation and talks in terms of the "Immersion Victim" rather than the "Drowning" or "Hypothermic" victim. A course of management for the "Immersion Victim" is outlined.

2. MECHANISMS

Following immersion, survival will depend on interaction of many factors; these include swimming ability, physical fitness, distance from the safe refuge, water temperature, body insulation and efficiency of buoyancy aids, sea state etc; Thus under normal circumstance a good swimmer in relatively warm water (15 - 25°C) will remain afloat until such times as he becomes too fatigued to continue to make swimming movements, when he will no longer be able to keep his airway clear of the water and he will quickly drown. This will happen relatively quickly in rough water.

If the water is very cold (<15°C) muscle temperatures fall quickly and co-ordinated motor activity becomes progressively more difficult so that drowning will occur relatively rapidly but if a lifejacket is worn it will keep the airway clear of the water and will, in most instances, prevent drowning. A lifejacket will also delay the onset of hypothermia by reducing the need for limb movement but eventually hypothermia will develop in all cases. Such individuals may be rescued deeply unconscious and apparently dead from hypothermia [6]. A more thorough desertation of the physiological disturbances occuring in acute hypothermia are to be found in AGARD Report No 620 [7].

A lifejacket is not always a guarantee against drowning; in rough sea states (state 6 and above) the wave face tends to be flat and vertical rather than sloping and sinusoidal as occurs in lower sea states and, as a consequence, the 'lifejacketed' body no longer floats freely over the waves, which means that the water continually breaks over the face and drowning will only be prevented for as long as there is voluntary control of respiration. Drowning will ensue when consciousness becomes impaired as a result of hypothermia. Thus submersion is not essential for drowning.

Another factor to be borne in mind in aircrew who have not removed their oxygen masks before water entry, is the danger of inhaling water through the oxygen hose unless a special anti suffocation valve is fitted [8].

Hyperventilation, with respiratory rates in the region of 60-70 per minute, has been observed in naked subjects during the first ten minutes of immersion in water at 10°C [9]. Tetany has been reported in one case [10]. Even expert swimmers may drown in the first few minutes of water immersion, if the water is particularly cold.

This hyperventilation may compromise ones chances of escaping underwater from a ditched helicopter.

One other problem in very cold water (circa 5°C) is the apparent inability of competent swimmers, unhabituated to cold water, to maintain swimming movements for any length of time, even when dressed in outdoor winter clothing [11].

Whatever the reason for the submersion, experimental evidence in animals [12] suggests a period of struggling during which large quantities of water may be swallowed in an attempt to avoid inspiration. Vomiting may occur at this stage. An increasing arterial carbon dioxide tension (P_{CO_2}) and falling oxygen tension (P_{O_2}) will eventually cause inspiration, with consequent inhalation of water.

It has been suggested [13], [14]. that, in anything from 10 to 20% of cases, the initial entry of water into the larynx may produce a severe laryngospasm, or closure of the glottis [15] which persists until asphyxial death supervenes, and this is the likely explanation of the so called 'dry drownings' found at postmortem. This seems highly improbable, as it is difficult to visualize how such muscle spasm could be maintained in the severe hypoxia which must be present in the terminal stages.

In the majority of cases the entry of water into the larynx and upper respiratory passages accompanies severe retrosternal pain and violent coughing. In animals, death follows quickly in fresh water due to ventricular fibrillation (VF) resulting from electrolyte changes associated with haemodilution and haemolysis following absorption of large quantities of fresh water from the lungs [16]. In sea water VF is unlikely [17], death being due to asphyxia and is a slower process.

The differences between fresh and salt water drowning have been admirably reviewed by Modell (1968)[17], but tend to be largely of academic interest from the therapeudic view point, as the basis pathophysiological problem is very similar in both situations, i.e. hypoxaemia, hypercapnea and acidosis[17], [18].

Regardless of the drowning medium, the organic and inorganic contents of the inhaled fluid produce an inflammatory reaction in the alveolar capillary membrane which quickly leads to an outpouring of plasma rich exudate into the alveolus [19],[20].

The loss or destruction of the normal surfactant [21] by the inhaled water can result in large areas of atelectasis which may further complicate the picture.

3.   PROBLEMS ARISING AFTER RESCUE

The immersed victim on rescue may then be either conscious, unconscious or even apparently dead. He may be suffering from hypothermia, alone, or complicated by drowning.

Immediately after rescue the temperature of the hypothermic individual will continue to fall for a short period before he begins to recover or death ensues. This is che so called 'after drop'[17].

At core temperatures below 33°C supraventricular cardiac arrhythmias may be encountered with vertricular arrhythmias occuring with core temperatures in the region of 30°C. Cardiac arrest due to ventricular fibrillation is possible at core temperatures of 28°C or below [22]. Cardiac arrest has usually occured by the time the core temperature has reached 24°C [23].

Even if the victim survies the immediate effects of immersion and appears to be making a reasonable recovery after rescue, there is a great danger of developing an acute pulmonary oedema any time from 15 minutes to 72 hours after the drowning incident, [17],[18],[24],[25]. as a consequence of the inflammatory reaction of the alveolar capillary membrane. A large series of post mortems by Fuller [24], in which survival times ranged from a few minutes to 19 days demonstrated that hyaline material will be found on the walls of the injured bronchioles, alveolar ducts, and alveoli of those who have survived from 12 hours to the third day.

Other possible delayed effects of drowning, or its treatment, include the development of a condition resembling the respiratory distress syndrome, which may be related to oxygen toxicity [26],[27]. If severe cerebral hypoxia is a feature of the incident, cerebral oedema[28] may prove a problem and lastly, when the drowning medium is polluted pulmonary infection is likely [24], [28].

4.   MANAGEMENT

Treatment of the immersion victim is aimed at the restoration of adequate ventilation and heart action, correction of the acid-base status, and rewarming. These priorities only alter because of the facilities available.

At the scene of the rescue, there are usually no facilities for the correction of the acid-base state and few facilities for rewarming, so that the major aims are, the provision of adequate ventilation, the assistance of the circulation where necessary and the prevention of any further heat loss from the body.

Attention has always been drawn to the requirement for immediate action and many authorities advise that no manoeuvres designed to drain the lungs of fluid should be performed [29],[30]. Others have found that a quick attempt to drain the lungs has often allowed much of the ingested fluid to flow out and this reduces the risk of regurgitation and subsequent aspiration pneumonitis [31]. Earlier work by Fainer et al [32], and more recently by Modell et al [33], seems to indicate that it is worthwhile to attempt to drain the lungs in salt water drowning.

It is important that expired air resuscitation should be carried out as soon as the mouth and oropharynx have been cleared. Practical experience has shown that restoration of adequate ventilation will often bring back satisfactory cardiac rhythm [34]. If a pulse can not be felt after the first few inflations, then closed chest cardiac massage (CCCM) should be started [35] in all but the hypothermic patient. All immersion victims should be removed to hospital as soon as is practicable. When suitable apparatus is available, ventilatory assistance should be given using 100% oxygen if possible via a mask and a Guedal airway. If the patient is very restless then a nasopharyngeal airway is best. Attempts at intubation by inexperienced workers have usually resulted in more injury and less adequate ventilation than the simple method described.

After rescue, the continueing fall of the core temperature of the hypothermic victim could lower the already low body temperature into the zone where unconsciousness can be anticipated (30°C) [23] or even into the zone where the myocardium becomes extremely irritable (28°C).

Conscious hypothermic patients therefore should be rewarmed rapidly in the most readily available hot bath (41°C). Unconscious hypothermic patients whose temperature is below 28°C may develop ventricular fibrillation (VF) spontaneously, or more usually following the slightest mechanical irritation[22]. A hypothermic victim whose core temperature is this low will almost certainly have no palpable pulse and is unlikely to be breathing at a recognisable level. If however cardiac massage is given to such an individual then VF will commonly result. The clearest guide to the likelihood of a victim being hypothermic is that he will be wearing a lifejacket or have some similar means of maintaining his airway clear of water, for, as discussed above, it is impossible for an immersed subject to achieve this depth of core temperature without drowning in the absence of some such support.

The first aid management of such victims is therefore the maintenance of an adequate ventilation and the prevention of further heat loss [6].

Figure 1 is a flow diagram outlining the procedure to be followed in the immediate management of the 'Immersion Victim' [36].
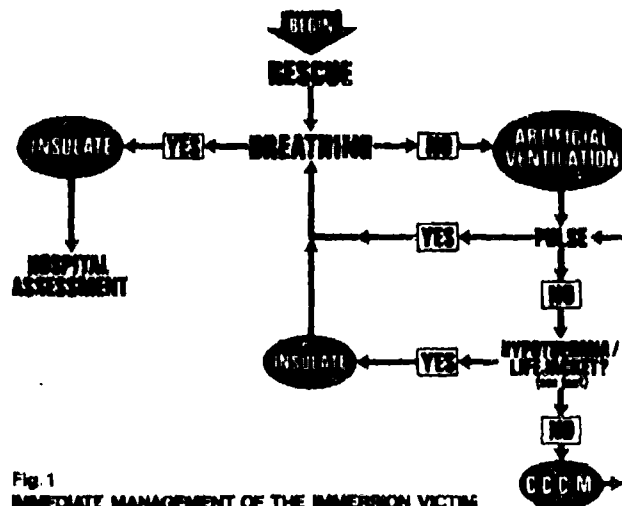

Fig. 1
IMMEDIATE MANAGEMENT OF THE IMMERSION VICTIM

5. ON HOSPITAL ADMISSION

While continueing to support ventilation and circulation by first aid measures it is now essential to correct the acid-base status of the victim and to assess any degree of hypothermia. An intravenous line using 8.4% sodium bicarbonate should be set up as soon as possible. The standard requirement is usually 150 mEq immediately, and 70 mEq for every subsequent 10 minutes during which adequate ventilation and circulation have not occurred. An electrocardiograph (ECG) should be taken to determine cardiac rhythm and if VF is present immediate DC counter shock (400 joules) should be applied except in the severely hypothermic patient (rectal temperature below 30°C). VF will not easily convert [37,38] in adult hypothermic subjects but rapid rewarming to above 30°C may produce a spontaneous conversion [39,41] or at least make the chances of electrical defibrillation more likely.[37]

Rapid rewarming of the myocardium is best accomplished by means of cardiopulmonary bypass technique [38,42] but not every hospital has this facility readily available. The next best means of rapid rewarming is by immersion in a hot bath at 45°C [23]. The practicalites of doing CCCM while rewarming are almost insurmountable but it has been shown that deeply hypothermic patients may suffer little anoxic damage during periods of up to 15-20 minutes circulatory standstill [41,43]. If it is considered inadvisable to discontinue CCCM for the duration required to rewarm the core to above 30°C, then a slow rewarm technique may be applied while CCCM is continued. Slow rewarm is probably best achieved through the respiratory tract by the methods described Lloyd [44] and Shanks & Marsh[45] while at the same time ensuring that further heat loss from the surface of the body is at a minimum.
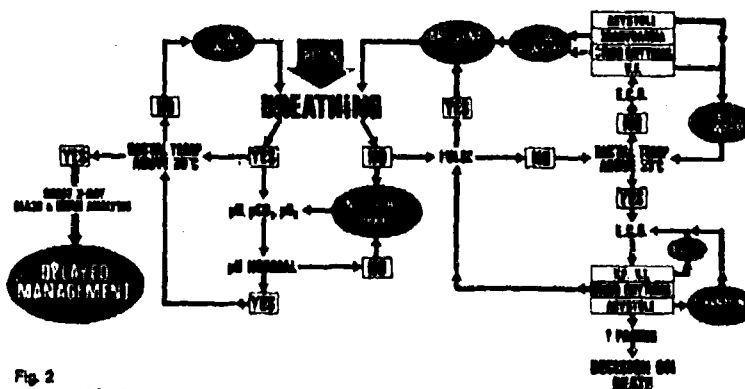

Fig. 2
INITIAL HOSPITAL MANAGEMENT OF THE IMMERSION VICTIM

Having started the bicarbonate the patient should be intubated and ventilated with 100% oxygen. Recent experimental [33] evidence in animals, and actual [33], [46], [47] evidence in near-drowned humans, have shown that the use of positive and expiratory pressure (PEEP) of 10 cm H_2O results in far better ventilation and control of oedema in near-drowned patients than standard intermittent positive pressure techniques with suction.

In victims who are likely to recover, these measures will provide an adequate heart action, but the return of spontaneous respiration will depend on the degree of anoxic brain damage suffered by the victim. Some authorities [28] recommend therapeutic hypothermia ($30°C$) as a means of lowering cerebral oxygen requirements and decreasing cerebral oedema (vide infra).

In non hypothermic subjects, whose acid-base state has been corrected and who are being supported by good ventilation, in whom an adequate heart action has not been restored, an intracardiac injection of 2-4 ml of 1/10,000 adrenaline and 10 ml of 10% $CaCl_2$ should be given. This may produce a reasonable rhythm or VF which can be treated as before. If this proves unsuccessful then intravenous or external cardiac pacemaking could theoretically be considered.

Figure 2 is a flow diagram summarising the management of the immersion victim on admission to casualty. [36]

6. DELAYED MANAGEMENT

The problems of delayed management are primarly those of 'secondary drowning' [24],[18] and later the development of a condition which closely resembles the respiratory distress syndrome.

Secondary drowning is characterised by a rapidly increasing pulmonary oedema associated with a tachycardia, a fall in pulse pressure and then in overall blood pressure associated with anoxaemia and subsequent changes in cardiac rhythm [17],[18].

For both conditions early ventilatory support with PEEP usually prevents the further development of this chemically induced oedema, while circulatory support by the infusion of up to 1 litre of plasma, under central venous pressure control, has usually proved sufficient to overcome that aspect of near drowning. Acid-base status should be normalised during the anoxic phase.

In such patients one must assume that there is not only chemical irritation but also bacterial contamination. The use of methyl prednisolone (5 mg per kg body wt. per 24 hours in 6 divided doses) has been advocated by Sladen & Zauder [48] to counteract both the pulmonary oedema and cerebral oedema secondary to anoxia, and the use of a wide spectrum antibiotic seems to be a reasonable precaution.

The flow diagram shown in Fig 3 outlines the suggested management of the immersion victim on admission to the hospital ward. [36]
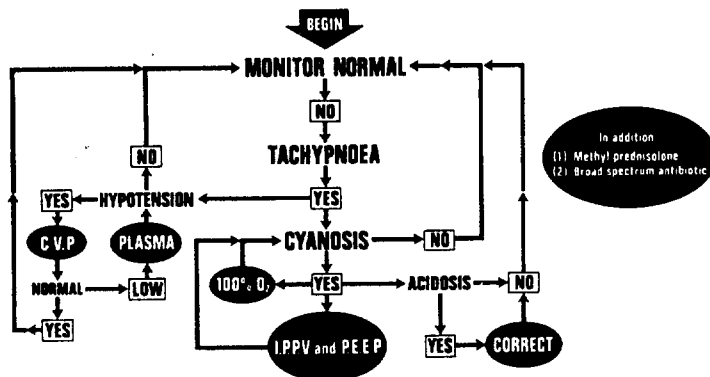
Fig. 3
DELAYED MANAGEMENT OF THE IMMERSION VICTIM

Cardiac arrhythmias secondary to hypothermia (e.g. atrial fibrillation, or flutter and varying degrees of heart block) which are frequently seen, do not respond to any form of anti-arrhythmic therapy and invariably revert spontaneously in 8-12 hours after the core temperature has returned to normal.

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MECHANICS OF HEAD PROTECTION

by

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If one is to appreciate the principles involved in protecting the head from injury, be it soft tissue damage, bone damage, concussion or permanent brain damage, it is essential first to have a clear understanding of the mechanism which cause injury. In some cases these are apparent. For example, if one hits the head hard enough with a heavy enough blunt instrument, skull fracture and brain damage will be inevitable: the problem remains, however, to define the word 'enough'. In contrast, the mechanics of production of concussion are still only poorly understood.

MECHANICS OF INJURY

Hydrostatic pressure, per se, has little effect on living tissue which, provided it contains no air, may be considered incompressible. This observation led Holbourne (1943) to state that 'linear acceleration forces tend to produce compressional or rarefactional strains which......have no injurious effect' and he attributed all head injuries to two basic mechanisms - deformation of the skull, with or without fracture, and sudden rotation. In the latter case the inertia of the brain would cause it to rotate less rapidly than the cranium and, because of its irregular shape and various attachments, local shear forces would be produced. It is shear forces, not pressure, which cause a nerve to cease to conduct impulses when squeezed by a pair of forceps. Thus, Holbourne con......ed that shear forces were essential for the production of concussion, or other brain injury.

In 1948, Ward and co-workers suggested that, whilst compression indeed did not cause injury, rarefaction could, and did. The suggestion was that a low pressure wave caused cavitation in the brain tissue, and that the subsequent collapse of these microscopic cavities, or bubbles, caused cell damage in their immediate vicinity. Lindgren (1966) measured intracranial pressure during experimental impacts and showed that, due to the inertia of the bra'n, a high pressure zone developed initially at the site of impact, with a complementary low pressure zone at the opposite pole. Thus, a linear head acceleration could lead to a low pressure shock wave, cavitation, bubble collapse, cell damage and concussion.

In some elegant animal experiments, Lissner and Gurdjian (1960) showed that a simple pressure pulse, in the absence of skull deformation, caused concussion. Furthermore, they obtained a clear cut relationship between pressure and duration for threshold pulses which could be related to pressure pulses consequent upon linear acceleration of the head. From this and other data has come the acceleration-time tolerance curve for human cerebral concussion (Figure 1) on which US helmet standards are based.
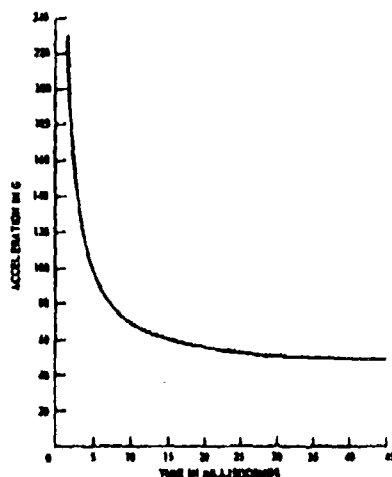

FIGURE 1. Tolerance of the human head

to impact acceleration.

We thus have a number of potential injury mechanisms:-

1. Direct local impact causing soft tissue, or bone injury. Here the degree of injury will increase with the energy of the impactor, and with decreasing contact area. Brain tissue deep to the site of impact may be damaged secondary to distortion, or fracture of the cranium.

2. Even in the absence of local injury, a direct impact will cause linear acceleration of the head, with the possibility of cavitation and concussive injury.

3. Direct impact may also cause angular acceleration of the head with the development of shear forces and local, or more widespread, brain damage.

4.   In the absence of head impact, forces transmitted through the neck may cause basal fractures (+Gz acceleration) or, by initiating high angular accelerations, concussion (±Gx or ±Gy acceleration).

TOLERANCE TO INJURY

Before considering methods for protection, human tolerance to these potential injury mechanisms must be discussed and, if possible, quantitated. One of the problems is to know what units to employ. For example, the deceleration of the impactor, or acceleration of the head are readily measured and frequently used in tolerance definitions. The units may be $ft. sec.^{-2}$, ms^{-2}, or G. If the head is freely mobile and its mass known, then the force applied to the head (or impactor, since action and reaction are equal and opposite) may be calculated (force = mass × acceleration) and expressed in pound weight (Lb.), kiloponds (kp) or Newtons (N). If the contact area is known, then the force may be expressed per unit area as a pressure ($Lb.in.^{-2}$, $kp m^{-2}$, Nm^{-2}). Finally, and perhaps most logically, the total transfer of energy, or work done on the head, can be computed and expressed in foot-pound weight (ft.Lb.), metre-kilopond (mkp) or Newton metre (Joule). Appropriate conversion factors are given in the appendix.

By general convention, acceleration (in G) tends to be used when discussing concussion, force (Lb.) or pressure ($Lb.in.^{-2}$) for bone fracture limits and energy in Joule (J) for head protection requirements. An example should make these relationships clear.

A head weighing 10 lb and travelling at a velocity of 30 $ft.sec.^{-1}$ strikes a solid brick wall. The frontal bone fractures and is depressed to a depth of 1 in. Assuming constant deceleration, the relationship between velocity ($ft.sec.^{-1}$), acceleration ($ft.sec.^{-2}$) and stopping distance (ft.) is given by

$$v^2 = 2as .$$ .... (1)

So, $30^2 = 2a \times \frac{1}{12}$ or $a = 5,400$ $ft.sec.^{-2}$ or   168G.

The force acting on the head (or wall) was 1680 Lb.

The kinetic energy of the head prior to impact is given by

$$ke = \frac{1}{2} mv^2 .$$ .... (2)

So, $\frac{1}{2} \times \frac{10}{32.2}$ (m is mass, not weight) $\times 30^2 = 140$ ft.Lb. or 190J.

Also of interest, since the head responds dynamically, is the duration of the impact (figure 1) and, again assuming constant deceleration, this is given by

$$V = at .$$ .... (3)

So, $30 = 5,400t$ and $t = 5.6$ msec.

We have now defined all the parameters of this particular head impact. Note, however, that had the head not fractured, the stopping distance would have been much less, perhaps one hundredth of a foot. In this case the deceleration would have been 5,590 G, the force 55,900 Lb., the duration 0.2 msec, but the input energy would still have been 190J. This example emphasises the profound effect of stopping distance on the forces involved in a given head impact, and shows how the skull and soft tissues could, by allowing deformation, actually protect the brain from excessive acceleration. Obviously, too much deformation will itself lead to local brain damage. The relationship between stopping distance, impact velocity and acceleration is given in figure 2.
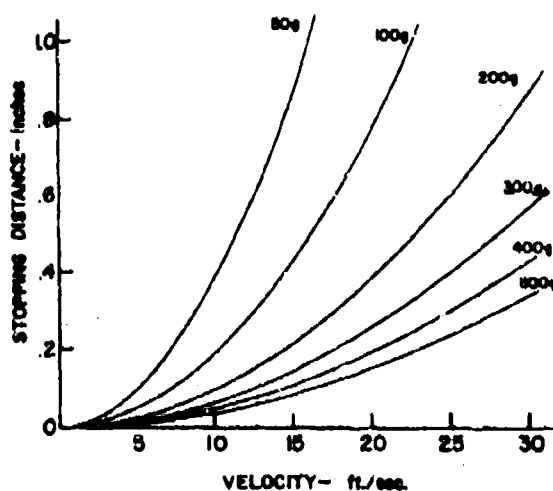

FIGURE 2. Stopping distance as a function of impact velocity with constant accelerations as parameters.

Let us now consider human tolerance to the four injury mechanisms referred to earlier.

Direct impact - soft tissue and bone injury

Information obtained from car crashes as well as from cadaver experimentation has provided reasonably repeatable bone strength data. Break strength depends upon impact site, and ranges from a mere 30 G for the nose, 40 G for the jaw, 50 G for the zygomatic arch, 100 G for 4 in.[2] of front teeth, 50 to 100 G for 1 in.[2] of temporoparietal bone and 100 to 200 G for 1 in.[2] of frontal bone (Swearingen, 1965). In each case the force may be obtained by multiplying the acceleration in G by a factor of 10. These injuries were produced by 'form fitting' moulded impactors so that soft tissue injuries were minimised. Obviously, much lesser impacts could cause soft tissue injury depending upon the impactor surface, and greater forces would be required to produce more depressed fractures with direct brain damage.

Forces required to produce deformation of the cranium without fracture are less well documented, but we have evidence that the cranium may be dented up to 0.5 in. (12.5 mm) without concussion. Here the estimated impact energy of 150 to 250 J was partly absorbed and distributed to the head through a protective helmet (Glaister, 1974).

Linear acceleration

Numerous animal studies have been conducted in attempts to measure tolerance to concussion and to scale the findings to man. Figure 1 gives one such prediction and shows clearly the effect of impact duration. This curve has led to the US requirement for protective helmets which states that, under appropriate test conditions, the headform acceleration shall not exceed 400 G, or 200 G for more than 2 msec, or 150 G for more than 4 msec (American National Standards Institute, 290. 1-1971). Equivalent British Standards (for example, BS 2495:1960) quote 500 G (no time limit), but this is currently being brought down to 400 G (transmitted force of 4,400 Lb. or 19.6 kN).

Swearingen (1971) stressed the significance of cranial distortion and concluded that the human brain can withstand crash impact forces of 300 to 400 G, or more, without concussion, or skull fracture, provided provisions are made to prevent deformation of the skull.

Angular acceleration

Ommaya and others (1970) have developed scaling factors from the results of animal experiments which suggest that a 50 percent probability of concussion in man, with a brain mass of 1.3 kg, would occur at an angular acceleration of 1,800 rad sec^{-2}, or at a rotational velocity of 50 rad sec^{-1} (480 rev min^{-1}). More direct information is needed, however.

Basal fracture

This injury mechanism undoubtedly exists - we have seen cases following helicopter crashes where there was no other head injury and where the protective helmets were unscathed. From other evidence, the force involved was considered to be well in excess of +30 Gz with a very snort rise time, but what the force would have been at head level is unknown. In +Gz impacts, however, the skull base is relatively stronger than other parts of the spine.

MECHANICS OF PROTECTION

From the foregoing, several possible mechanisms are apparent whereby a helmet could protect the head.

1. It could distribute an impact load so as to prevent, or reduce, soft tissue injury. This mechanism was recognised by the Emporor Nestorius in 1760 BC when he provided his Macedonian warriors with hard leather helmets.

2. In a similar way a helmet could prevent deformation of the skull and so increase tolerance to linear acceleration to, perhaps, 400 G. This protective mechanism is stressed by Swearingen (1971).

In both these cases the requirement is for a strong inflexible shell. However, if the shell is separated from the skull by an appropriate distance, some flexion, or distortion, of the shell becomes acceptable. In this case the load has to be transmitted to a large area of cranium by a suitable suspension system. A measure of the potential benefit which can be afforded by a rigid helmet shell may be provided by a simple example:

An aircraft runs out of runway and decelerates at a modest 4G, so throwing the pilot's unprotected forehead against the top edge of his instrument panel. Moving through 12 in. of travel prior to impact the head acquires a relative velocity of 16 ft.sec.$^{-1}$ and energy of 55J. The subsequent contact area measures 3 in. × 0.5 in. If there were no fracture, the head would stop abruptly (say, in 0.12 in.) and the applied pressure would be some 2,650 Lb.in.$^{-2}$ (18,000 kN m^{-2}). Undoubtedly, the frontal bone would have been fractured. The same head, protected, strikes at the same velocity (though the impact energy is increased by the added mass of the helmet, to 75J). Now a stopping distance of 0.6 in. is available (see below), the load is distributed (no fracture) and the head acceleration is reduced to 80G for 6 msec (no concussion).

(However, it must be noted that had the head been prevented from contacting the instrument panel by attention to crashworthiness in the original design of the aircraft and harness, the head acceleration would have been only that of the slowing aircraft - 4G. Also it may be noted that an energy absorbing and load spreading capability could have been provided in the design of the instrument panel - and so be taken off the head. Head protection should be a last resort, the primary aim being to eliminate potentially lethal head impacts.)

3.   By providing a finite stopping distance, a helmet can reduce the peak acceleration imposed in a given impact. Note that the reduced acceleration will be applied for a longer time, the product of acceleration and time, velocity change, being the same. These features have been seen in the previous example, an increase in stopping distance, from one hundredth to one twentieth of a foot, decreasing the head acceleration from 400 to 80 G, though the duration rose from 1.25 to 6.25 msec.

The practical maximum limit to the stopping distance which can be built into a helmet is about 1 in. (25 mm). Much more than this and the helmet becomes unacceptably bulky. Even this one inch is reduced by the relative inefficiency of energy absorbing materials, so that only perhaps 0.6 in. (15 mm) is actually available in which to reduce the relative velocity of head and struck object to zero.

There are two basic energy absorbing systems which can be employed in helmets, though many others have been considered. Current RAF helmets employ a fibreglass shell which breaks up on impact. The impact load is transmitted to the head and distributed widely by means of a suspension harness which initially provides an air gap of about 1 in. Energy is absorbed by the shell inelastically each time a glass-fibre ruptures, or is pulled out of the resin matrix. Peripherally, energy is absorbed by crushable foams. Use of this technique implies a compromise with the requirement for a strong, rigid shell. A second mechanism, more favoured in the U.S., makes use of a layer of crushable foam beneath the shell. These materials crush to about 40% of their initial thickness. However, a stronger shell can be employed. Factors which may affect the choice of major energy absorbing system are set out in the table below.

4.   Less obvious is the fact that, by absorbing energy inelastically, energy transfer to the head is reduced to a minimum. For example, if the head were to bounce off the impacting surface with a coefficient of restitution of unity, the overall energy change would be doubled. This factor favours the frangible shell concept and has been discussed in detail by Rayne (1969).

5.   So far, no mention has been made of protection against rotational acceleration. A very heavy helmet could reduce head angular acceleration by increasing the inertia of the whole head, but only at the expense of excessive weight and an increased risk of neck injury. This mechanism is never intentionally employed. However, if a head strikes a surface at an acute angle, it may either slide along it, or roll along it, depending upon the friction of the contact area. By making the helmet shell glassy smooth, and by eliminating external protuberances, the tendency to slide can be increased and rotational acceleration reduced.

6.   A final means by which the head could be protected is by prevention of crushing when the head is trapped between two colliding surfaces. This appears to be a rare mechanism of injury, however, and the shell would have to be very stiff to add materially to the crush resistance of the human skull.

Table 1.   Comparison of two energy absorbing systems for helmet use

A. Crushable foam/hard shell	B. Frangible shell/suspension harness
40% of available stroke lost by crushed thickness of foam.	Some stroke lost through elastic extension of suspension tapes.
High heat load, unless combined with an air gap and harness.	Can be well ventilated and cool.
Tends towards a relatively high coefficient of restitution.	Low coefficient of restitution.
Low surface friction.	Initially low surface friction may increase following impact.
Not easily damaged in routine use, but any damage invisible.	Easily damaged in routine use, but damage visible.
Capable of giving good ballistics protection.	Poor ballistics protection.
Only accepts one major impact per site, but load spreading capability remains uncompromised.	Only accepts one major impact per site, but subsequent load spreading capability is compromised.
Tends to be heavier than B.	Tends to be lighter than A.

Extent of protection

All the mechanisms for protecting the head which have been discussed only protect the area actually covered, and overall protection is compromised by the need to provide an adequate field of vision and head mobility. As has been mentioned earlier, the bones of the face are particularly vulnerable to injury, though the eyes are quite well protected by the margins of the orbital cavity.

A particular problem arises at the margins of the helmet, for here the shell is inherently weaker and the discontinuity leads to a local concentration of stress. Tape suspensions are ineffective at the helmet margin and energy absorbing foams have to be used.

Visors are not considered to provide a protective capability in current helmets. Indeed, they are generally designed to be stuck out of the way in an impact as a broken visor could do more damage than none at all. It may be noted that visors are not covered by current standards of head protection

(Glaister, 1975). This situation is rapidly changing with the introduction of new materials, such as poly-propylene, which do have a protective capability.

Helmet retention

Helmets must be retained following a survivable impact so that protection is still available in the event of a second blow. Multiple impacts are not uncommon in the experience of users of RAF aircrew helmets (Glaister, 1974). For example, on ejection, a canopy strike could be followed by a strike against the separating seat and a final ground strike on landing. Furthermore, crashes rarely impose a single axis of deceleration and multiple head impacts are likely to occur.

The consideration that neck injuries could be produced if the helmet were too firmly fixed to the head led initially to the provision, in the neck strap of RAF helmets, of a shear pin designed to part under a load of 130 - 150 Lb. (580 - 670 N). Consequent upon rather frequent helmet losses the strength of this pin was doubled some four years ago. The pin was then nearly as strong as the strap attachments and has since been deleted. Helmet losses still occur, however, especially in high-speed ejection. These losses may be accounted for by a recently demonstrated aerodynamic lifting moment which measured 460 Lb. (2,050 N) at an air speed of 600 kt (Hawker and Euler, 1975). This force is shown plotted against air speed in figure 3a and, for comparison, figure 3b illustrates USAF helmet loss rates, again plotted against air speed at ejection.
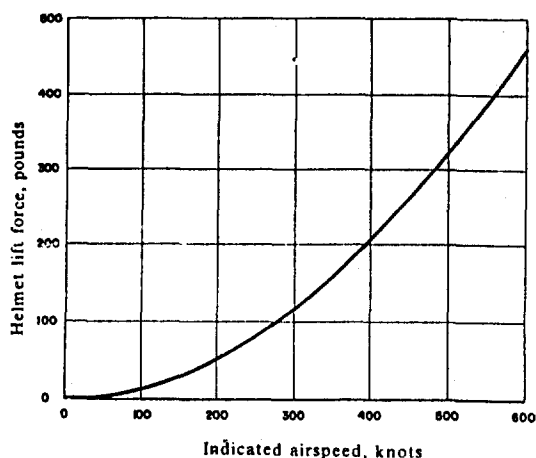

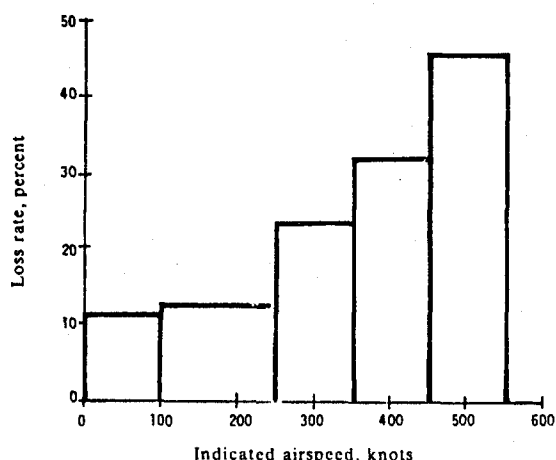FIGURE 3a. Helmet lifting force plotted against airspeed.   FIGURE 3b. Helmet loss rate plotted against airspeed.

Assessment of protection

The various standards which are currently used by NATO Air Forces for the assessment of protective headgear have recently been reviewed by an AGARD Working Party (Glaister, 1975) and will not be detailed here. Briefly, standards cover the three main aspects of helmet design, namely:

1. Impact protection. The helmet is struck under controlled conditions against a flat or hemispherical anvil and the transmitted force is measured. Current RAF helmets are designed to withstand an impact energy of 203 J, US helmets are designed to withstand multiple impacts of lesser energy (about 120 J).

2. Penetration resistance. The helmet is struck against a conical anvil having a 0.5 mm radius tip. In relevant UK standards the impact energy is 16 J and failure is either excessive local deflection of the shell (> 9.5 mm), or penetration. US standards employ a similar anvil at 29 J impact energy, but failure is indicated only by electrical contact between anvil and headform (i.e. maximum local deflection of the shell plus penetration).

3. Helmet retention. After a moderate preloading period, the strap is loaded progressively. Failure is indicated by displacement in excess of 25 mm for a load which is currently 890 N (UK standards), or 1,333 N (US standards).

In addition, the standards cover requirements for such factors as flammability, extreme cold, heat and humidity (prolonged soaks prior to testing as above) and individual impact testing of padding materials. It must be noted, however, that these standards are drawn up for civil use (racing car drivers and vehicular users) and that military applications may compromise some of their specific requirements.

Windblast protection

In high-speed ejection, the body is suddenly thrust into an airstream which can exert a windblast pressure (Q force) as great as 8.9 Lb.in.$^{-2}$ (58 kN m^{-2}) at 600 kt. The direct effect on the face of this pressure causes petechial and conjunctival haemorrhages and, if the mouth is open and unprotected, blast damage to the lungs. Face protection is, therefore, essential in high-speed ejection and may be provided

by a mask and visor, or by a visor which seals against a helmet fitted with a chin bar as in the case of the RAF type 5 helmet. Both approaches have been shown to have the potential to protect the face in high-speed ejections, provided that polypropylene visors of adequate strength are fitted.

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APPENDIX

Conversion factors

Gravitational constant (g) = 32.2 ft.sec.$^{-2}$ or 9.807 m.sec^{-2}.

To convert ft. to m.   multiply by 0.305

"   "   Lb. to kp.   "   " 0.455

"   "   kp to N.   "   " 9.807

"   "   Lb.in.$^{-2}$ to kN m^{-2} "   " 6.895

"   "   ft.Lb. to J   "   " 1.356

AUDITORY COMMUNICATION

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INTRODUCTION

The problem of noise in aircraft is not new but one which is becoming increasingly important and critical. The complexity of many modern aircraft necessitates at least a two-man crew, and the relationship between these crew members must be so close that mistakes are not made and time is not wasted with the unnecessary repetition of information. The link between the crews members is usually effected only by means of speech, so that any degradation of this speech link is of vital importance both to the successful completion of the sortie or mission and to the lives of the crew. The speech link must therefore be rapid, reliable and accurate. By far the most significant factor acting to degrade the quality of the speech signal is the ambient cockpit noise. It is, moreover, true to say that if the high prevailing levels of ambient noise were lowered or removed that problems of auditory communication would cease to exist. For this reason it is important first to examine the nature of noise in aircraft.

The Sources and Nature of Noise in Aircraft

It is obvious that different types of aircraft produce different types of noise. In high performance single and two seat aircraft the predominant sources of ambient cockpit noise are:-

a.   Boundary layer noise. This is caused by the layer of air adjacent to the skin of the aircraft being turbulent causing the skin and canopy of the aircraft to vibrate. This vibration is manifested to the aircrew as airborne noise.

b.   Cabin air conditioning systems. Cabin air conditioning systems often require large masses of air to be forced through small orificies and the turbulence associated with the pressure drop across the orifice inevitably generates high noise levels.

Whichever of these noise sources is more important depends upon the type of aircraft, and on the phase of flight - the boundary layer noise, for example, becoming more important at low altitude and high speed.

In contrast, the important sources of noise in helicopters and propeller driven aircraft are mechanical, i.e. the engines and gearboxes, though aerodynamic noise from the rotors and propellers also play a significant role.

Consequently, the natures of the noise in the aircraft outlines above are different. In the high performance strike aircraft the noise is not only of a high level (possibly in excess of 110 dB) but this high level is maintained throughout a wide band of frequencies (for example, between 63 Hz and 8 KHz). The noise in helicopters, though of an overall high level, is likely to be concentrated toward the lower frequencies. Thus while the noise level may be over 100 dB at 63 Hz and 125 Hz it will probably have reduced to only 70 dB at 4 KHz and 8 KHz. There is a further difference in so far as the noise in strike aircraft is generally distributed evenly and continuously through the aduio spectrum, but the noise in helicopters tends to be concentrated in narrow frequency bands (often associated with the rotation of individual gears in the power train).

Minimising the ambient noise level is, of course, important and can be effected by some or all of the following means:-

a.   Maximising the canopy thickness.

b.   Damping the walls of the crew compartment.

c.   Smoothing the boundary layer by removal or redesign of excresences.

d.   Ensuring proper design, and minimising the mass flow of air through the cabin conditioning system.

e.   Proper design and maintenance to smooth the operation of mechanical points.

In practice, however, it is often difficult to produce significant reductions in ambient noise without incurring other unacceptable penalties, particularly in terms of increased weight. It is therefore important to attempt to isolate man as far as possible from the noise in his environment and this, of course, is the role of the personal equipment.

Personal Equipment and Communication

a.   Oxygen Mask Microphones

It is perhaps, surprising that the attneuation of oxygen masks is not of crucial importance. This is because although an oxygen mask is a poor attenuator (and, at certain frequencies may actually amplify the ambient noise) the speech signal inside the mask is of very high level. A given vocal output which would register about 75 dB at 1 metre from the lips in a free field, may produce a sound pressure level in excess of 120 dB inside the confined volume of an oxygen mask. The consequence of this is that even in a very noisy aircraft, the level of aircraft noise inside the mask is likely to be at least 15 dB below the level

of the speech signal. This difference in levels is perfectly adequate to convey intelligible speech, as is any difference in excess of about 12 dB at this point.

b. Other Microphones

In aircraft where oxygen masks are not used, more severe problems exist. They are only ever partially overcome by the use of throat microphones or noise-cancelling boom microphones. Throat microphones work by pressing the transducer against the larynx. They are extremely resistant to ambient noise but unfortunately are rather poor transducers of speech as their location prevents them from being sensitive to many "formants" of speech that are not produced in the throat (e.g. the "voiced" parts of speech).

Noise cancelling boom microphones on the other hand, are good speech transducers, but are relatively sensitive to ambient noise. There are, therfore, clear cut penalties and advantages associated with each of these types of microphone and the choice will depend on the specific microphones available, the aircraft being flown, and the preferences of the crew.

c. Headgear

The point other than the mouth at which ambient noise can enter the communications system is, of course, at the ear. At this point, in order for the speech signal to be intelligible, its long term "average" (root mean square) value should exceed the ambient noise level at the ear by at least 9 or 10 dB. This difference, however, cannot simply be achieved by increasing the level of the speech signal for two reasons. The first is that when approaching levels of 100 dB at the ear the aural reflex plays a significant part in protecting the inner ear by preventing these high energy levels being transmitted to it. Thus a measured difference between signal and noise (signal:noise ratio) at high levels may not produce the same result in terms of intelligibility as that same signal noise ratio at lower sound pressure levels. The second reason is that a definite maximum level exists at which the speech signal may be presented if ear damage is to be avoided. Deciding what this level should be is difficult and depends upon a number of factors. Noise 'dose' is a cumulative quantity in as much as a short exposure to a high level of noise will equate in damage risk terms to a longer exposure to a lower level, and the risk of damage of course, increases with increase of dose. Ways of calculating noise dose and associated risk are clearly set out in ISO recommendation R1999 and other similar documents, but it is up to individual organisations to decide what level of damage risk is acceptable for aircrew. Generalising very broadly however, it is possible to say that it is unsatisfactory to produce signal levels at the ear much in excess of 100 dB.

It is therefore a clear requirement of the headgear to reduce the ambient noise level to at least 10 dB below this figure of 100 dB, and this task presents some difficulty in certain situations - especially when the situation is examined more closely. This is because the attenuation of any flying helmet or other ear protector increases with increasing frequency. Thus the attenuation of a typical device may vary between 5 dB to 10 dB at 63 Hz and 125 Hz up to over 40 dB at 4 KHz. However, the frequency band over which aircraft communications systems operate is limited from about 300 Hz to 3 KHz - this being the frequency domain in which the information bearing parts of speech are carried. The attenuation of the flying helmet considered above may, on some wearers, be little more than 10 dB in this frequency region and thus, in an aircraft with an ambient noise level of over 110 dB at these frequencies, the helmet cannot reduce the noise level sufficiently to enable an intelligible signal to be presented.

The attenuation of flying helmets is therefore most critical and much recent effort in the design of new flying helmets has been devoted to maximising the amount of noise exclusion which they provide.

Intelligibility Assessment

Considerable mention has been made above of the intelligibility of communications systems. The intelligibility of a given system depends on a number of factors. The primary one is the difference between the levels of speech and of the noise interfering with it. This is particularly true at certain frequencies (for example in the octaves centred on 500 Hz, 1 KHz, and 2 KHz), and this fact is exploited by techniques like the Articulation Index which use the difference between the speech and noise levels in certain octave bands in a simple calculation, the result of which gives an indication of the quality or intelligibility of the speech.

There are however other factors influencing the intelligibility level attained, including the size of the vocabularly in use, the listener's experience of the speaker, and so on. In aviation, the vocabularly size is usually limited, with consequential high intelligibility, but important situations may arise, for example between a forward air controller and ground attack aircraft, where a large vocabularly size must be used, and consequently a large signal noise ratio is required in order to maintain adequate intelligibility.

However, in testing systems it is difficult to determine what level of intelligibility is the minimum acceptable. It is easy, using standard intelligibility tests (in which some speakers simply read a list of words carefully selected for their phonetic constitution to a set of listeners) to compare one system with another, or to evaluate possible improvements to a system. The problem lies in determining what is adequate, and this is complicated by the fact that what is adequate on the ground is unlikely to be adequate in the air. It is perhaps intuitively obvious, but has also recently been shown to be demonstrably true that simple psychomotor workload can produce large effects on auditory processing capacity even when the simplest kind of auditory communications task is used, the effects of environmental stress on communications task may be guessed at but are as yet unresearched, though it is unlikely that the presence of heat, anxiety, vibration and all other stresses to which aircrew are exposed will improve their capacity for comprehending auditory communications.

CONCLUSION

The above represents a brief outline of the important aspects of auditory communications in aircraft for consideration by human factors workers. It is likely that aircraft will become noisier as the performance demands made on them increase, and that ways of improving personal equipment and communications systems, and methods of evaluationg these improvements will consequently necome increasingly important. It is possible that in the long term, radically new forms of transducers will become available, that electronic devices currently under development will be used to provide active "antiphase" noise suppression at the ear, and that sophisticated forms of automatic gain controls combined with voice operated switching of communications systems, will go a long way toward solving the problem. In the forseeable future however, the task of the human factors workers in the field of communications may be regarded as striving to maintain the acceptable rather than pursuing perfection.

EYE PROTECTION AND PROTECTIVE DEVICES

by

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SUMMARY

This paper discusses the major ocular hazards encountered in military aviation and describes some protective measures which may be adopted. The hazards considered are solar glare, bird strike, wind blast, miniature detonating cord, lasers and nuclear flash.

INTRODUCTION

Excluding agents of chemical warfare the most important ocular hazards encountered in military aviation fall into three categories. Solar glare, trauma and high energy light. Protective devices against these hazards must be compatible with existing aircrew equipment assemblies and not inhibit the safe and efficient performance of aircrew tasks.

Solar Glare

Protection against the discomfort and the reduction in visual acuity caused by glare from direct, reflected or scattered sunlight, is essential. In transport aircraft where slow donning and doffing is not a problem such protection may be provided by sunglasses. In high performance aircraft where protective helmets are worn photo stress is usually avoided by means of a tinted visor which is integral with the flying helmet. The visor should be capable of adjustment by the wearer to provide protection against external glare sources whilst permitting a view of his instrumentation below. In the fully lowered position the visor should be capable of preventing the ingress of all unfiltered light.

The filter for use in the aviation environment should have a luminous transmittance of between 10-15%; a transmittance significantly higher being only of cosmetic value. The densities of the filter(s) before each eye should be closely matched to avoid false projection (Pulfrich Effect). The tint must be neutral to avoid adverse effects on colour discrimination particularly the recognition of red warning signals. As discomfort from glare is eliminated it is important to ensure that infra red wavelengths outside the visible band (800-1400 nm) are also attenuated to avoid the possibility of retinal burns.

As with all transparencies interposed between aircrew and the external scene care must be taken to ensure that the field of view is as wide as possible, and that the optical properties and the physical parameters conform to specification.

Birdstrike

Protection of the face against birdstrike. Fig. 1. The hazard of birdstrike is always present during flight (both day and night) at low level. Approximately 85% of birdstrike in the UK occur at altitudes below 500 ft agl whilst only 7% occur at altitudes above 1,000 ft agl. The incidence of birdstrikes in low level flight is such that a hit in the cockpit area is a relatively common emergency (with respect to the various emergency functions to be provided by headgear). Whenever possible the strength of cockpit transparencies should be such that they will not shatter when a bird is hit. The strength necessary to meet this requirement when an aircraft flying at high speed hits a heavy bird may however be prohibitive. If practical, secondary protection to the aircrew should be given by a tough screen mounted within the cockpit. Again however this requirement may be incompatible with other functions, e.g. external vision, escape. Furthermore there are many aircraft in service at present in which protection of this type is not provided and yet they are being operated at high speed at low level. When a bird impact occurs onto a cockpit transparency both pieces of the bird and splinters (some of them large) of the transparency fly towards the head and shoulders of the aircrew member. The pieces of aircraft canopy in particular are propelled towards the face of the occupant. The most vulnerable organ is the eye and temporary or even permanent blindness may follow a birdstrike in the cockpit area. In the absence of other forms of protection (strong transparencies or internal cockpit screens) a helmet mounted visor made of a strong transparent material such as polycarbonate (3 mm thick) is essential for aircrew operating at high speed at low altitudes. The visor should protect all the uncovered area of the face as well as the eyes. Thus, the lower edge of the polycarbonate visor should abut closely (less than 5 mm gap) against the oronasal mask. As there is virtually no hazard of birdstrike above 2,000 ft agl the crew member should be able to remove the polycarbonate visor from in front of his eyes when flying above this height, since any layer in front of the eyes produces a small but significant impairment of vision. Whilst it is desirable that the user should be able to lock the polycarbonate visor in the down position for blast protection, there is no requirement to be able to position it in any position other than fully up or fully down. Although it would simplify and lighten the headgear if the strong polycarbonate visor could also act as the antiglare visor there are many flight conditions in which birdstrike protection is required without the antiglare function e.g. low level flight at dusk and night. A dual visor system is therefore essential where birdstrike and glare protection are required. Fig. 2.

Blast Protection

The head is exposed to very high aerodynamic forces on ejection at high speed. These aerodynamic forces impart very high angular accelerations to the head and impact the head against the seat at high velocity. In addition the blast may damage the tissues of the face, in particular the eyes, by causing gross displacement and rupture of tissues. Furthermore the blast may displace the headgear which may well then be lost altogether. Protection against the effects of blast on ejection includes the retention of the headgear and the prevention of damage to the uncovered portions of the face and neck. Retention of headgear is necessary in order to provide impact protection to the head during the subsequent stages of the ejection sequence and the delivery of oxygen to the ejectee after escape at altitudes above 25,000 ft.

The UK approach to the blast problem is to rely on the protection given by the rigid flying helmet which is provided with a strong chin strap and oxygen mask suspension system. The eyes are protected by the polycarbonate visor which must be locked down on ejection. This system provides adequate protection against blast up to 600-650 knots.

Miniature Detonating Cord

Some aircraft, notably the Harrier, are fitted with Miniature Detonating Cord (MDC). This device consists of an explosive charge contained within a lead coat which is applied to the underside of the canopy. Fig. 3. On ejection MDC shatters the canopy into relatively small fragments prior to the aircrew leaving the cockpit. The device has proved to be of great value in minimising personal and equipment damage on a through canopy ejection.

There have been a number of occasions on which lead spatter from MDC has caused superficial damage to the face and eyes. The most severe damage has been corneal penetration to a depth of .3 mm by small particles of lead. Fig. 4. In this example the pilot had his visor elevated and deliberately kept his eyes open. It is considered unlikely in the extreme that any ocular damage will result if the visor is lowered and the eyes are closed. In order to prevent lead spatter tracking down the inner surface of the visor various guards have been developed both solid and of foam plastic, these devices may have the adverse effect of increasing visor misting.

Lasers

Lasers are devices which produce beams of monochromatic light which are usually of small diameter, intense and highly collimated. The energy density within the beam only decreases slowly with increasing distance from the laser. The eye has the ability to focus the collimated beams of some lasers and to concentrate the energy into small image sizes on the retina. Fig. 5. Thus, lasers can damage eyes at considerable distance from the source.

Neodymium, gallium arsenide and ruby lasers which emit at 1060 nm, 900 nm and 694.3 nm respectively are the most important lasers encountered in military aviation. The applications of these lasers include ranging and target illumination.

Laser protection is best provided by the adoption of safe working distances. STANAG 3606 gives guidance as to the method of calculating the Nominal Ocular Hazard Distance (NOHD). It must, however, be realised that the calculated NOHD does not make an allowance for atmospheric conditions giving rise to 'hot spots' or for intra beam viewing using optical instruments with a magnifying effect. The necessity for pilot protection from his own laser is debatable. The likelihood of a specular reflector in the range area orientated normal to the beam must be small, the probability has been calculated as less than 10^{-6}. Should such a reflector be present, its reflectivity at the laser wavelength is not likely to be high. It is considered that pilot protection is not necessary provided the target and surrounding area do not contain specular reflectors e.g. windscreens.

Where protection is considered necessary this may be provided by goggles or visors with the requisite optical density at the laser wavelength. Care must be taken to ensure that the luminous transmittance, effect of the tint on colour recognition and optical properties of any protective device are adequate for the task.

Nuclear Flash

The fireball resulting from a nuclear explosion is capable of producing direct and indirect flash blindness and indeed may cause a retinal burn. By day the small pupillary diameter and the optical blink reflex should prevent retinal burns at distances at which survival is possible. Similarly indirect flash blindness from scattered light within the atmosphere and the globe itself does not pose a problem. Direct flash blindness from the image of the fireball on the retina is difficult to avoid, but again at survival distances the irradiated area will be small. Even in the worst case of the fireball being imaged on the macula, para macula vision should allow all vital flight procedures to continue. At night with a dilated pupil the situation is much worse. Retinal burns are possible and more importantly from the operational stand point, indirect flash blindness may deprive the aviator of all useful vision for unacceptably long time periods. In short, protection against nuclear flash is not required by day but is vital at night. (Vos et al, 1964).

A number of protective measures have been proposed. If an exterior view is not required or only required infrequently it would be possible to cover all transparencies with opaque blinds. It has been advocated that filters with a fixed 1-2% luminous transmittance be worn but these are not necessary by day and are of limited value at night. Another suggestion has been an eye patch which may be removed when one eye has been affected, but this is essentially a two shot device. What is required is a visor which could be worn at all times when nuclear flash is a possibility. This visor should have a very high luminous transmittance when 'open' and a very low transmittance when activated by a nuclear flash, clearing rapidly when the flash is removed. The visor should, preferably, be made of polycarbonate or other high impact resistance material so that it may replace the one intended for bird strike protection in the dual visor system. Photochromic compounds are being developed which go some way to meeting these criteria. These compounds are activated by the ultra-violet component of the nuclear flash and darken rapidly to provide optical densities of approximately 2. They clear rapidly following the flash but may produce an afterglow. The spectral absorption may not cover the total desired range of 400-1400 nm but can be centred where desired and sideband filters added. These compounds have been doped in acrylic where their useful life is limited due to oxidation, successful doping of polycarbonates has not yet been achieved. The most promising host material to date is epoxy resin where the shelf life is unlimited. Epoxy resin may be laminated with polycarbonates to produce the necessary impact resistance.

An alternative United States approach is to use an electro optic shutter of Lead Lanthanum Zirconate Titanate in a ceramic wafer (PLZT). This device reacts within a few microseconds to produce optical densities in excess of 3.

Although these characteristics appear ideal PLZT has two disadvantages. The open state luminous transmittance is low, about 22%, and it would be difficult and expensive to form into a curved visor.

REFERENCE

1. Voe, J.J., Frederikse, J.W., Walraven, P.L. and Boogaard, J. Some reflections on the danger of and the protection against nuclear flash blindness and retinal burn. Institute for Perception RVO-TNO Report No. 1ZF 1964-25.

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Figure 1

Fractured windscreen on a Jaguar aircraft, resulting from a strike by a herring gull.
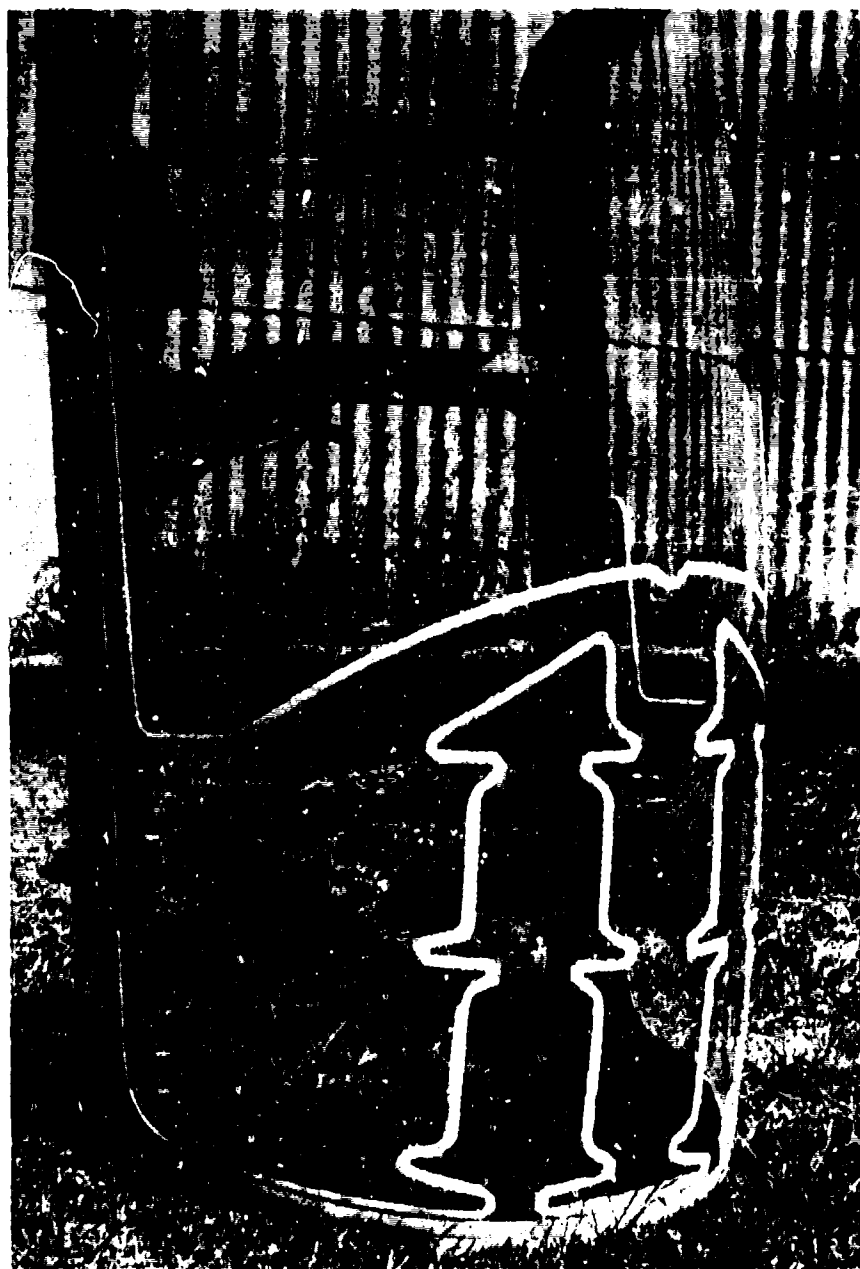
Figure 2

Dual visor helmet

Figure 3

Miniature Detonating Cord applied to a Harrier canopy
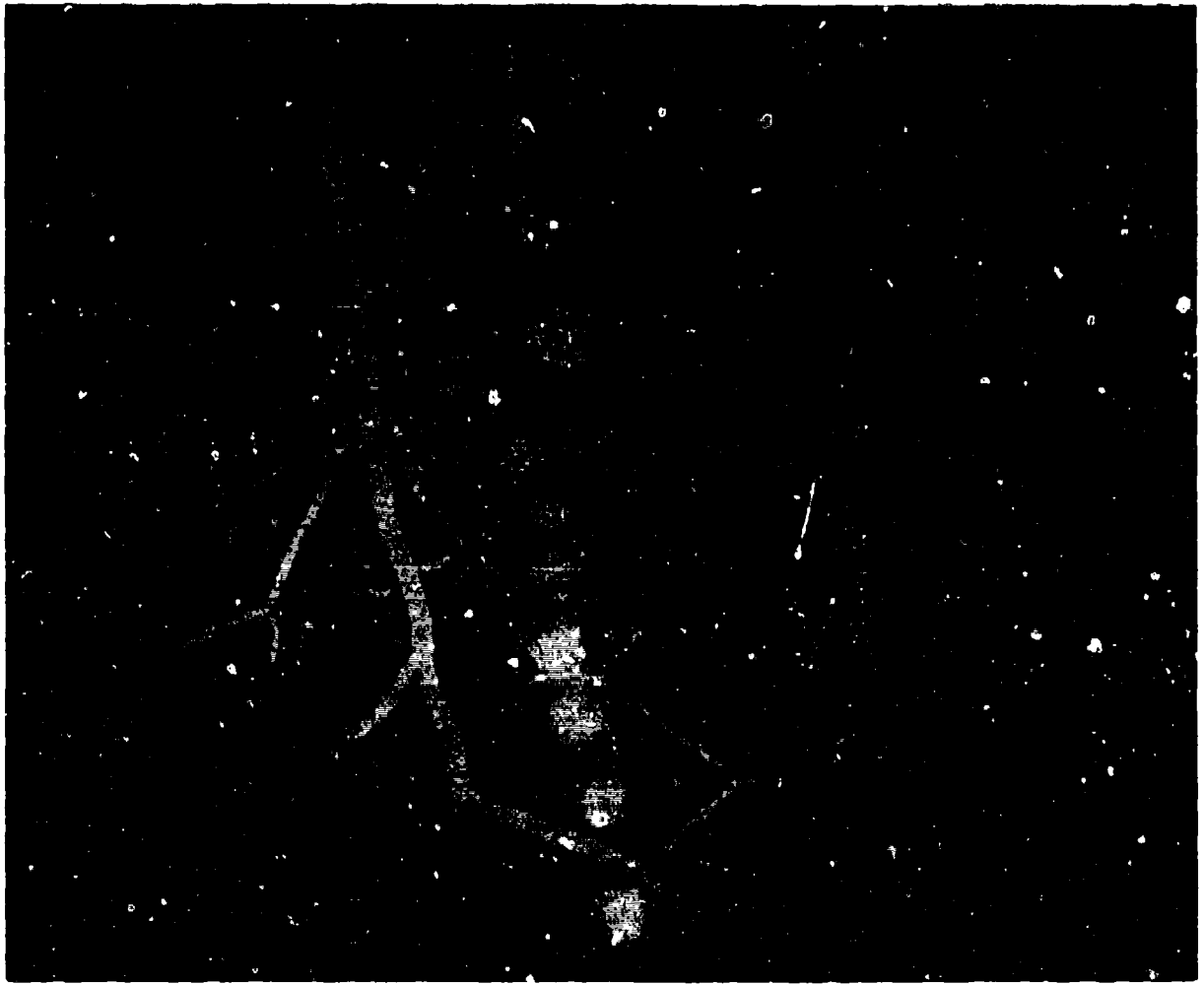
Figure 4

Lead spatter from M.D.C. on face and eye

Figure 5

Fluorescent angiogram of laser lesions on a rhesus monkey retina

HELMET MOUNTED SIGHTS AND DISPLAYS

by

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SUMMARY

The possible applications of helmet mounted sights and displays are considered. Brief details of the software and hardware problems which may be experienced with such systems are given before outlining in more detail the psychological problems encountered. The manner in which the rate of visual information processing by the pilot may be increased by varying physical parameters is discussed.

INTRODUCTION

Modern high speed fighters are required to operate in situations in which the pilot not only has to endure high physiological stress but also has to work at the limits of his mental capacity. It has long been realised that the human, even when highly trained, is limited in his ability to take in information through the peripheral sensory organs and process it centrally within the brain (Broadbent, 1971; Cherry, 1953; Moray, 1969; Triesman, 1969). The sensory modalities are not mutually exclusive, in that they rely upon the same central processor, consequently systems which redistribute sensory information across the modalities do not necessarily improve the rate of information intake. It has been estimated that within the flight environment more than 90% of flight information is taken in through the visual system, thus systems which are able to present visual information more concisely to the pilot reduce his information load.

The development of high luminance cathode ray tubes (CRT's) has encouraged the production of the now familiar head-up and head-down displays (HUD and HDD, respectively), which present computer generated symbolic information to the pilot or navigator superimposed either directly on the outside world (HUD) or a TV generated image of the latter (HDD). HUD's and HDD's are at present employed in a number of roles designed to improve the pilot's efficiency and extend the operating range of his visual system. These roles include presenting:-

a.   Avionics symbology.

b.   Weapon aiming symbology.

c.   Low light TV generated images of the outside world for night flying.

Inevitably hardware problems have repeatedly hampered the successful application of the above display techniques, but more recently improved CRT's and associated optics have permitted reliable systems to be produced. However, although many of the hardware problems may have been surmounted, the software, the display format itself, is proving a much more complex problem, especially as more and more information is being displayed. The problem is one of what? when? where? and how? should information be displayed to the pilot to improve his efficiency.

HELMET MOUNTED DEVICES

By positioning small optical devices proximal to the eye it is possible to subtend visual angles at the eye far greater than those possible from much larger devices on the instrument panel. Thus a small, lightweight display carried on the helmet may partially or totally replace the necessity for a large, heavy, space consuming HUD or HDD in certain conditions and supplement it in others.

SOFTWARE AND HARDWARE PROBLEMS

Many of the software problems associated with such displays are similar to those encountered with HUDs and HDDs, however, a host of new hardware and psychological problems arise. Briefly, the hardware problems are related to the role envisaged for the display. Simple filament or light emitting diode sights and displays pose problems far less severe to those encountered for complex raster generated displays. The former are by their very nature small, lightweight devices which can be integrated relatively easily into the helmet, although the optical interface to the pilot is by no means simple. The visual information must be reflected into the eye or eyes either from the inner surface of the visor or a small additional reflector held in front of the eye. Similar optical interfacing is required for the raster display, however where and how to house the miniature CRT may be a major problem. Carrying the CRT on or within the structure of the helmet increases the overall weight of the helmet and any eccentric loading may increase neck fatigue in the pilot and introduce a potential ejection hazard.

Positioning the CRT remote from the head but optically coupling it to the head by fibre optics is accompanied by a detriment in optical resolution.

PSYCHOLOGICAL PROBLEMS

The psychological problems are complex and are determined by both the hardware and the character-

istics of the task in which the hardware is to be employed. The simple helmet mounted sight (HMS) is of little use to the pilot unless it can be linked to some servo controller within the airframe which is capable of positioning the sight image over the target to be attacked or whose navigation co-ordinates are to be stored within the computer. The solution adopted is to employ a fixed sight of small exit pupil and use the helmet as the controller. Thus by moving the head to position the sight over the target and measuring the azimuth and elevation angles of the helmet electro-optically it is possible to compute the target's position relative to the airframe, even at large offset angles far beyond the limits of conventional HUDs and HDDs. This head position sensing device is fundamental to any helmet mounted sight system and is important in overcoming some of the psychological problems inherent in helmet mounted display systems (HMD's). The technique relies upon a good positive fit between the helmet and the head of the pilot.

(i) Head Motion and Disorientation

The human head can be rapidly positioned with reasonable precision in a no vibration environment. However, in the flight environment, particularly at low altitude, transmission of vibration to the head requires the helmet azimuth and elevation angles within the servo loop to be transformed to reduce the errors caused by involuntary head motions. This transformation may be achieved either by filtering or by introducing different non-linear control to display ratios between helmet and target sensor into the control loop at different phases of the task.

Simple HMDs present static symbolic information to the pilot. The presence of horizontal and vertical lines within the display are potentially disorienting at low altitudes as they are stabilised relative to the head and their visual movement may conflict with that of the horizon of the outside world and vestibular motion cues. This problem becomes more marked in raster displays where there may be both visual movement within the display and between the display and the outside world. The effect is particularly marked in the roll axis. These disorientations may be reduced if not eliminated by feeding back helmet angles to the symbology to partially stabilise it relative to the airframe.

(ii) Information Processing

Early raster displays were designed under the misapprehension that if different visual information were presented independently but simultaneously to the two eyes both channels of information could be processed simultaneously by the central processor, the brain. It has already been stated that the human is limited in its ability to take in and process sensory information and in the above situation the brain is unable to process the two channels of visual information simultaneously in a parallel manner. Rather, sequential processing occurs, the brain oscillating at low frequency between the two channels of visual information, sampling from both channels. This phenomenon is known as binocular rivalry and involves a shift of attention from one information channel to the other.

### (iii) Binocular Rivalry

Factors Affecting Rivalry

Binocular rivalry is a complex phenomenon (Ogle, 1964; Levelt, 1965), the rate of attention shifting being determined by the interaction of several physical parameters. These include the relative mismatches in (a) luminance; (b) colour; (c) accommodation; (d) image complexity; (e) image magnification and (f) field of view across the two eyes. In normal binocular vision the above parameters are very nearly equivalent across the two eyes. However, in existing displays rarely is more than one of these five major parameters equivalent.

The available high luminance CRTs are unable to produce luminances anywhere near equivalent to those experienced from reflected sunlight. The light transmitted from the CRTs is also usually confined to the green portion of the spectrum. The image presented on the display can take many forms ranging from simple symbology to complex symbology to a magnified TV image of a portion of the outside world which may or may not be aligned with the portion of the outside world being viewed directly by the non-display eye and which may or may not have symbology superimposed upon it. The displayed information can be focused at infinity or at any suitable predetermined optical distance.

As the physical composition and the information content of the stimuli presented to the two eyes, whilst using a HMD, may have both similar and different elements, it is important to consider which elements are utilised by the visual system and whether they cause independent or common effects across the two eyes.

(a) Luminance

All visual information, whatever its nature, must inevitably enter the visual system via the photo sensitive retinae of the two eyes. The amount of energy incident upon the cornea of the eye is not equivalent to that impinging upon the retina. The retina, although sensitive to a large range of luminances, is incapable of dealing directly with the extreme luminances encountered from reflected sunlight. Thus a control mechanism exists which is capable of reducing the high luminances to within the working range of the retinal elements. This is achieved by the iris of the eye which is capable of varying the pupil diameter. Iris control is achieved by a closed loop system the input to which is the light energy incident upon the retina. This energy produces afferent neural potentials within the optic nerve which are transmitted to the brain. If the frequency of these potentials is beyond the bandwidth of the optical system, ie the amount of light impinging upon the retina is too great, efferent neural potentials are transmitted to the iris causing it to constrict and thus reduce the light energy passing to the retina. The central controller, the brain, is able to monitor both afference and efference simultaneously and thus establish the intensity of the light incident upon the cornea of the eye.
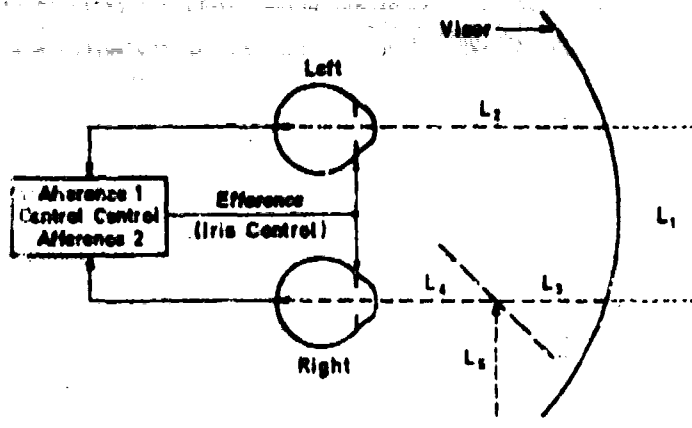
LUMINANCE CONTROL

FIGURE 1

The above describes the situation which exists for a single eye. However, when two eyes are considered it is apparent that it is possible to arrive at a situation in which two eyes are subjected to markedly differing levels of illumination. (Figure 1: L_2 to the non-display eye, L_4 to the display eye.) Under these conditions the above control mechanism does not permit independent adjustments to be made to the two iris. Rather, their movements are yoked, the operative input to the control mechanism being the higher level of illumination.

In the HMD context, where the luminance of the CRT may be several orders of magnitude less than that of the outside world, this latter phenomenon may result in the amount of light passing to the retina of the display eye being severely reduced, such that the apparent brightness of the display is diminished. By reducing the light transmitted to the non-display eye by increasing the optical density of part or all of the visor this effect can be diminished at the expense of reducing vision to the outside world. (L_1 reduced to L_2 for the non-display eye and L_4 for the display eye in Figure 1.) This latter reduction may be critical if the pilot is required to perform a target detection task prior to using the HMD.

The mismatch in illumination of the two eyes not only affects the apparent brightness of visual information but also influences the ability to shift attention in the binocular rivalry context (Figure 2). With equal illumination the ability to shift attention from outside world to display and back is equivalent in both directions. However, when the outside world illumination is greater than that of the display more time is required to shift from the outside world to the display than is necessary to move in the opposite direction. The amount of time spent attending to the display is also less than that spent to the outside world. With the display brighter than the outside world the above would be reversed.
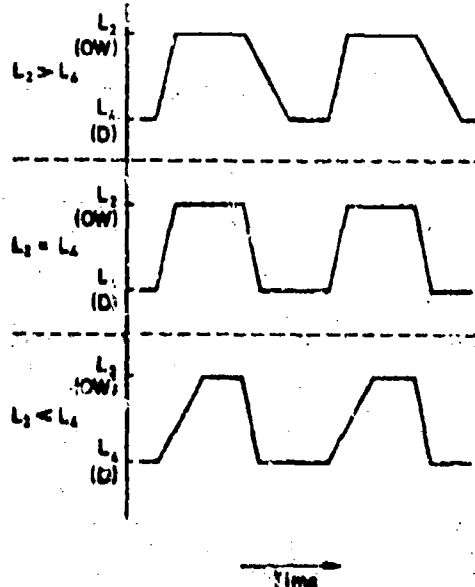
ATTENTION SHIFTING

Time
FIGURE 2

The extent of these attention shifting effects appears to be dependant upon the magnitude of the illumination mismatch and the attentional importance of the information displayed in each eye.

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(b) Colour

In the binocular rivalry situation the control of attention shifting appears to have a voluntary component. Voluntary control may be facilitated if the two visual information channels are independently labelled so that the central controller can readily distinguish and rapidly switch between the two sets of information. It has been already pointed out that the extent of voluntary control is partially governed by the illumination at the two eyes. Thus the absolute level of neural excitation within each information channel and the mismatch in excitation level across the two channels may be important factors affecting voluntary control.

Not only does the overall level of excitation appear to be important but also the type of excitation. The introduction of coloured tints to the visor and the colour of the CRT phosphor and its associated reflector affect the ability to separate the two sets of information within the brain. Thus colour coding can be utilised to facilitate attention shifting. Again, this improvement in voluntary control is achieved at the expense of degrading the information entering from the outside world in that tints applied to the visor affect the ability to detect contrast edges in the outside world. However, careful selection of both visor tint and CRT phosphor transmission wavelengths may result in contrast enhancement and not contrast degradation.

(c) Accommodation

The voluntary control of attention shifting appears also to be influenced by accommodation processes. As for iris control, accommodation cannot occur independently within the two eyes. Accommodation is to a certain extent under voluntary control, thus the central processor must select a single set of information if two sets of information are presented independently, in different focal planes, to the two eyes. In the HMD context it may be beneficial to focus the displayed information at an apparent viewing distance of a metre or less, rather than at infinity.

(d) Image complexity

The major processes affecting the transmission of information to and the separation of information within the brain have been outlined but now the brain must be considered as a cognitive processor as well as a peripheral sensory modality controller. The physical aspects of the visual stimuli contribute to the binocular rivalry process but the information content of the stimuli is also an important factor. It has been already stated that the displayed information can take many forms ranging from simple symbology to complex pictorial representations of portions of the outside world. The former present less of a problem as far as binocular rivalry is concerned as the brain is able to fuse simple symbology with information from the outside world, as in the HMS context. It has yet to be established how complex the symbolic information must become before binocular rivalry ensues. This point is governed by the format and content of each display and must be individually assessed. The rivalry phenomenon is accompanied by the pattern recognition problems inherent in HUDs and thus the two cannot be investigated independently. Although binocular fusion of outside world and display information may be achieved the brain may consider the two sets of visual information as completely separate patterns and thus process them independently rather than as one integrated whole.

When more complex information is displayed the problems of rivalry and pattern recognition may occur simultaneously. In this situation only by carefully considering both the physical characteristics and information content of the two channels of visual information can be a viable solution be achieved. Additional cognitive factors also influence the ability of the pilot to function efficiently under these conditions. If symbolic information is being presented on the HMD the pilot must be confident that spurious information is not being displayed as this will cause him to focus his attention predominantly to the outside world.

Similarly, if the displayed information is derived from a TV camera slaved through a servo control system to his head, unless he is confident that the TV is following his head exactly he will fail to recognise targets presented on his HMD.

(e) Image Magnification

In this latter situation the problem of pattern recognition becomes marked when the TV camera presents a magnified image of a portion of the outside world to the display. The non-display eye is presented with visual stimuli of unity size whilst the display eye may receive stimuli several orders of magnitude greater in size. This increase in magnitude is applicable both to size and the velocity of movements in the outside world. This problem is inevitably related both to the field of view of the TV camera and the visual angle subtended at the eye by the display. A narrow field of view is desirable for the camera if details are to be discernable in the display. A large subtended angle at the eye enhances discrimination. However, further problems may be introduced if this angle is excessive. Peripheral, non-display information entering the display eye will be excluded and may result in a decrement in the ability to monitor the flying task. Visual search and movement identification within the display may become problematic as the relationship between non-display and display information within the central controller cannot be maintained.

As for iris and accommodation control, saccadic (ballistic) movements of the eyes are yoked (Milsum, 1966). Thus image sizes and motions on the retinas of the two eyes will be incompatible in amplitude if the display is an enlarged representation of the outside world. Thus when attention is shifted from one information channel to the other the gain of the efferent control to the extraocular muscles of the eye has also to be changed and the eyes repositioned to place the area of interest on to the fovea of the attended eye. This repositioning and recalibration of extraocular gain can rapidly be achieved with training. However, particular attention must be paid to eye dominance as normally one eye drives the other when making saccadic movements.
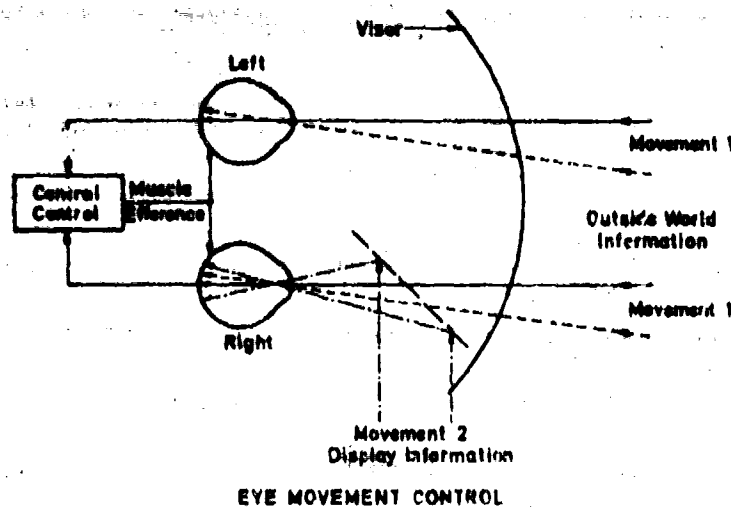
EYE MOVEMENT CONTROL

FIGURE 3

If movement information from both the display and the outside world is permitted to stimulate the retina at or proximal to the fovea conflicting afferent information is transmitted to the central controller. The central controller is only able to respond to one set of movement information and which one is attended to is determined by the velocity of the movement and both the luminance and contrast of the moving object (Figure 3). This problem can be surmounted by employing an appropriate interface between the CRT and HMD and the eye.

(f) Field of View

The magnitude of the angle subtended by the display at the eye also influences the configurations employed for displaying symbology. In normal vision the fovea of the two eyes are bilaterally represented in the hemispheres whilst the nasal retinae cross via the optic chiasma to the opposite hemispheres. As the images on both retinae are approximately equivalent the result is that information from the left hemifields enters the left hemisphere whilst that from the right hemifields passes to the right hemisphere. Whereas the non dominant hemisphere may only process information on the visual basis, the dominant hemisphere may process information both visually and in terms of verbal content (Schmit and Davis, 1974). Consequently, although interchange of information can take place between the two hemispheres via the corpus callosum, certain types of symbolic information may be processed more rapidly if presented to the hemifields projecting to the dominant hemisphere.

When binocular rivalry occurs, as with the HMD, the images on corresponding hemifields conflict. The information projected to each hemisphere is incompatible and has to undergo some form of decoding process before being subjected to further central processing. Under these conditions the time saved by transmitting information requiring verbal decoding direct to the dominant hemisphere may result in only a marginal increase in performance.

Memory Processes

Another facet of the binocular rivalry phenomenon is that recognition of pattern similarities across the two eyes cannot be achieved by simultaneous comparison of the two retinal images. Because of the sequential mode of operation in the central controller during rivalry, pattern recognition must be achieved by comparing the retinal image from the attended eye with a stored representation of the retinal image from the non-attended eye. If rapid responses are required pattern recognition may have to be achieved using memory processes. The problem associated with magnification within the display may become acute as the discrepancy in the detail stored in memory and that visible within the display will be considerable. Such discrepancy will lead to an increase in processing time within the brain before recognition can be achieved.

CONCLUSION

The psychological problems encountered whilst using a HMS are considerably less than those which exist with HMDs. With the latter, the complex interaction of psychological effects does not preclude a satisfactory solution from being achieved. Careful attention must be paid to every aspect of the optical interface if the two channels of visual information are to be distinguishable by the pilot. The format of symbolic information and the relationship between pictorial information and the outside world must be such as to reduce incongruities to levels which do not seriously increase the demands made upon the cognitive processes within the pilot. Training rapidly improves both performance on the flying task and the ability to process and utilise the displayed information. Although hardware designs impose limitations upon the operational roles in which HMDs may be usefully employed, improved designs may reduce these limitations to more acceptable levels.

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WARNING SYSTEMS IN AIRCRAFT
CONSIDERATIONS FOR MILITARY OPERATIONS

by

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INTRODUCTION

The demands upon the crews of military aircraft are intense and little time is available for aircraft systems management. The primary aim of the sortie is to reach the target, deploy the most effective weapons and to return, so automation is employed as far as possible. The workload can vary greatly according to the type of sortie, terrain and hostile forces, but it rarely permits adequate surveillance of all aircraft systems. If failure occurs in flight, inattention or inappropriate action could jeopardise the safety of the aircraft. The failure could become progressive as the large measures of redundancy usually incorporated in modern military aircraft could permit the flight to continue if quicker action were taken at the right time.

In order that aircrew should be informed when such a failure occurs, warning systems are used. These present the crew with information about the defect as unambiguously as possible, and also indicate, in some instances, the correct response for the crew to make. The purpose of this article is to present the principles employed in the design of warning systems in aircraft.

PRIORITIES

Three priorities of warning have been established:-

1. Warning signal. This is defined as a signal indicating the existence of an immediate catastrophic condition requiring immediate action, or limitation to the flight envelope of the aircraft.

2. Cautionary signal. This is defined as a signal showing existence of a hazardous or impending hazardous condition requiring attention, but not necessarily immediate action.

3. Advisory signal. This is a signal used to indicate the aircraft configuration and condition of performance, the operation of essential equipment, or to attract attention for routine purposes.

These signals are usually presented in three ways, by visual, auditory or tactile signals.

Visual Signals

This is by far the most common method used for the presentation of all types of information as the visual sense is the most discriminatory. Colours are used to good advantage and the priorities of warning are assigned the following colour codes. Warning signal, red; cautionary signal, yellow or amber; advisory signal, green, white or blue. The advisory signals are further subdivided by function. Thus green signifies that a unit or component is within tolerance or is satisfactory, whereas white or blue is used to advise of a state of position or action without implying either a safe or unsafe condition.

In addition to colour coding, warning signals also use the appropriate legends to indicate what system or failure is present. In practice these displays take the form of small lights or lighted panels which are marked with the appropriate legend so that the legend becomes legible when illuminated. Where the panel is too small to encompass the appropriate word, standardised abbreviations are used. Care is taken that the abbreviations used are unambiguous and lists of approved abbreviations have been prepared to ensure standardisation. Aircraft designed more than twenty years ago tended to have signals dispersed around the cockpit so that warning signals and other controls of a particular system were grouped together. Whilst this may make recognition of a particular signal easy and facilitate remedial action, it tended to make the cockpit haphazard with signals of varying priorities spread around all the cockpit displays. Modern military aircraft group all visual warning systems together as a standard warning system (SWS). The SWS is sited outside the blind flying panel but within the 30° cone of vision of the pilot. This position ensures that any warning will be immediately noticed. The SWS presents a small panel to the pilot bearing a number of illuminated windows. When the system is activated, the appropriate window illuminates and if it is a warning signal, ie one requiring immediate action, additional signals or 'attention getters' are also activated. These attention getters consist of more red lights placed in the direct line of vision of the pilot. The attention getters flash and auditory warnings are also heard to reinforce the urgency of the situation to the pilot. The attention getter lights and audio warning can be switched off by use of a cancel button on the SWS, but the illuminated caption on the SWS remains until the emergency situation has passed. If a fire warning is present, a red light illuminates in the appropriate fire extinguisher button, also situated on the SWS, to indicate to the pilot the actions he should take. The cancel button only acts for one specific warning and subsequent warnings, or those of higher priority, activate the whole system once more. Cautionary and advisory signals are also presented on the SWS. On some aircraft the warning system is physically split into a standard warning system and an auxiliary warning system (AWS). The AWS presents the cautionary and advisory signals which are not reinforced by attention getters, lights or audio warnings.

Other types of visual signals are mechanical in nature. Rods or flags can protrude into the pilot's line of sight in the cockpit or from various surfaces of the aircraft to supplement cockpit information. These are usually striped white and black or red and black for visual distinction purposes. Colour markings

of instrument displays also fall into this category and the colour of the instrument background (either disc/pointer or counter) gives information on the condition of the system indicated. Electromechanical visual warning indicators are usually fitted to modern flight instruments such as the attitude and horizontal situation indicators. These warnings are small flags which drop across part of the display to indicate failure of power or input. The flags are labelled appropriately and are either coloured or striped red. Other types of visual warnings consist of illuminated panels to order abandonment of the aircraft, except in those aircraft fitted with seats side by side or with command ejection systems. Visual warnings can also be used with head up displays and other electronic displays. A flashing letter W across the centre of the head up display has been advanced as a possibility as there is a limitation in the use of colour in electronic displays of current aircraft. The concept of an SWS is likely to remain and some sort of attention getter in the head up display will be used to transfer attention to the SWS when necessary. Visual warnings could also be employed with good advantage in helmet mounted displays.

Auditory Signals

These are of two forms, verbal and non-verbal, the latter being much more common. Electronically stimulated bells are used to enforce warning signals appearing on the SWS. However most modern aircraft now employ a 'lyre bird' auditory warning for this purpose which has become standardized among NATO forces. The lyre bird signal consists of a tone rising from 600 to 1,700 Hz in 0.85 seconds and repeated once a second (Fig 1). Auditory signals are also used in Naval aircraft to supplement information on airspeed or angle of attack on the approach to landing. A fast airspeed (or low angle of attack) on the approach is characterised by a 1,600 Hz tone interrupted at a rate (1 - 10 Hz) corresponding to the airspeed. An airspeed marginally faster than the optimum is accompanied by a 900 Hz tone plus 1,600 Hz tone interrupted at a rate 0 - 1 Hz according to the airspeed. When the optimum approach speed is achieved, a 900 Hz tone is heard. Airspeeds below the optimum carry auditory signals of 900 Hz and 400 Hz interrupted at 0 - 1 Hz and 400 Hz interrupted at 1 - 10 Hz depending on the airspeed of the aircraft.

Verbal auditory warnings are also used. With these systems, either a tape recorded or electronically generated voice is presented to the crew listing the system or service at fault, the specific location of the fault and the nature of the emergency, eg 'engine, No 4, fire'. Some verbal auditory warning systems continue the signal with the correct recovery procedure for the crew to follow.

More sophisticated auditory signals could be employed in aircraft operating in hostile areas. Here hostile radars may illuminate the aircraft and the crew would wish to know what class of radar is being used, from what direction, and whether the radar illumination is locked onto the aircraft. It may be possible to demodulate the radar signal received by the aircraft and present it as an auditory signal to the crew. The exact nature of the signal would then allow trained aircrew to distinguish between the various types of radar and to decide on the procedures to be adopted. These signals might possibly be supplemented by a visual display of some sort.

One must also include here the auditory identification signals which are superimposed upon TACAN, ILS, and other navigational channels. These are presented aurally to the crew and must be identified correctly (usually by morse code) to eliminate false navigational information.

Tactile Signals

In addition to visual and auditory signals, tactile signals are also used. The most widespread example of this is the stick shaker which warns the crew of airspeeds approaching the stall. These types of warning are used mainly in transport type aircraft. In addition to shaking the control column in some aircraft, the system physically pushes the stick forward to enable the aircraft to recover from the impending stall.

The Harrier VTOL aircraft employs a rudder shaker tactile warning to inform the pilot of excessive conditions of yaw, a potentially dangerous condition. The tactile warning is delivered to the rudder pedal that should be depressed to correct the yaw condition, hence the warning and the corrective action required are combined. Other mechanical warnings are employed in the mode of automatic terrain following. Here the aircraft is guided by radar to follow the contour of the terrain as closely as possible to avoid detection. Failure of the system could be catastrophic so, in addition to the SWS being activated, the aircraft is automatically manoeuvred into a safe climb.

Experience has shown that the visual display of warning, cautionary or advisory signals is the most effective and unambiguous manner in which to present essential information to the crew. Once the attention of the crew has been obtained they only have to read the caption to ascertain the details of the emergency. Auditory warnings to reinforce visual presentation are acceptable but become difficult to distinguish when numerous. Warning signals are presented infrequently so that discrimination is from memory, and this could be misleading. Audio warnings used for airspeed data differ in this respect as they are used much more frequently. It has been recommended that the number of non-verbal audio warnings should be limited to avoid confusion.

Tactile warnings can be used to give graduated information, eg as the situation becomes more critical, the shaking increases in intensity. Apart from the examples given of tactile warnings there is no evidence that tactile warnings are more efficient than visual or audio warnings combined. However, tactile warnings could have a bigger part to play in those aircraft without an automatic flight control system, eg combat helicopters where the pilot always has his right hand on the control column. Here tactile displays presented as moving surfaces or plungers which expand so as to become palpable could give either warning (eg radar altitude low) or director information. Two axis plungers could direct the pilot either to hold a given course or to manoeuvre the aircraft to acquire a target; the stick being moved in the direction that the plunger indicates. Combinations of plungers or surfaces could be used to signify different emergencies or degrees of emergency. Clearly more work is required to ascertain whether this concept has any advantage.

CONCLUSION

The concept of a visual display combined in an SWS is probably the most efficient method of presenting essential emergency information to the crew. Attention getters and audio warnings should be used to assist this presentation. Apart from a few specific cases, audio warnings do not have distinct advantages over visual displays. In some aircraft, tactile warnings can be used to good effect and extension of tactile displays to other situations should be examined.
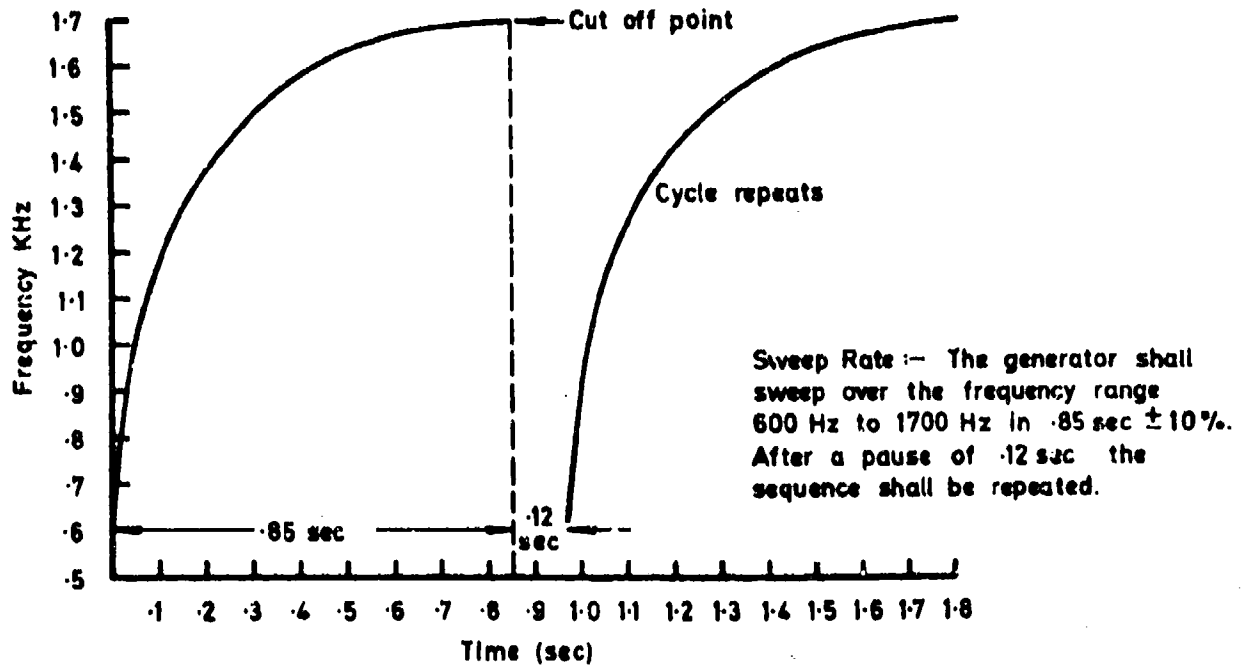

Sweep Rate :- The generator shall sweep over the frequency range 600 Hz to 1700 Hz in ·85 sec ±10%. After a pause of ·12 sec the sequence shall be repeated.

Fig.1   Master audio warning frequency characteristics

ADVANCES IN MILITARY COCKPIT DISPLAYS

by

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INTRODUCTION

The aim of this paper is to concentrate on the major developments which are influencing military cockpit design and the aircrew task. More than twenty five years ago Williams (1947) undertook an analysis of the pilot's task. While specific features may have changed the following quotation is pertinent to the contemporary situation: "Between the knowledge of what control movements to make and the knowledge of the purpose of a mission lie all the areas of information which together result in the accomplished flight. Since the only course of action open to the pilot is through manipulation of the aircraft controls, it follows that all the information he receives must eventually be filtered down to this level in order to participate in the flight at all. These pieces of information somehow work together in an organised way, and for purposes of analysis must be fitted into some descriptive pattern – thus the problem is first to break away from the notion of specific ways for presenting information and second, trying to develop a scheme into which all the various pieces of information will fit in a logical way". Carel (1965) consolidated Williams' analysis by developing the broad functions of a vehicle guidance and control system in order to provide a starting point for determining the pilot's overall task. He suggested that the operational use of a vehicle implied the following functions:

1. The selection and identification of a goal (for example a ground target or destination).

2. The measurement of the position of the vehicle relevant to the goal.

3. The selection of a path to the goal consistent with vehicle constraints.

4. The measurement of path error or the computation of predicted error at the terminal goal given present performance.

5. The selection and use of sensing and control mechanisms to physically realise a control law and thus reduce the error or make good the path.

6. The selection of components for the synthesis of the sensing and control mechanisms.

7. The selection of material for the required components.

Carel further suggested that the above functions resolve themselves into the attempt to obtain answers to the four questions:

1. Where in the world am I with respect to the goal?

2. What is and what should be my velocity vector?

3. What is and what should be my attitude and angle of attack?

4. What should I do with the controls?

Roscoe (1974) represented these sub goal functions in a diagram representing the hierarchical nature of the flight task as shown in Fig. 1. He points out however that the pilot must also take into account what he describes as the constraining factors of the flight:

1. The performance characteristics and present condition of the aircraft.

2. The presence and flight paths of traffic in the vicinity. The relationship of that traffic to the aircraft (friendly/hostile), and the need to avoid or intercept it.

3. The weather, both local and en route.

4. The geography and topography of the terrain over which the flight is being made.

5. The characteristics of the crew or passengers that impose constraints upon the flight.

6. The body of rules and agreed procedures that govern flight in the particular airspace.

In the military context the above discussion of the control and guidance functions performed by the pilot, must be set against the background of increased aircraft performance, greater weapon systems effectiveness, demands for total 24-hour all weather flight capability and the need to use operating profiles which disadvantage hostile defence systems. To satisfy these requirements a wider range of information sources are now being drawn upon, for example infra red radar, low light television, laser ranging, inertial navigation systems and ground based radio and navigational aids. In their initial form each sensor has tended to be designed as a mainly independent system having its own information display and so the number of displays in the cockpit have increased.

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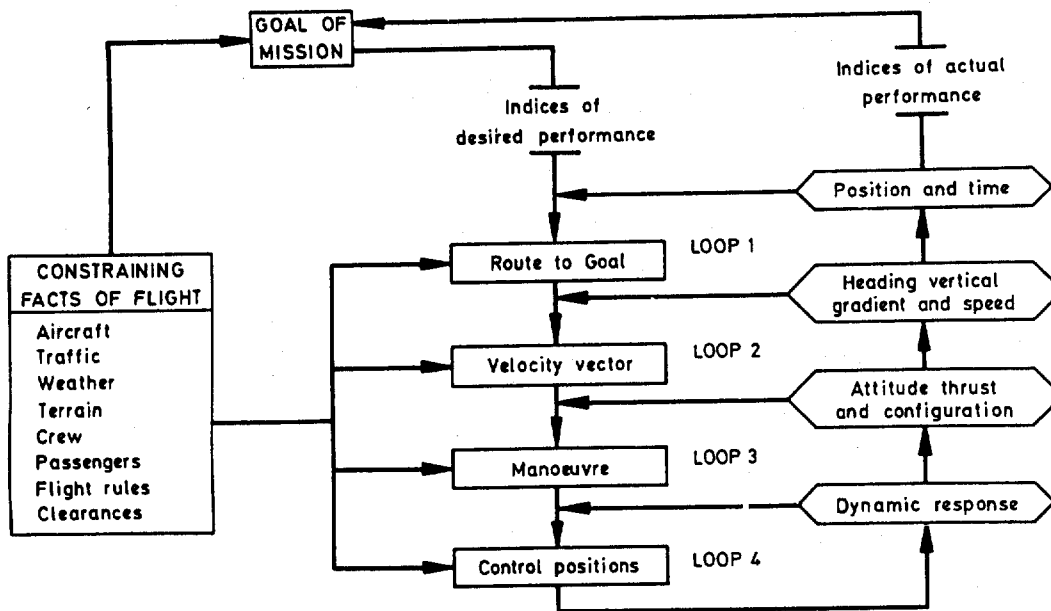
FIG.1. THE HIERARCHICAL NATURE OF THE FLIGHT TASK

(from Roscoe 1974)

The trend towards increased cockpit complexity has led to the recognition of the following constraints:

1. The physical workspace of the military aircraft cockpit is severely limited with the consequence that there is little spare space available to add additional displays.

2. With the trend towards greater freedom of vertical operation, i.e. V/STOL capability, the need for greater external vision from the cockpit reduces the areas which can be used for the display of information within the cockpit.

3. Trends towards combining information on to one display have not always proved successful.

4. Delays arise as the pilot has to change eye position from outside the cockpit to inside the cockpit and back again.

5. If the pilot is forced to select and process raw data from multiple information sources he is subjected to high workload and speed and load stress.

The consequence of the above constraints has been the demand for display systems which satisfy the requirements of using onboard computing facilities to integrate information so that the pilot's task is simplified and he is less heavily burdened. Linked to this aim is the recognition of a need for more flexible display systems than the conventional electro-mechanical systems which have formed the basis of aircraft instrumentation over the last three decades. The major requirements for such a display system are that it should have:

1. Multi-sensor capability, i.e. the display should be able to accept information from a range of inputs.

2. Multi-function flexibility, i.e. the information displayed should be capable of being changed to meet the needs of a particular flight phase.

3. Multi-format flexibility, i.e. it should be possible to display the same information in a variety of formats.

The display device which currently has the capability of fulfilling these requirements is the cathode ray tube (CRT). The CRTs performance in terms of resolution, accuracy, brilliance and environmental resistance is significantly better than other types of modern displays. On the other hand the physical constraints of electro optical systems ensure that the size of such displays is large. Also compared with other types of addressable systems the associated weight and cost of the necessary symbology generation is significant. The idea of the use of CRT displays in flight usually raises the question of their reliability. Evidence is now available which indicates that reliability is less of a problem than was first thought it might be. Marconi-Elliott Avionics Systems, manufacturers of the widely used cathode ray tube used in the A7 A and E aircraft, have now evidence based on over a million flying hours. Their experience

has shown that much of the initial emotional worries and concern regarding the reliability of the glass tube are largely unjustified. Such reliability problems that have occurred have been associated with the high speed analog digital conversion circuitry and a tendency for ground crews to use the CRT display in a very high brightness mode for long periods as a navigation attack system check out display. In this context it is worth noting that in one single year in the United States military operations 80% of all tube failures were associated with the gradual etching by burning of the test display format caused by prolonged operation of the display system in the entirely static check out mode. When the display systems were operated within specified limits CRT lives in the order of 1,400 hours were being achieved.

The application of multi-function, multi-mode displays can be considered in relation to the planes of operation encountered in flight. Currently two basic configurations can be found in use. The first is a vertical situation display, a forward looking presentation providing a spatial reference in the X and Z axes of azimuth and elevation. This display fulfils the role of the attitude indicator or the attitude director indicator with additional capability for weapon aiming and the display of basic information such as altitude, airspeed and heading. With additional multi-sensor capabilities the combination of electronically generated, low light television and infra red forward looking information can be superimposed on the display.

The second configuration is the horizontal situation display, a downward looking display of information in the X and Y co-ordinates of azimuth and range. This display presents heading information and, in addition, bearing information with regard to radio beacons, targets and other identifiable way points on the ground. Ultimately the aim is for horizontal information such as the moving map, radar and electronically generated navigational symbology to be capable of being combined onto one presentation. However, at the moment this development awaits the availability of the high resolution multi-colour display capable of displaying topographical map information in adequate detail. A compromise can be achieved by the use of optical combining systems which superimpose radar and moving map information. Systems are now becoming available in which map information can be overwritten with alphanumeric data displays using light emitting diodes (LEDS).

In addition to the vertical and horizontal situation displays another display which is now available in a variety of prototype forms is the profile display. The profile display gives a sideways looking indication of the vehicle's behaviour in relation to the X and Y axis, i.e. elevation and range. Information of this type is particularly relevant to V/STOL operations where a sophisticated approach path may be required to be followed in order to achieve an effective deceleration and transition from forward to vertical flight. Among the parameters which studies have shown to be necessary to the pilot are:

1. Ground speed and direction: to enable the pilot to arrive over the landing spot at the desired touch down speed.

2. Vertical speed: most V/STOL aircraft have a low normal acceleration capability in the approach configuration and it is important for the pilot to be aware of the proximity of the safety boundary.

In all three of the above display configurations there are a variety of options open to the designer with regard to the way in which information may be displayed (see Suvada, 1973). Probably the most significant one at this time is with regard to the vertical situation display whether it should present its information head up or head down. The head up display calls upon the philosophy that the pilot needs to look out of the cockpit and therefore the information should be located so that he does not need to remove his eyes from the outside visual scene. In addition if the display can be made to appear at optical infinity he will not need to change the accommodation of his eyes or change his attention from one display to another. These two aims are achieved by the use of a collimated presentation, optically mixed with his forward view. The concept derives much from the gunsight but the opportunity has been taken to improve both the information content of the display and its method of presentation. The head up display has found favour in military aircraft for example, Jaguar, Harrier and the AV8A.

Developments have also been taking place in head down vertical situation displays. Again the multi-sensor, multi-function capabilities of the display are utilised but no attempt is made to combine the display directly with the outside visual world. The argument for this philosophy is that where the end goal does not require a continuous scanning of the outside world there is an advantage in presenting as much information as possible head down in a larger format than available with the head up display.

While the present time sees the cathode ray tube favoured as the primary media for the presentation of flexible information developments are progressing towards the application of other display techniques. The most promising of these is the move towards the use of solid state display techniques. However it is likely that these will supplement the cathode ray tube, rather than supplant it. This means that devices such as liquid crystals and light emitting diodes will be applied to the display of alphanumeric graphic displays which will displace electro-mechanical displays. Progress has been made with the design of light emitting diodes in recent years. The brightness of LEDs has been increased to a level where they are now totally compatible for use in head up and head down displays. Their addressable nature and the high resolution which can be achieved by these displays make it possible to construct complex alphanumeric and graphic displays which are often considerably more effective than the electro-mechanical ones they replace.

To summarise, in this paper the attempt has been made to examine the background against which recent advances in display technology have taken place in relation to the military cockpit. Emphasis has been placed upon providing an adequate assessment of the information needed by the aircrew in order to perform their task and from this evolve a display system capable of presenting information in a flexible manner. In order to do this the demand for a multi-function, multi-sensor information processing and display system has presented itself and a number of solutions to the problem have evolved. At the present time the most widely used form of display is the cathode ray tube which has the required flexibility.

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MAP DISPLAYS

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SUMMARY

The major types of map displays are distinguished and their functions are described. The principal design parameters are reviewed with particular reference to user requirements and human factors, and an outline is given of current problems of map annotation, display legibility and brightness, radar-map matching and display complexity.

INTRODUCTION

En route navigation accuracy of less than 0.5 nm is an essential requirement of low altitude tactical operations. This can be achieved by conventional map reading techniques, supported by extensive pre-flight planning, but the navigation workload places enormous demands on the pilot in flight. Consequently, geographic disorientation is a major cause of mission failure in single-seat aircraft.

A variety of map displays have been developed to ease the burden of in-flight navigation. Three major types of map displays can be distinguished:-

a.   Direct-view roller map displays, consisting of a strip map mounted on motorized rollers with a cross-track cursor indicating present position.

b.   Optically projected map displays (PMDs), with a microfilm transparency of the original map back-projected onto a display screen with the aircraft's present position indicated by a moving symbol against a fixed map image, or by a fixed symbol against a moving map image.

c.   Electronic map displays - cathode ray tubes (CRTs) or light emitting diodes (LEDs) - with all the displayed information, including the map, generated by electronic techniques.

The moving components of these displays are driven from the aircraft's navigation data sources, i.e. VOR/DME, doppler, inertial platform. Across this categorisation there are a number of displays that combine CRT displays of symbolic or radar information with optical or direct-view presentation of map information. A detailed description of contemporary map displays is given by McGrath (1971).

Currently, direct-view map displays are favoured in helicopters (e.g. Puma and Wessex) and transport aircraft (e.g. Andover and Hercules) for their simplicity and cheapness. Projected map displays are used in long range low altitude strike aircraft where their large map storage capacity and flexibility are appreciated (e.g. Harrier, Jaguar and MRCA). All-electronic displays are likely to be incorporated in the next generation of strike aircraft, provided the problems of cost, weight, computer capacity and colour imaging are satisfactorily resolved. Multiple sensor combined displays and the flexibility of electronically generated displays are particularly attractive because of the efficient way in which they utilise the cockpit space occupied by map displays, usually about 6 inches diameter, which is difficult to justify for a single display function.

ADVANTAGES

The main advantages of map displays can be listed as follows:-

a.   Workload.   They reduce pre-flight planning time and provide an immediate, continuous monitoring of the aircraft's geographical position, reducing navigation workload and head-in-cockpit time, and improving the pilot's control of the aircraft.

b.   Interpretation.   Navigation information is presented in a way that is easily interpreted, i.e. with reference to a map, thus reducing the likelihood of gross navigation errors.

c.   Correlation of Navigation Systems.   Map displays provide a means of cross-checking the outputs of navigation systems such as doppler, radar, inertial platform and visual reference to the ground.

d.   Map-Computer Linkage.   They are a convenient means of communicating with the onboard navigation computer, checking its integrity, updating its accuracy, and inputing navigation problems.

e.   Map Storage.   PMDs store and display large areas of mapping at a variety of scales. Up to 3,000 sq ft of original charting can be stored on 35 mm microfilm in some displays.

f.   Navigation Data Storage.   Map displays store and display a variety of navigation information in addition to that depicted on maps, e.g. track marker and steering information, digital readouts of present position, waypoint and destination co-ordinates in lat and long, ground speed, wind speed and direction, time-to-go and range-to-destination.

g. Anticipation. They improve the ability of the user to anticipate and recognise features on radar and on the ground, and thus provide a timely updating of the navigation system.

DESIGN ISSUES

During the development of PMDs a number of design issues arose that are peculiar to map displays and illustrate some of the major human factor problems encountered.

a. Fixed Map or Moving Map. Considerable human factors research and debate has centred on the question of whether the map should move and aircraft symbol remain fixed, or vice versa. Researchers concluded on the basis of experimental evidence that pilots conceive of the earth as the fixed component of the navigation system, and that therefore, in map displays, the map should be the fixed component against which the aircraft should move (Roscoe, 1968). This philosophy has also guided the design of altimeter and aircraft attitude displays. The disadvantages of this format are that frequent map changes are required when the aircraft reaches the edge of the display, and that the important "view-ahead" of the aircraft is not optimised. These criticisms have resulted in all current PMDs having a moving map format.

b. Track-Up or North-Up. As a consequence of the decision in favour of a fixed map format, map displays were initially orientated with the map north-up. This was supported by the argument that this would facilitate reading of map lettering. More recently, with moving map formats, it has become apparent that users prefer the map to be oriented track-up, i.e. with the track line pointing to the top of the display, and that they only require occasional reference to the north-up mode when lettering needs to be read. Most operational displays now have optional north-up and track-up modes to be selected at will.

c. Centred or Decentred Present Position. Early PMDs were designed for convenience with the aircraft symbol in the centre of the display. A centred present position is useful for flight planning and when programming and reading-in way-point co-ordinates. But in-flight, in the track-up mode, pilots have little interest in the area behind the aircraft and this occupies half of the display with a centred present position. Consequently, recent displays have an optional decentred present position at the bottom of the display, leaving the entire diameter of the display for "view-ahead". This also has advantages for correlation with ground mapping radar, with the sweep origin at the bottom of the CRT.

d. Scale Magnification. Initially, PMDs were designed to project the map-image back to its original scale. This resulted in serious legibility problems for small detail on conventional maps designed for hand held viewing distances (variable, between 6 and 18 inches) when viewed in map displays at panel-mounted distances (about 30 inches). To counter this, recent displays over-magnify the map image by factors as large as 1.63x, with a limited optical scale change facility to vary the apparent viewing distances (McGrath, 1972). But with a display of fixed size, map magnification affects the map area shown, reducing the view-ahead. The problems of long, fixed viewing distances for map displays are unlikely to be entirely solved until special purpose mapping is provided that takes this into account.

e. Image Brightness. High ambient cockpit illumination of the order of 100,000 lux presents problems when viewing a map image back-projected onto a translucent screen. To make the map image independent of ambient brightness, field lens optical systems have been used which form the primary map image within the display where it cannot be reached by extraneous light, unless it enters by the exit pupil of the lens system at the pilot's normal head position (Briggs, 1972). Such a system also has advantages when optically combining a CRT generated radar image with the map image. CRTs with sufficient brightness and persistence time have not been available, and a field lens system is necessary to permit the use of conventional CRTs without brightness problems (Webb, 1965). Field lens systems have the disadvantage of limiting the viewing angle and freedom of head movement. Moreover, indifferent optics easily result in image-field flatness problems, causing the map image to appear distorted. This has serious consequences for map interpretation, range estimation and causes considerable eye strain. Operational experience with simple back projection systems, such as used in the Jaguar, suggests that a legible map image can be obtained with a bright light source, without recourse to a field lens system with all its disadvantages. However, the argument for using a field lens system in a combined radar/map display still remains valid.

CURRENT PROBLEMS

The design issues discussed above have largely been resolved. A number of problems still exist and new ones are emerging as operational experience with map displays is gained. Some of these problems are discussed below:-

a. Map Annotation. The need to annotate maps has been a perennial problem with PMDs where the maps are stored on microfilm. With hand-held maps, navigation information such as routes, fuel status, restricted and danger areas are normally added during pre-flight planning, and the maps are often enscribed in-flight with reconnaissance information and targets of opportunity. Optical combination with CRTs has been proposed as one future solution, and digital read-outs go some way towards overcoming the problem on some of the current displays. Aircrew solve the problem by carrying identical hand-held maps, enscribed with route-planning information, and work back and forth between the map display and the hand-held map. This clearly defeats one of the major objectives of map displays: to unburden the pilot of the need for paper maps, except as a back-up in case of system failure. A variety of microfilm annotation techniques are being explored, such as light sensitive film coatings, but until practical solutions are found the full potential of PMDs is unlikely to be realised.

b. Display Legibility. A second, and equally important reason for carrying hand-held maps is that the legibility of PMDs leaves much to be desired. Poor legibility can arise from a number of factors:

ambient lighting, long viewing distances, screen grain effects, poor optical resolution, and excessive microfilm reduction factors. But the major source of difficulty stems from the continued use of conventional maps in the displays, with poor colour rendition, inadequate contrasts, unnecessarily fine detail, irrelevant information and extensive clutter, particularly on 1:250,000 scale mapping. To some extent colour and contrast problems can be improved by advances in microfilm processing, but the legibility problems seem so severe that it is likely that anything short of special purpose mapping will be ultimately unacceptable to the user. Recent research at the IAM and RAE, in conjunction with the Mapping and Charting Establishment has identified the important design parameters for maps for projected systems. Alternative map formats, colour codings and symbology have been studied together with analyses of map content and user requirements, and considerable progress has been made towards developing detailed map specifications (Barratt et al, 1975; Taylor, 1974a; Taylor, 1975).

c. Night Vision. During the day, the problem is to display a legible map image that is sufficiently bright to overcome high ambient brightness. At night, the pilot requires a legible map image that does not destroy his dark adaption and night vision sensitivity. Until recently, this problem has tended to be neglected because little night flying has been carried out in aircraft with PMDs. However, recent attempts to extend night capabilities have demonstrated that existing displays may be too bright at their lowest intensity levels for safe operation at low altitudes. The solution often proposed in the past has been to introduce red filters, but recent research has shown that red light for map reading gives little advantage in terms of increased night vision sensitivity and has serious and prohibitive consequences for map legibility because of the loss of colour coding (Taylor, 1974b). Reverse format "black maps" present a partial solution by restricting the light transmitted to information items only (Roscoe, 1967). But these have limited application and are unlikely to be acceptable for daylight use. Moreover, the problems of giving an adequate relief representation on "black maps" seem intractable. An engineering solution is likely to be the only acceptable one for the user, such as a rheostat dimmer rather than the present step switch. To some extent the field lens optical system has some advantages at night in that light only leaves the display through the exit pupil; light does not scatter around the cockpit as with back projection systems, and the pilot can avoid seeing the light by moving his head out of the exit pupil.

d. Radar-Map Matching. "Black maps" have also been evaluated as a possible solution to the brightness problems of combined radar and projected map displays (CRPMDs). In the CRPMD the map image is optically combined with same-scale forward looking radar generated on a CRT and viewed superimposed. Such a system has advantages for increased radar interpretability, facilitating the early recognition of radar features, and provides a continuous monitoring of the navigation system. When the images appear desynchronised, the map can be slewed by a hand-controller to eliminate error and update the navigation system. "Black maps" have advantages for increasing the contrasts of superimposed radar returns, but again, the problem of relief representation has proved difficult to overcome. This is particularly serious for radar-map matching in mountainous regions where returns from steep slopes and ridges provide the major source of useable information. Recent developments have favoured modified conventional positive formats, with selective portrayal of radar significant features and enhanced representation of relief by layer tinting and shadow shading methods (Barratt et al, 1975).

e. Complexity of Operating Modes. A problem that map display designers are becoming increasingly aware of is that, with the trend towards more alternative operating modes and functions, pilots are having difficulty knowing and remembering what mode the display is in. Confusions easily arise between centred and decentred modes and track-up and north-up stabilisation, and without any positive indication inherent in the display face the operating mode is not always immediately obvious. The solution to these problems probably lies in better engineering rather than improved training of operators.

CONCLUSION

Map displays provide an elegant solution to the hitherto much neglected problem of navigation workload in low altitude tactical operations. Many basic design issues have now been resolved, but it would be wrong to suggest that the area is without problems, particularly with respect to legibility and cartographic support. However, the advent of highly flexible and multiple function electronic displays, will make map displays a common feature of future avionics systems. Already their value is widely recognised and there is no better way to illustrate this than by quoting a USAF A7 pilot with 3500 flying hours and 200 hours with PMDs who when asked about the value of map displays, characteristically replied:

"The map display is an absolute necessity. In order to have radar compatibility correlation with a map display is essential. The map display also gives us our only means of updating the navigation system when we don't have predetermined co-ordinates of a visual or radar fix. It is an outstanding aid in avoiding obstacles or international boundaries in dirty weather or at night. I would rather have the map display, when it is functioning correctly, than any other system in the aircraft" (McGrath, 1971).

This reply was typical of those given by 105 pilots surveyed. If map displays are such an essential operational requirement as these users seem to suggest, then it is even more important that acceptable solutions are soon found to the problems that remain.

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PHYSIOLOGICAL LIMITATIONS TO HIGH SPEED ESCAPE

by

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The forces which must be imposed for satisfactory high-speed ejection approach, or even surpass, the limits of human tolerance at several stages in the ejection sequence. These forces are:-

1. The +Cz acceleration of the ejection seat.

2. The -Gx acceleration due to wind drag.

3. Direct (pressure) and indirect (flail) effects of wind blast.

4. Other inertial forces (centrifugal, tangential) due to seat instability.

5. Opening shock of drogue parachute and main canopy.

6. Ground impact.

Of these forces the first must be increased to achieve tail fin clearance at high speed, the second and third increase with the square of indicated air speed, the fourth increases with airspeed, and the fifth must be increased if escape is to be successful in the high-speed low-level case. Only the last force is uninfluenced by aircraft speed at ejection and the message is clear - high speed has a major effect on forces imposed during assisted escape from aircraft.

In the following notes these forces will be considered in turn, in relation to the mechanism of injury, incidence of injury, tolerance to injury and in particular, to the influence of air speed at ejection.

+Gz acceleration

Inertial force acting in the head to foot direction (reaction to a headwards, or +Gz acceleration) is carried predominantly by the spinal column. Overloading of the spine causes compression fracture and the commonest site of injury is where the load is greatest in relation to cross sectional area. This is most frequently T12 - L1, but fractures are not uncommon from T5 to L2, and occur rarely around C5. As Kazarian has pointed out, the joint surfaces of the articular facets change direction at T12 so that below this level they can no longer be load bearing. This discontinuity causes a stress concentration at T12-L1 and must be a further factor in the observed frequency of fractures.

In 331 non-fatal ejections experienced by the RAF from 1960 - 1973, the overall incidence of spinal compression fracture was 43%, but it must be stressed that many of these were symptomless and that the incidence is strongly correlated with the degree of effort made to diagnose the condition. Corresponding figures for other NATO Forces are: USAF, 10%; US Army, 34%; FAF, 22%; IAF, 17%; GAF, 10%; HAF, 18%; CAF, 13%. Thus, spinal fracture is still an all too frequent cause of injury in otherwise successful ejections.

Tolerance of the spine to +Gz acceleration depends upon: the vertebral load bearing capacity governed by factors such as age, anthropometric variation and musculo-skeletal development; load distribution as affected by seat design, harness configuration, pre-ejection posture and system of ejection initiation; catapult performance; and human dynamic response. Tolerance is best related to the Dynamic Response Index, since by this means the influence of rate of rise of acceleration (rise time, jolt), peak acceleration and duration of acceleration are effectively combined into a single numerical index which may be related to the risk of spinal injury. However, the other factors listed above must also be taken into consideration. The DRI may be considered as the steady-state (infinite time rise) acceleration which would have produced the same degree of spinal compression. A value of 18.0 predicts a spinal injury rate of less than 5%; a value of 20.4, a rate of less than 20%; and a value of 23, a rate in excess of 50%. These predictions are supported by USAF and UK ejection experience.

The influence of airspeed on the incidence of spinal injury is not clear cut and in theory, since the peak DRI usually occurs early in seat travel, no influence would be expected. In recent RAF ejections, 107 out of 323 aircrew who ejected at under 300 kt suffered spinal injury (33%), whereas at speeds in excess of 300 kt, 27 out of 32 suffered injury (84%). Statistically, this difference is highly significant. By way of contrast, Martin Baker have looked into Phantom ejections using their H7 seat, and find a 5% injury rate at speeds less than 300 kt (170 ejections) and an identical figure for 98 ejections made at greater speeds. Broken down into narrower speed bands, these figures even suggest that injury rates are greater at the lowest speeds (28% injury rate for 14 ejections made at speeds less than 100 kt), but numbers are too small for statistical significance to be obtained. However, high wind-drag deceleration could force the back against the seat and so improve spinal alignment, just as wind-drag forces acting in other directions could increase the spinal loading.

The DRI technique has been extended to include other force vectors (±Gx, ±Gy), but our current feeling is that the prediction becomes grossly pessimistic - a view admittedly shared by Peter Payne, the originator of the DRI concept (personal communication).

-Gx acceleration

On entering still air, the man/seat combination is exposed to wind-drag deceleration given by:

$$\text{deceleration (G)} = \frac{\rho \ V^2 \times \text{frontal area} \times \text{drag coefficient}}{\text{ejected weight}} \qquad \dots\dots\dots (1)$$

Tolerance to these forces was established by the pioneering work of Stapp, but wind-drag is not well simulated by decelerator track experiments. Thus, on the track, the decelerative force is transferred to the body by the restraint harness, whereas in wind-drag, the entire frontal area is exposed to the dynamic pressure and the body is squeezed between this and the inertia of the ejection seat. This situation is more akin to experimental +Gx acceleration (rearward facing seat crash case) in which tolerance is higher. Tolerance may be of the order of 50 G (for realistic durations of exposure) and for typical seat configurations this implies a 600 to 750 kt ejection depending upon seat orientation (Figure 1).
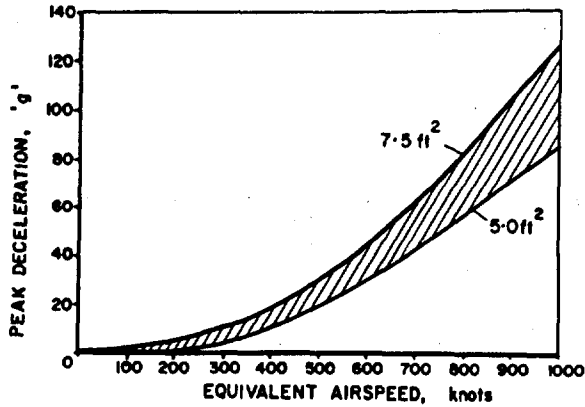

FIGURE 1. Effect of airspeed at ejection on peak wind-drag deceleration of seat for maximum (7.5 ft^2) and minimum (5.0 ft^2) presented areas.

It may be concluded that wind-drag deceleration is not currently a limiting factor in high speed ejection, and this is borne out in a recent survey of windblast injuries where no injury was seen which could be attributed solely to this mechanism. Two points need to be made however. First, it is not known how wind-drag deceleration affects tolerance to spinal compression injury (in rocket seats the two forces are acting simultaneously and may be additive), and second, in an encapsulated ejection system, the deceleration becomes identical to that experimentally imposed on decelerator tracks and human tolerance is probably lower. How encapsulation affects peak deceleration depends to what extent the ratio of frontal area to weight is affected (see equation (1) above).

Windblast – direct pressure effect

Windblast, ram pressure or 'Q' force is given by the expression:

$$Q = \tfrac{1}{2} \rho \ V^2 \qquad \dots\dots\dots (2)$$

where ρ is air density. Thus, windblast is proportional to the square of the indicated airspeed. At 300 kt the ram pressure is some 2.2 psi (15 kN m^{-2}) whereas at double this airspeed the pressure is quadrupled (Figure 2).
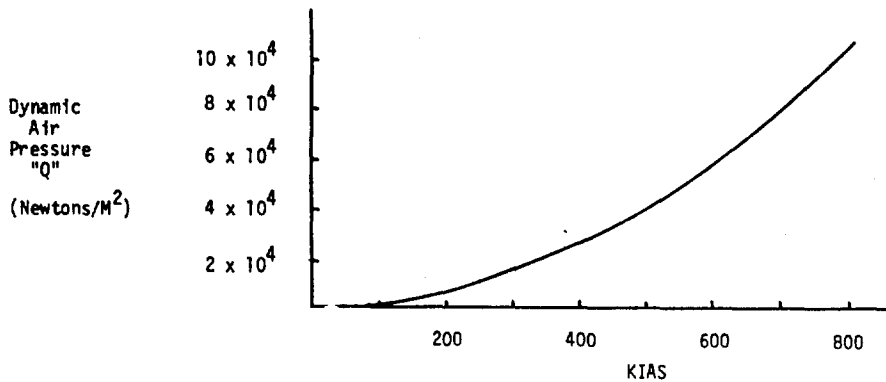

FIGURE 2. Dynamic Air Pressure vs. Airspeed

The direct effect of ram pressure on man is bruising and petechial haemorrhages over exposed areas of skin, and conjunctival haemorrhages and, if the mouth is open and unprotected, blast damage to the lungs.

In a recent FAF review of 23 ejections carried out at speeds in excess of 400 kt, there were two cases of lung injury. One was mild with clinical signs of mediastinal emphysema, the other was fatal. Such injuries are, however, rarer than this incidence would suggest.

Tolerance to ram pressure was investigated by Stapp (where interpretation was confused by simultaneous deceleration) and by Fryer using equivalent pressures (up to 7.2 psi, or 50 kN m^{-2}) produced by lower velocities in water. In these latter experiments gross physiological effects were not seen and petechial haemorrhages only occurred at the highest levels of pressure investigated (and at sites of low surface pressure due to cavitation, an effect not present in windblast).

For brief duration (0.5 to 1.0 sec) blast exposures, Bowen and co-workers quote a 90% survival rate from 30 psi (200 kN m^{-2}) and an LD_{50} of nearly 40 psi (275 kN m^{-2}). On this basis, primary blast injury should not be a limiting factor in high speed ejection (Figure 2). This supposition is supported by some calculations made by Payne who has shown that divers from cliffs at Acapulco impact the sea (voluntarily!) at 80 ft/sec. 47 kt into water is equivalent to 1,330 kt in air at sea level, and subjects the diver, initially, to a Q force of 44 psi (308 kN m^{-2}).

Of more concern is the effect of ram pressure on personal equipment. The frequency of helmet loss (US figures give 50% at 500 kt) is accounted for by a recently measured aerodynamic lifting moment of 460 lb (208 kg) at 600 kt. Note that the neck strap of current RAF helmets breaks at around 350 lb. In addition, oxygen hoses, masks, life preserver stoles, pockets and so on, are all very vulnerable to destruction from high levels of windblast.

Windblast - flail injury

From equation (1) above, it is apparent that, unless the limbs have identical area to weight ratios and similar drag coefficients to the torso, differential forces will be produced. The situation is made worse by the ejection seat which adds mass to the torso without greatly affecting its frontal area. Thus, when exposed to wind-drag, limbs will decelerate more rapidly than the torso. Two mechanisms of injury occur. First, limbs may be forced beyond their normal range of movement, so damaging joints and causing dislocation, fracture dislocation, and ligamentous injury. Second, limbs may be brought up sharply against a solid part of the seat structure so that bones are fractured. In the absence of leg restraint the femur is particularly vulnerable to this injury mechanism.

Forces tending to displace limbs were measured by Fryer, and his results have recently been confirmed by wind-tunnel experiments. For example, there is an outwards acting force on the knees of 108 lb (50 kg) at 400 kt and this is trebled on the leeward knee at a yaw angle of 30°. Outward forces on the arm are lower - 81 lb (37 kg) at 400 kt. As would be expected, the backwards acting force on the arms is greater - 189 lb (86 kg) at 400 kt, and this force decreases in yaw. All these forces increase with the square of the indicated airspeed and forces too large to be opposed by muscle action are readily attained in high speed ejection. The incidence of flail injury would, therefore, be expected to rise sharply with ejection speed and this prediction is borne out in practice (Figure 3). In non-combat ejections, major flail injury has occurred with the following frequency: USAF, 3.4%; FAF, 12.5%; SAF, 5.4%; RAF, 5.9%. Average ejection speeds in these series were around 200 kt. Ejection speeds increase markedly in combat situations and US experience in South East Asia has shown average speeds at ejection of 388 kt for USAF POW's and 438 kt for USN POW's. Major flail injury occurred in 25% and 34% respectively, and since many ejectees were missing - and probably injured - the real incidence could have been as high as 70%. With current systems the risk of major flail injury at an ejection speed of 700 kt is estimated to be 100% (Figure 3).
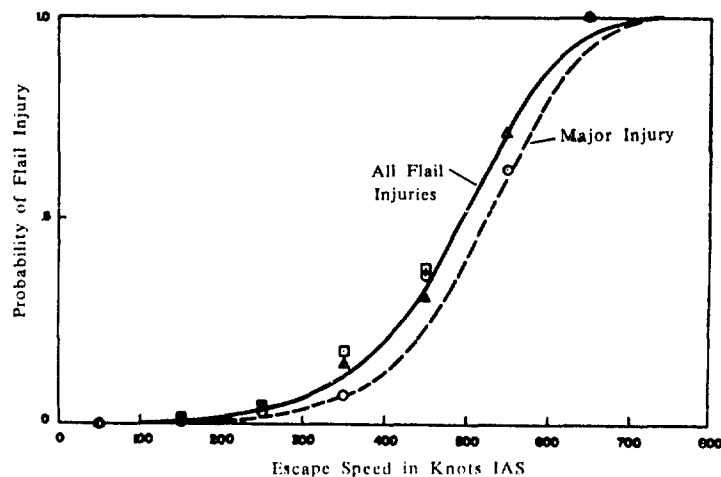

FIGURE 3. Effect of airspeed at ejection on the incidence of flail injury. Data is from USAF, USN and RAF ejections.

Head flail is less of a problem provided that the seat remains stable, but consciousness was lost (due to head flail?) in 4 of the 23 FAF ejections referred to above. In 940 USAF non-combat ejections, head and neck injuries occurred in 21 cases, whereas upper limbs were injured in 64, and lower limbs in 115.

Roughly similar distributions are seen in other series. At current ejection speeds, head restraint may be adequately obtained by the provision of mating contours between helmet and headrest. However, head flail has the potential to cause fatal brain and cervical cord injury.

Protection from limb flail injury may be achieved in three ways. The first consists of trussing the ejectee so that no independent motions of limbs can occur. The second, and more acceptable, method relies on achieving a stable seat from the moment that it leaves the aircraft. In this way only simple limb restraint is needed in a single, known direction. The third solution is to dispense with the ejection seat altogether so that differential limb forces are reduced. In an ideal posture (head first into the airstream), the tolerance of the Acapulco diver could be attained without limb restraint.

Other inertial forces

Current ejection seats (with few exceptions) are inherently unstable and tend to pitch back at high ejection speeds. Once some pitch, or yaw, has developed (due to small aerodynamic off-balance forces) the motion rapidly builds up so that the seat may tumble, or spin, over several revolutions, at rates of up to 180 rpm. The forces which lead to these motions are again proportional to the square of the indicated air speed. Seat motion of this nature has two consequences. First, inertial forces are developed which may be tangential or centrifugal. Centrifugal force increases with exposure time as the rotational speed builds up, and its effect on the seat occupant depends upon the location of the centre of rotation. Spun about the heart, venous return will be severely impaired whilst the head will be subjected to $-Gz$ and the legs to $+Gz$ forces. A head 24 in (600 mm) from the centre of rotation would be subjected to -22 Gz at 180 rpm. Unconsciousness has been produced experimentally by a ten second exposure to 160 rpm, but in practice the duration of exposure (at this stage in the escape sequence) is too brief for significant fluid shifts to occur. The main problem of these motions is that limbs, or head, may be displaced and subjected to wind blast from any direction, so that the risk of flail injury is greatly increased. In addition, parachutes and drogues may become entangled when deployed.

A second effect of seat instability may also have serious consequences. If the seat is not aligned at the time of drogue parachute deployment, very high snatch loads may be produced along axes other than the $+Gz$. These forces, particularly if the seat has yawed through $90°$, could cause neck injury, or concussion due to high angular acceleration of the head. Such injuries have been seen, but are not common. However, as ejection speeds increase, and in particular as the delay between ejection and drogue parachute deployment is reduced to improve the low altitude performance of the escape system, such injuries must be expected to increase in frequency. Again, the remedy is to ensure that the seat is stabilised from the moment that it separates from the aircraft. This stabilisation can be (and has been) achieved aerodynamically.

Parachute opening

It has been stated recently that major injury due to parachute deployment only occurs when mechanisms designed to prevent operation at excessive speed, or altitude, have failed. The most likely injury mechanism is a snatch load on the neck, particularly if the body is incorrectly aligned, and this could produce cervical vertebral fracture or other neck injury, or concussion. Neck injuries do occur in ejection, but the incidence is low and such injuries as there are may have developed at any stage in the ejection sequence and are difficult to relate specifically to parachute deployment. Thus, there were two neck injuries in a series of 113 ejections from A-4 aircraft and a further two in 40 ejections from A-5 aircraft. Death due to atlanto-occipital separation has also been seen when a main parachute was deployed accidentally at high altitude.

A parachute must travel a distance equal to 6-8 times its diameter before becoming fully inflated. Inflation time decreases, and opening shock increases, therefore, with velocity. Free fall occurs at an effectively constant IAS so that the true velocity change increases with altitude. In addition, canopies inflate more rapidly with increasing altitude.

A current problem area concerns high-speed, low-level ejection where an excessive (or even adequate) delay between ejection and main parachute opening leads to a potentially fatal loss in altitude. Thus, deployment of the drogue parachute must be obtained early, when seat velocity is still high. If this occurs with an adverse body attitude, neck injury is possible. There seems little doubt that the use of a ballistic spreader gun to reduce inflation time of the main parachute has been associated with neck injury. Thus, in recent ejections from the two aircraft types referred to above, but with the use of a spreader gun, there have been 9 injuries in 74 ejections from the A-4 and 5 out of 10 (two of them fatal) from the A-5 aircraft. A possible mechanism is that use of the spreader gun causes opening forces to rise and be maintained early in the inflation, before the body has become correctly aligned.

Landing injury

Between 30 and 40% of ejection injuries may result from landing. Whilst ankle injuries can be attributed directly to landing, spinal injury could be the result of ejection forces, or landing, and it is difficult to differentiate between these two mechanisms. Indeed, the distribution of spinal injuries in parachutists is very similar to that of ejectees, except that the spread of fractures above T11 is lacking. However, since landing injury is unrelated to ejection speed, it is not a limiting factor in high-speed ejection and will not be considered further.

CONCLUSIONS

Many of the potentially injurious forces developed during the ejection sequence are increased by ejection speed, some of them by the square of the indicated airspeed. However, tolerance to high-speed ejection may be greater than the 600 kt hitherto accepted and, with correct body alignment, may even be double this figure. For this aim to be realised, research and development must first be directed towards the achievement of a stable seat trajectory from the instant of separation from the aircraft.

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It is not intended to provide a comprehensive list of references to all the facts which have been quoted. However, most of them may be found in recent AGARD publications, in particular:-

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AGARD Advisory Report No. 72 on 'Spinal Injury after Ejection' by R. Auffret and R.P. Delahaye, Feb. 1975.

Readers are also referred to the following two publications:

AGARD Conference Proceedings No. 88 on 'Linear Acceleration of Impact-Type'. Ed. D.H. Glaister.

AGARD Conference Proceedings No. 134 on 'Escape Problems and Manoeuvres in Combat Aircraft', Ed. W.L. Jones. Feb. 1974.

PRINCIPLES AND PROBLEMS OF HIGH SPEED EJECTION

by

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SUMMARY

This paper describes the principles of ejection - to recover aircrew uninjured, which is best achieved by the use of as simple an escape system as technically possible. Once the system has been initiated all sequences automatically follow and there is no further action required by the ejectee until he is descending on a fully deployed parachute. The hazards of ejection and the development of the open ejection seat system up to the maximal capability are briefly described. The sequences of ejection on a typical Martin Baker Aircraft escape system are outlined to stress the simplicity, and therefore technical reliability, of this system as used in the majority of Service aircraft in the UK Services.

This paper should more aptly have been entitled "The Principles of Ejection and the Problems of High Speed Ejection". The principles must be applied right across the capability range of an open escape system to achieve, in the one operating mode, escape at zero speed with a high sink rate and at an adverse attitude to escape at maximum speed at low level. The current requirement is for escape up to 650 knots.

Firstly the Principles:

1. To recover aircrew by means of an escape system without injury to their persons over the whole flight range of an aircraft.

2. That the escape system must be as simple as technically possible.

3. That the escape system must be fully integrated so that it will react, in minimal time to a single simple triggering system.

4. That the need to communicate verbally, or by any other means, the need for the crew to eject be eliminated entirely from the system and that where necessary a system of Command ejection be accepted.

The need to recover aircrew wholly uninjured is an ideal. All the sequences of ejection are potentially traumatic. Recent Royal Air Force experience suggests that under peace time flying conditions 28% of aircrew are capable of being returned to full flying within seven days. It is a standard procedure in the Royal Air Force that all aircrew who have ejected are examined by a Consultant in Orthopaedics and are subjected to full spinal X-ray within twenty four hours of ejection; and these procedures occupy the greater part of one to three days depending on the availability of facilities, so that a return to full flying within days is acceptable. Minor injury during the sequences of ejection prevented a return to full flying in a further 8% of ejections. Major ejection injury including spinal injury occurred in 50% and landing injury in 8%.

The design of an escape system, which must include the clearance of the ejection path by removal or destruction of the cockpit canopy and by the retraction of the control column or other equipment, such as navigational devices and weapon sights, from the ejection path, must depend on the design, role and performance of the aircraft. Modern developments have considerably extended the flight capability of some aircraft types into a very low, even negative, speed range which may be associated with high vertical sink rates and into higher speed ranges not previously considered to be safe for an open ejection seat system. The now obsolete 'V' bombers of the Royal Air Force were originally intended to have capsule escape systems but this was technically not possible in the late 40's and early 50's. The great advantage of the module or capsule is that it provides vital protection against air blast effects in the high speed range but the problems of separating and controlling the module or capsule are such that these have not infrequently been replaced by a conventional open seat system.

The earliest ejection seat system was simply a device to separate the crew from the aircraft. This overcame the problem of climbing out of the cockpit or of finding the way to an escape hatch or door. The crew still had manually to jettison the cockpit canopy, to fire their seat by a face blind, no alternative seat pan handle was fitted at this time, manually to operate their seat harness release and manually to deploy their parachute canopy. All this took time and the earliest ejection system capability did not always exceed manual escape capability but at least separation from the aircraft, a major cause of failure to escape in the 1939-45 conflict, was eliminated. Later fully automatic and fully integrated systems were introduced and with these escape capability increased very rapidly and by the late 1950's most aircraft in Royal Navy and Royal Air Force service were equipped with a system capable of recovering aircrew at a speed in excess of 90 knots with the aircraft level, at ground level. Some systems, however, still had major weakness in escape in flight in that the time delays required for whole system operation were excessively long. The linkage of cockpit canopy jettison to initiation of the seat system eliminated an additional vital action and was known as SLE - single lever ejection. Where the cockpit canopy must be jettisoned before the seat can be fired a time delay must be included at the primary breech and in some systems this time delay was initiated only by the separating cockpit canopy, so that if this canopy failed to go the ejection could not proceed. Initially most of these time delays were of one second and the time delays on the seat system sequences were also longer - up to five seconds

for automatic release. This was an era of development and time delays were progressively decreased as a result of operational experience, engineering development and the critical examination of escape systems used for all types of aircraft of the day. Barometrically controlled time delays are necessary to prevent too early separation from an ejected seat, as this could produce parachute entanglement with the seat system and parachute deployment damage and excessive speed or at excessive altitude. In some aircraft seat initiation operates the canopy jettison system but ejection gun breech initiation is prevented until the departing cockpit canopy has removed a restrictor from the main gun breech mechanism after which an additional pull on the initiating mechanism is required to extract the freed main gun sear. Ejection experience suggests that the canopy jettison and breech initiating pulls are indistinguishable. In other aircraft ejection initiation operates the canopy jettison system and starts a time delay unit in the ejection gun breech, but if the canopy does not jettison the gun will fire at completion of the time delay and the ejection will be through the retained cockpit canopy. Ejection through a separating cockpit canopy is likely to be highly hazardous. Intentional through the cockpit canopy ejection was initially accidental but later became routine from a number of aircraft and had the great advantage of saving time. Through cockpit canopy ejection has always been more hazardous than ejection after cockpit canopy jettison, producing a very much higher incidence of spinal injury and a high incidence of equipment damage which has been prejudicial to ultimate survival. Therefore an alternative method of breaking the cockpit canopy was desirable and research with cord explosives has resulted in the application of Miniature Detonating Cord, MDC, to the inside of the canopy. This cord contains an explosive contained within a tube which totally disintegrates when fired. At the present time the only material which can be used for this purpose is lead. A thin lead tube containing explosive is backed by two layers of thin lead foil and is enclosed in a polyolefin tube and rolled to a D shape with the foil backing in the curve of the D. This is stuck straight side of the D outwards on the inside of the cockpit transparency in a pattern designed to produce maximal fragmentation of the cockpit canopy when the MDC is fired by initiation of a detonator on upward seat movement or manually for emergency ground egress, or for rescue from the outside of the aircraft. MDC cord is applied to the central area through which the pilot or crew will be ejected and also around the periphera of the canopy. The lead in the lead tubing and the lead of the lead backing will inevitably react onto the aircrew and tends to be focused by the canopy curvatures. Some additional protection must therefore be provided to prevent this lead splatter reaching the eyes or damaging the stole of the life preserver or other equipment.

The timing of the sequences of ejection has varied through the development period of the last twenty five years. Initially timings were long to allow the drogue system time to align the seat before separation and parachute extraction, but the evolution of the dual drogue system and high energy drogue bullet and the need for more rapid system function resulted in progressive reduction in the time delays, but the increase in seat capability provided by the addition of a rocket pack to apply sustained thrust after seat/aircraft separation, in order to increase seat height and trajectory, resulted in an increase in the time delay in the BCDU to 2¼ seconds from the normal 1¼ seconds, but the G stop was removed. Timing at adverse attitudes can become very critical and at low altitude the addition of rocket thrust can adversely affect ejection capability. This is an area which may offer improvement in the next few years as the efflux from the rocket pack could, perhaps, be controlled so that the line of thrust to the centre of gravity of the seat/man system could be controlled to vector the seat into an altitude gaining trajectory. The ability to select a long or a short time delay to seat man separation has existed for years, this being determined by Q sensing, but the addition of alternatives to seat system functions adds complexity and can only be acceptable if such systems are simple and well proven and if the next-in-sequence system automatically provides a back up against single system failure. In the design of British Escape systems the main principle has been SIMPLICITY for RELIABILITY. Complexity has been avoided as this leads to more difficult servicing and thus to a less reliable system.

The mechanics of ejection are simple. Ejection initiation may be by the use of the seat pan handle for preference - for preference because this is the control most easy to reach and to activate in an emergency. It also positions the hands and the arms inboard of the seat to reduce the possibility of elbow scuffing in ejection for narrow cockpits or through the cockpit canopy even though this may be fragmented by MDC. A face blind has advantages when time is not critical, eg. at altitude and when speed can be turned into altitude, as it helps to retain the head and head equipment during exposure to high speed air blast, but it cannot be recommended for any aircrew initiating ejection after the cockpit canopy has been jettisoned either manually or by the earlier ejection of another crew member as the airblast may then displace the hands rearwards and so make face blind contact more difficult or the airblast may displace the face blind from its stowage which displacement will not normally produce initiation. The precise sequences following initiation vary from aircraft to aircraft depending on whether the ejection is through the cockpit canopy, broken or not by MDC, or whether the canopy must be jettisoned before ejection can follow. The sequences of ejection are triggered by upward seat movement:

i Ejection initiation may also automatically lower the helmet visor and may also fire MDC. (Buccaneer, Jet Provost 5).

ii After one inch of seat movement upwards MDC may be fired. (Harrier FR9 Nav).

iii Auto-tone is turned on.

iv The aircraft to seat portion of the Personal Equipment Connector (PEC) disconnects and emergency oxygen is turned on.

v Static rods on the rear bulkhead trigger the drogue gun Time Delay Unit and the Barometrically Controlled Time Delay Unit (BCTDU), and the Rocket pack initiating cable starts to extend.

vi   The upward movement of the seat pulls the leg restraint lines through the snubbers as the legs flex at the knee and hold the legs back into the restrained position. Arm restraint may also be tensioned at the same time.

vii   At full tension (900 lbs) the leg line rivets break, separating the leg restraint line from the cockpit floor, and arm restraint is also separated.

viii At full ejection gun extension the rocket firing cable is also fully extended, extracts the firing sear and fires the rocket pack.

ix   The drogue gun fires at completion of the run of its Time Delay, ($\frac{1}{2}$ - 1 second).

x   The drogues are extracted and seat alignment commences.

xi   Above barometric capsule height (10,000 feet or 5,000 metres) the BCTDU will be held. Below barometric height it runs for its Time Delay (1$\frac{1}{2}$ - 2$\frac{1}{2}$ seconds), and then sequentially releases (a) the drogues from the scissor release (b) the seat locks and leg restraint lines and on most seats the man to seat portion of the personal equipment connector.

xii   The drogues with pull transferred to the extraction line open the parachute container, extract and stream the parachute which then deploys. Deployment may be assisted at low speeds by anti-squid lines which carry the load between the pulling drogues and the parachute risers and thus allow the periphera of the canopy and the associated shroud lines to separate and inflate quickly, and so the parachute to deploy more rapidly. At higher speeds - in excess of about 200 knots - the anti-squid lines break so that seat loading is reduced. Taschengurts also produce loops of periphera which act as scoops to separate the periphera rapidly and so assist rapid parachute canopy deployment.

xiii As the parachute deploys the harness is pulled away from the seat to which it is retained during parachute extraction by the sticker straps, these being desirable to prevent seat parachute interference.

xiv   The seat falls away and the crewman descends on his deployed parachute.

xv   On some seats the man portion of the PEC is separated by a lanyard from the life preserver at seat man separation.

The mechanism used to produce the sequences of ejection is very reliable. The pitch, yaw and rotation of the seat immediately after separation from the aircraft may produce very unpleasant vestibular sensations which may suggest that the alignment system has failed. Such sensations must be regarded as normal and should be ignored.

Thus the modern escape system has developed into a simple, integrated system requiring only one action by aircrew up to full parachute deployment. The use of Command Ejection is a valuable method of saving time. Command Ejection is the automatic ejection of one crew member by the initiation of ejection by another and this may have to involve some additional time delay to ensure that individual escape systems do not collide or interact and to allow the commanded crewman time for the system automatically to position him for ejection. In the past it has been traditional that the Captain of an aircraft should be the last to leave and this was reasonable if he was trying to control the aircraft to assist his crew to abandon, but in modern aircraft with individual escape by ejection this no longer applies, and the need for all the crew to be clear of the aircraft as rapidly as possible after the Captain has declared an emergency requiring abandonment makes Command Ejection the preferred method. It completely eliminates the communication time, and communication may be difficult to impossible under conditions existing in the aircraft. It also eliminates the crew reactiontime. In the past Command Ejection systems have been excessively complex, to the extent that they have, in some aircraft, been de-activated. Sequenced ejection, the timing or holding of one individually initiated ejection so that collision with another individually initiated ejection cannot occur is sometimes necessary and is also complex as it must work either way. This Institute has developed a philosophy that the pilot, who alone is aware of the precise behaviour of his aircraft, should, when he so decides, initiate his own ejection without the need to communicate this to his crew when conditions are critical. The IAM system uses the upward movement of the pilot's seat to return the Observer or Navigator to an acceptable erect attitude by tensioning his shoulder restraint harnesses and after a minimal time delay, initiated by the pilot's ejection initiation, the Observer or Navigator is ejected. The Observer or Navigator still retains his normal ejection capability with individual initiation. The system is capable, with minor modification, of being used in reverse, in which case the Observer or Navigator would intentionally select Reverse Command ON so that his ejection initiation could eject a fully restrained unconscious or otherwise incapacitated pilot. The system has the very great advantage of extreme simplicity and of requiring no pre-flight or in-flight action other than the removal of a sear pin paired to the main gun sear pin. The adoption of this system in RAF and RN tandem aircraft could have produced nothing but benefit if applied retrospectively to ejection experience over the last four years. It would have saved at least two lives lost through the waste of time to communicate the need to eject and by collision with part of another aircraft escape system. It would also have prevented a near collision and have prevented a near failure when a canopy failed to jettison due to aerodynamic loading.

To revert to the Principles - SIMPLICITY, RELIABILITY with RAPIDITY are the keynotes for surviveable ejection.

High speed ejection poses problems all associated with the ability of man to tolerate high speed air blast of short duration. These effects are maximal at low level, $\frac{1}{2}roV^2$ where ro is the air density and V the speed applies and the effects increase dramatically with the increase in V^2. Whenever possible speed should be converted into altitude but time is so critical that this has seldom been possible in RAF

ejection experience and appears not to have been practical, or perhaps desirable, in USAF/USN ejection experience in South East Asia. In the period 1968-1974 a TAS of 340 knots was exceeded on only three occasions in about 140 ejections and serious air blast and limb flail injuries have not occurred. The loss of a protective helmet cannot always be attributable to air blast but these have been lost in high speed ejections and blast injury to the eyes has occurred, subconjunctival haemorrhage resolving in 12-15 days. Air blast damage to equipment has been minimal but test experience suggests that some scuffing of Immersion Coverall neck seals may have been produced by air blast on ejection and not by contact with the life preserver or parachute risers as originally suggested.

US ejection experience in South East Asia has put the speed of ejection up by about 100 knots and a high percentage of ejections were occurring at speeds in excess of 400 knots. This has produced a much higher incidence of upper and lower limb flailing involving injury and limb fracture, and this was a primary cause for aircrew being unable to evade capture and of their inability to survive subsequent to water entry.

Protection against the effects of air blast was first provided on the Mk 8 ejection seat for the TSR 2. Positive shoulder harness retraction preceded head retraction and retention. Leg restraint was conventional but arm restraint was also provided, cords being applied in tunnels on the outer coverall from shoulder to wrist, the cords being tensioned by upward seat movement. The head retraction cords were severed before seat man separation and leg and arm restraint were released conventionally. The TSR 2 seat was extensively tested but was never used in anger. On the Mk 10 seat for the MRCA and Hawk leg restraint is again conventional and arm restraint is similar to that on the Mk 8 seat. Head restraint is not applied but the head will be located in a shaped headrest into which the enclosed helmet will locate. The visor of this helmet will be automatically closed at ejection initiation and the seat also provide automatic shoulder harness retraction. Testing of the system and associated flying clothing assemblies has revealed weaknesses which suggest that ejection in excess of 600 knots on an open seat is likely to be a traumatic experience but should not be anything like as traumatic as the alternative.

Current statistics suggest that the majority of ejections will continue to be at lowish speeds and at lowish altitudes. Some alternative time delays may become necessary to enable the system to function effectively at both ends of the speed scale and these must be capable of failing safe, so that should one mode fail the next will automatically operate.

CURRENT AND FUTURE ESCAPE SYSTEMS

by

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INTRODUCTION

The role of escape systems in fixed wing military aircraft is now well established. Almost all combat fixed wing aircraft in NATO countries are equipped with ejection seats and considerable effort is spent on improving the performance of these seats for future aircraft. The subject is vast and this article will be limited to describing some of those areas where current escape systems are deficient and some ways in which future systems seek to overcome those deficiencies.

ESCAPE PATH CLEARANCE

Before aircrew can escape a clear path must be provided as quickly and safely as possible. Cockpit canopies can be removed manually, by pneumatic or hydraulic pressure or by pyrotechnic cartridges. All these methods rely to some extent upon the assistance of wind blast to remove the canopy. Under conditions of stall, spin or high sink rates, airspeed is low and the clearance of the canopy will be slower at a time when the available time for safe ejection is least. Some aircraft systems avoid this problem by ejecting the crewman in his ejection seat through the canopy material. However, this brings in its train the risk of head and neck injury. For VTOL aircraft, where any delay could be fatal, the canopy transparency is dispersed by micro detonating cord (MDC) - a thin cord of explosive applied to the inside surface of the canopy. As the ejection seat starts to move, the MDC fires, fractures and fragments the canopy and ejects the particles out of the ejection path. Aircraft which use stronger canopy materials would require bigger charges of MDC which would be injurious to the crew. In some of these aircraft, rocket power is used to jettison the canopy quickly, a process that is relatively independent of airspeed.

TRAJECTORY CONTROL

When escaping from aircraft at low altitude, the trajectory of the escapee must be controlled to reduce the risk of ground impact before the parachute has inflated. In most current escape systems, the ejection seat is stabilised by drogues. Where rockets are used, directional control is used to cope with differing positions of the centres of gravity of the man/seat complex. Cables attached from the seat to reel devices in the cockpit can stabilise the seat on ejection and tractor rockets can produce very stable trajectories at moderate speeds. Future escape systems are likely to employ a variety of active guidance systems for trajectory control. Gyros and fluidic sensors have already been used to drive vernier rockets to control trajectories, but the real challenge remains to produce an escape system with a trajectory that is height seeking. This system will alter the path of an escapee away from the ground. One promising proposal is to use the electrostatic gradient just above the earth as guidance for this purpose.

PARACHUTE PERFORMANCE

The aim of any escape system is to suspend the escapee below an inflated parachute as quickly and as safely as possible. Thus the trend has been to shorten time delays between ejection and parachute opening. At high speeds, this results in greater forces being imposed upon parachute and man. At altitude and high speeds the aim is to reduce speed and altitude so that the environment for the escapee is as favourable as possible. Current escape systems use time delays between escape and parachute opening fixed at the shortest allowable time based on low altitude conditions. More advanced escape systems use a variety of time delays selected from altitude and airspeed data so that the optimum delay for the exact pre-escape conditions can be used. The mechanism for the time delay can be either electronic or pyrotechnic. Other systems deploy the parachute early, but in a reefed condition, and only open the parachute fully when it is safe. A variety of devices are used to reduce parachute opening time. Perhaps the most effective of these is the anti-squid line, or pull down vent line, which increases the drag of the parachute and by relaxing the shroud lines allows the parachute to inflate more quickly. In some systems, pyrotechnic devices are used to spread the periphery of the parachute mechanically to reduce inflation time, but this can increase the forces imposed upon the escapee at high speed. Parachutes deployed and opened by mortars can also reduce parachute inflation time. The use of better designed parachutes can significantly decrease both opening time and the forces imposed without such disadvantages as higher terminal velocity or instability. These improved parachutes have a wide application in many types of escape systems.

BLAST PROTECTION

As aircraft performance increases, the pre-ejection speed rises and the blast effects on the escapee become more serious. The ejection seat is useful as a splint for the torso against Q force at high speed, but it provides little protection for the limbs, and in some cases, the head. Leg restraint devices are used with many ejection seats to restrain the legs and prevent flail. Data from returned prisoners of war in South East Asia confirm that hostilities produce an increase in the speed at ejection, that these higher speeds produce more limb injuries and that limb injuries seriously affect chances of evading the enemy. For modern high speed combat aircraft more effective limb restraint devices are proposed and restraint of the arms may also be used in a manner similar to that of leg restraint. Other forms of arm restraint have been proposed, such as paddles and nets outboard of the arms. Time will tell which are the more effective.

Head movement and flail is a serious problem at high speed as head injuries would considerably reduce the chances of survival. Many methods have been proposed, but the simplest, a cord device attached to the helmet, has been rejected because of the disadvantages of the connection and disconnection before and after each sortie, tension of the cords on the helmet and possible limitation of head movement in flight. Mechanically deployed face screens tensioned by airblast remain a strong possibility, while matching contours of helmet and headrest show some promise considering the simplicity of the system. Inflatable devices around the head and neck are other concepts that deserve investigation. The ultimate in protection is the capsular form of escape where the crew are cocooned from the moment of escape until ground or water is reached. At very high speeds, capsules have a distinct advantage, but the weight and cost penalties are enormous.

If some degree of injury can be accepted in the very few high speed escapes which occur, then the open ejection seat remains the most effective means of escape. Success rates from a wide variety of sources confirm the efficiency of the ejection seat which has now reached a high degree of sophistication.

However, some profitable avenues for research in escape systems remain. These include improvement of tractor rockets or ballistic tractor devices for high speed conditions, the development of an effective height seeking trajectory control, improved limb and head restraints and the extension of assisted escape systems to helicopters.

HELICOPTER ESCAPE AND SURVIVABILITY

by

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Most fixed wing combat aircraft are fitted with ejection seats. Most other aircraft carry parachutes and it is only in transport aircraft or derivatives from transport types that no escape system is provided.

Helicopters are not so equipped and parachutes are only carried on some test flights. However, a recent survey of British military aircraft accidents has shown that the fatality rate for helicopters is almost 3 times greater than that for fixed wing aircraft. Even if no escape system had been fitted to the fixed wing aircraft in the survey, the fatality rate for helicopters would still have been higher. Thus, rotary wing aircraft seem more hazardous than fixed wing aircraft.

Accidents will always be with us and as helicopters will be used more and more, it would seem logical that the case for escape from helicopters in flight be re-examined. From the point of view of cost effectiveness, the US Army have discovered that it costs 2 to 3 times more to replace one crewman than it does to replace the helicopter.

At present, only auto-rotation can be used for descent following an emergency in flight. But auto-rotation is designed for only one type of emergency, namely power loss, and it cannot be used under conditions of main or tail rotor failure, mid-air collision, fire or explosion, transmission freeze-up, pilot error or disorientation. In addition, helicopters frequently fly at altitudes and speeds and over terrain where auto-rotation cannot be used. In the British survey of accidents, only 20% were within the parameters for safe auto-rotation. Thus auto-rotation is not the answer.

If an escape system of some sort had been available, the helicopter fatality rate could have been halved. Data from the USN, USMC and US Army accidents show that between 43% and 47% of fatalities in helicopter accidents can be avoided if escape systems are provided; the German and Italian figures also agree. The surveys also show that the majority of fatal helicopter accidents occur at low speed (below 100 knots), at low altitude (75% below 500 feet, 30% below 100 feet), and in a nearly level attitude.

Recently, an international study group set up by the NATO Advisory Group for Aeronautical Research and Development (AGARD) has been reviewing accident statistics and possible methods of in-flight escape from helicopters. The Study Group confirmed that there was a good case for in-flight escape and concluded that the following methods were the most fruitful avenues of research:

1. For retrofit onto existing helicopters.

a. Manual bale-out. Individual parachutes are the simplest form of escape system and carry little cost, weight, space and development time penalties but are limited in performance as they cannot be used at low altitude. However, had parachutes been worn some 22 lives could have been saves in 10 years in the UK alone. The Study Group recommended that all helicopter crews carry parachutes always.

b. Sideways extraction (Fig 1). Here a small rocket is used to pull the crewman sideways out of
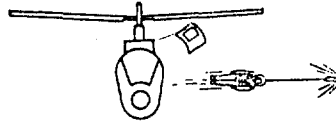

Fig 1. - Sideways extraction.

the cockpit by means of a nylon strap attached to his harness. When clear of the rotor, a parachute is opened and the rocket is detached. This method could also be used for crew in the rear of a helicopter. The system could offer better performance at altitude but will never work at ground level. It requires some modifications to the helicopter and some development, although the system is at present in use in some American aircraft. The Study Group recommended that research be started immediately on this system.

2. For Helicopters on the drawing board but not built.

a. Upward extraction or ejection. These methods (Fig 2 and 3) require that the main rotor be removed before escape. It is impractical to stop, slow or
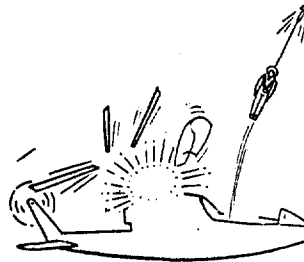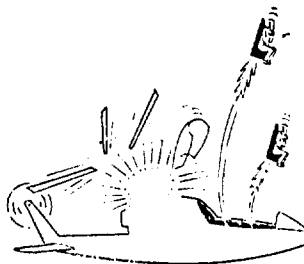

Fig 2. - Upward extraction.

Fig 3. - Upward ejection.

fold the rotor and explosive removal of the blades individually or of the disc in toto is the only practical method. When the rotor is removed, a lightweight ejection seat or an extractor rocket can be used. American research has already shown that this can be done reliably but there would still be some development required.

b. Sideways ejection with an L-shaped trajectory (Fig 4). To avoid having to remove the rotor, the

crewmen is ejected first sideways and then (when
clear of the rotor disc) upwards. Tests have
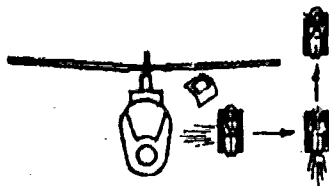already shown this to be feasible by means of 2

Fig 4. - L-shaped ejection.

rockets firing in sequence and it is a means of
improving the performance of the system at low level
while leaving the rotor intact. The Study Group
recommended that both upward ejection with rotor
removal and sideways ejection schemes should be
developed for future helicopters.

3.   For helicopters not yet conceived.

     The Study Group recommended that all new
helicopters incorporate in-flight escape from
conception. Here the best choice is probably by
means of an escape capsule (Fig 5). In this method,
the whole of the aircraft, part of the aircraft, or
even just the cockpit is lowered by parachutes.
The capsule includes all the occupants but entails
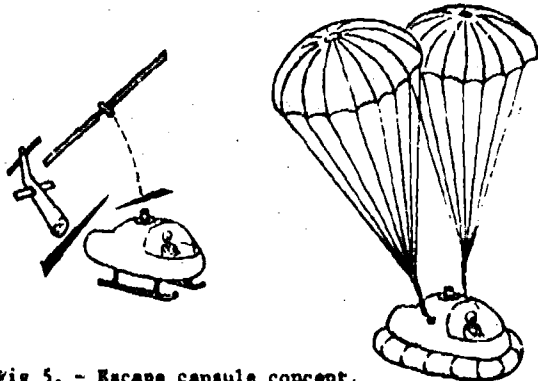considerable development and a weight penalty.

Fig 5. - Escape capsule concept.

     There are many other methods and variations
that have been considered, and helicopter aircrew
may have ideas of their own. The important point
is that if no research is done, no method will be
produced at all and helicopter crews will never
enjoy the protection that most fixed wing aircrew
now have.

THE PHYSIOLOGY OF HIGH G PROTECTION

by

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The introduction of several new combat aircraft which have the structural integrity and the engine power to execute manoeuvres at high levels of acceleration for considerable periods of time reintroduces the concept that certain operations, particularly air to air combat, may be physiologically limited rather than limited by aircraft design parameters. An acceleration level of 9G sustained for 60 seconds has been suggested as a point to which acceleration protection should be aimed, although higher G levels for shorter periods of time can be expected.

For some decades the accepted methods by which the physiological compensatory mechanisms of the pilot are enhanced are:

1. The pneumatic anti G suit, increasing peripheral vascular resistance and preventing venous pooling in the lower limbs and

2. Voluntary measures such as muscle tensing and the M1 manoeuvre, increasing venous return, and raising intra-thoracic pressure and hence systemic blood pressure.

These measures have been adequate as the physiological limits of their effectiveness have, for the most part, been similar to airframe limits in the 6-7G level. With this amount of protection a pilot, seated in a conventional ejector seat, can remain conscious with adequate vision. This indicates that a mean blood pressure at the eye greater than the intra ocular pressure is being maintained. The pilot is required to work hard at muscle tensing which in itself may be fatiguing and some performance decrement may result. Exposures to higher acceleration levels indicate that above the 6G level, a man conventionally protected is in increasing danger of visual loss and loss of consciousness. In a recent joint United States Air Force and Royal Air Force study (1) twelve experienced centrifuge subjects were subjected to +8G_z for two periods of one minute each. They were equipped with anti G suits and performed the M1 manoeuvre. Of the possible total of twenty four minutes spent at 8G, only seventeen minutes were achieved due to loss of vision or consciousness. Additionally, there is some evidence, from animal studies, that exposure to high, sustained acceleration may result in a degree of cardiac damage.

In order to maintain adequate vision the mean blood pressure at the eye must exceed the 20-25 mm Hg intra ocular pressure and, for some margin of safety, a pressure in the order of 50 mm Hg would be acceptable. At +8G_z, a further 190 mm Hg pressure is required at heart level simply to overcome the hydrostatic pressure drop resulting from the 30 cm vertical distance between heart and eye. Therefore, at heart level a pressure of 240 mm Hg must be developed. This is at least a twofold increase over the normal value. At this high level of arterial blood pressure the aortic baroreceptors will be exposed to a pressure considerably in excess of that which is normal and they will function to reduce the blood pressure. At this level of acceleration therefore, maintaining venous return alone, as a conventional anti G suit does, is likely to have little, if any, effect. The problem at high G levels centres around this great disparity of pressures at heart and eye level. Protection must be centred around attempting to reduce this difference.

The reclining seat is perhaps the most practical method at the moment. This method of reducing the effective heart to brain distance is not new and has been the subject of much discussion and experiment. By reclining the back of the pilot's seat a +G_z environment is changed to one with a combination of +G_z and +G_x.

The vertical heart to brain distance of a pilot reclined in this way is the cosine of the angle of the seat back from the vertical. Given a heart to brain distance of 30 cms when vertical, then at 66° from the vertical, the vertical heart to brain distance will be 12 cms. At this angle the blood pressure required at heart level to maintain the desirable 50 mm Hg at the eye is 120 mm Hg which should be easily maintained during acceleration. Thus, by using a reclining seat a situation which imposes a severe cardiovascular stress may be alleviated to the point where a normal blood pressure will suffice. However, a seat with a back angle of 66° from the vertical would mean a complete reappraisal of the cockpit. The forward vision from such a cockpit particularly in the landing configuration is likely to be severely restricted. One aerodynamic factor is of note in this situation. When tight turns or pulling up manoeuvres are performed the lifting surfaces of the aircraft are required to generate an increased amount of lift corresponding to the amount of G pulled. In order to do this the lifting surfaces have to be presented to the relative airflow at an increased angle of attack, i.e. the aircraft flies in a nose up attitude to the airflow. The pilot's seat is effectively reclined to the G vector by the same amount as the angle of attack has increased. In some new aircraft this ability to fly at large angles of attack may assume practical proportions in increasing G tolerance. Consider an aircraft equipped with a seat with a back angle of 60° from the vertical. This would result in a halving of heart to brain distance. If this aircraft were capable, in high G manoeuvres, of flying at a 15° increase in angle of attack then the relative back angle to the G vector would be 75° giving an effective heart to brain distance of 8 cms when a blood pressure of 120 mm Hg would be adequate for approximately 12G.

Whilst a reclining seat does result in considerable reduction in cardiovascular stress during increased acceleration the +G_z component is still significant with the result that in those areas below the heart there will still be pooling of blood and some lowering of venous return. To prevent this a conventional anti G suit would still be useful and such a suit has been shown to increase peripheral greyout thresholds even at back angles of 75° from the vertical (2).

From the cardiovascular aspect the reclining seat, when large back angles from the vertical are used, can provide a good method of providing protection. If the respiratory system is considered the situation is less promising.

A reclining seat, to be effective in relieving cardiovascular stress, subjects the pilot to a large $+G_x$ component. When subjects are exposed to $+G_z$ there is a relatively small decrease in vital capacity (VC), some 15% decrease at $+6G_z$. This is due to a reduction in inspiratory capacity, residual volume (RV) and functional residual capacity (FRC) remaining constant. Changes in regional ventilation perfusion ratio within the lung result in a fall in percentage arterial oxygen saturation to approximately 85% at $+5G_z$. Subjects exposed to $+G_x$ showed a marked fall in VC with a reduction in expiratory reserve volume (ERV) which at $+3G_x$ has virtually disappeared. Further increase in $+G_x$ produces a further reduction in VC until at $+6-7G_x$ the VC is only half the one G volume. Arterial oxygen saturation falls in a similar manner to that seen during $+G_z$ again having fallen to 85% at 5G. The reduction in VC seen during the $+G_x$ is attributed to the increased weight of the chest wall and restriction of diaphragmatic mobility by the abdominal viscera. The reduction if FRC is known to predispose to acceleration atelectasis. In order to overcome these respiratory difficulties it has been suggested that a system of positive pressure breathing should be used. Positive breathing increases systemic arterial pressure which would be an additional bonus for the pilot although the effect of diminishing venous return to the heart would need to be counteracted by further inflation of the anti G suit. The increased intra pulmonary pressure would tend to ease lifting of the chest wall increasing total lung capacity (TLC) and FRC. The increase in FRC would result in a larger number of alveoli being available for effective gas exchange and the tendency to atelectasis would be reduced particularly if the gas supplied under pressure contained some nitrogen or similar inert gas.

Thus, one possible method of high G protection involves a reclined seat, a conventional anti G suit and a positive pressure breathing facility.

The second method which might provide the degree of protection needed is water immersion. This method, again, has been appreciated for some time and has been shown to be at least partly practical in the Franks Flying Suit. During flight trials of the Franks suit in 1944 considerable protection was claimed, some pilots reporting accelerations of up to $+9G_z$ without visual symptoms. The suit was not adopted due to considerations of bulk, weight and discomfort.

The concept of water immersion is attractively simple and offers the advantage that no supplies to the suit are required in the aircraft.

In the case of total body immersion any lateral hydrostatic pressure gradient is balanced by an identical pressure outside the body thus, cerebral and retinal perfusion should remain unaffected by acceleration of any magnitude or direction. Very high accelerations, in the order of 30G, have been tolerated for short periods of time using total body immersion as protection (3). Immersion to eye level has been reported to enable a subject whose normal greycut threshold was $+3G_z$ to tolerate $+16G_z$ with no visual loss. Obviously immersion to this degree is unacceptable in aircraft but immersion from the heart level down may be feasible. In such a situation an increase in $+G_z$ would have no effect on the venous return to the heart with no pooling in the lower limbs and abdomen above that seen at $+1G_z$. Thus, the compensatory changes seen normally during unprotected acceleration exposures could be directed exclusively to maintaining cerebral blood flow. A further possibility is to increase the tonicity of the liquid surrounding the body so that the pressure exerted by the suit exceeded that created within the body by increased acceleration. This would tend to have a direct effect on the pressure at heart level and enhance venous return. A similar effect could be seen by raising the level of the liquid cover to the neck including the arms in the suit. With such a suit not only would there be a direct effect on the arterial pressure and increase in venous return with increase in G, but the hydrostatic column to be supported would be reduced from heart to brain distance to neck to brain distance, a reduction of possibly 50%. Despite the suit giving adequate protection to the systemic vasculature the pulmonary effect seen at high $+G_z$ would obviously still be present. In this situation again a pressure breathing facility would be of use. The concept of surrounding aircrew in liquid from the neck down may seem outlandish but the possibility of obtaining good G protection at high levels without major cockpit redesign is attractive, particularly as a liquid filled suit may be used for thermal conditioning in some aircraft. The anthropometric and bioengineering problems of such a suit may however, make it unattainable.

In summary, the conventional anti G suit is unlikely to provide sufficient protection at high sustained G levels. Of the two possibilities for improved protection, the reclining seat with an anti G suit and pressure breathing is probably the practical solution although the liquid filled suit has attractive features if the practical problems could be overcome.

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A COMPARISON OF RECENT ADVANCES
IN BRITISH ANTI-G SUIT DESIGN

by

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SUMMARY

Comparisons in the field of a knee length anti-G suit and an external anti-G suit, with the standard British anti-G suit worn close to the skin, are described and the results discussed.

The present form of anti-G suit used by the Royal Air Force and the Royal Navy is that worn close to the skin, separated from it by a thin undergarment. This form of garment has always been considered to provide the maximum physiological protection, the most rapid onset of protection, the minimum bulk and the minimal possibility of snagging hazard. Its disadvantages in service are:

1. The difficulties of donning and doffing - especially in haste, which usually prevents its being removed between sorties.

2. It results in the wearing of nylon close to the skin which is considered in some circles to be a hazard.

3. It is often uncomfortable when worn over an Air Ventilated Suit (AVS).

4. When worn in conjunction with long underwear, it inflicts a high degree of thermal insulation in the leg and pelvic area resulting in heat stress and sometimes considerable discomfort from sweating, not only in tropical climates but even in summer temperate regions.

British aircrew have requested in the past that consideration be given to some form of externally worn anti-G suit.

The main theoretical disadvantages of such an anti-G suit seemed to be:

1. Reduced physiological protection.

2. Less rapid response.

3. A considerably greater interaction and snagging hazard in the cockpit.

Initially therefore an anti-G suit with reduced surface coverage, attained by the exclusion of the below knee portion of the suit, was considered. Preliminary studies on the human centrifuge in the United States and at this Institute (Crossley, R.J. and Glaister, D.H. 1970; Lemon, J.H. 1970; Crossley, R.J., Lemon, J.H. and Turner, G.M. 1972) showed the mini anti-G suit, as it was called in fond memory of a female garment highly popular with the male population in recent times past, was as effective a means of protection against +G$_z$ acceleration as the full length garment. Calf pain during acceleration on the centrifuge was reported by a few subjects but was not reported by a number of pilots who wore it in flight (Reader, D.C. 1972). Crossley et al 1972, recommended that a full experimental trial should be conducted to assess the response of aircrew to the suit when it was worn during routine squadron operations. This trial was carried out in 1973/74 and was reported by Crossley, R.J., Allnutt, M.F., Harris, B., Lemon, J.H. and Turner, G.M. in March 1974.

The mini anti-G suit differs from the in service Mk 6 and 7 series in that it covers the abdomen and thighs only and as a result does not require a closure sliding fastener. It is fitted instead with a tensioning sliding fastener.

The heat load imposed is obviously less by the amount of reduced leg coverage, and whereas it still cannot be doffed very easily (ie without removing the flight coverall) it is easier to remove and to don than the full length suit.

Three sizes of suit were employed in the trial and a total of 54 subjects flying in RAF Lightning, Phantom and Gnat aircraft took part. The majority of subjects (thirty-six) were Phantom aircrew, half of whom were pilots and half navigators. The subjects used the mini anti-G suit for all operations for a period of nine weeks, reverted to their full length G suits for two weeks and then continued with the mini suit for a further period.

The subjective results of the trial are summarised as follows:

Twenty-four aircrew (45%) preferred the mini anti-G suit on all counts.

Five (9%) preferred the mini suit on the ground but thought the suits equivocal in the cockpit.

Sixteen (30%) preferred the full length suit in flight but still preferred the mini on the ground.

Four (7%) thought the suits equal on all counts.

Five (9%) preferred the full length suit.

Approximately a third of the aircrew subjective opinion was that the mini G suit gave less protection against $+G_z$ acceleration than the full length suit.

Six of the fifty-four aircrew in the trial reported calf discomfort when exposed to $+G_z$ whilst wearing the mini suit. All six were Phantom aircrew - 4 pilots and 2 navigators. Five of these described only discomfort - a feeling of fullness or a dull ache but one pilot did complain of severe pain.

Centrifuge studies suggest that pain occurs at and above $+6G_z$. A combined USAF SAM/RAF IAM centrifuge study (Crossley, R.J., Burton, R.R., Leverett, S.D. Jr., and Shubrooks, S.J. Jr. 1973) indicated that the calf pain could be prevented if the subjects tensed maximally during the acceleration. Caution is required in transferring this information to the flight situation as the exposure on the centrifuge, whilst prolonged, was not repetitive. However, the weight of available evidence suggests that calf pain occurs on exposure to $+G_z$ acceleration when wearing the mini anti-G suit only when the wearer is relaxed. It remains to be repeated, however, that significant calf discomfort did occur in the RAF trial and in a similar US flight trial of a mini anti-G suit significant calf pain was reported at 6G. It is possible that calf discomfort and pain can occur even in tensed, experienced, aircrew at accelerations of $+6G_z$ and above. Therefore the mini anti-G suit could not be recommended unequivocally in the trial report and an intensive comparative trial of the mini and full length anti-G suits in Hunter and Phantom aircraft performing high $+G_z$ manoeuvres was suggested.

After study of the above report a decision was made not to proceed further with the mini anti-G suit but to try out the concept of an external anti-G suit similar to that worn by the United States, the Federal Republic of Germany, and Italian aircrew.

The need appeared to be greatest in the case of Harrier aircrew deployed in Europe where the aircrew can spend long periods in the field at a high degree of readiness with virtually no cooling facilities. Therefore, six prototype external anti-G trousers, designed by the Ministry of Defence (Procurement Executive), were manufactured for trial by them. The trousers incorporated the same bladders as the Mark 6 and 7 series; they were adjusted and fitted by laces on the thighs and calves, and on the right and left side of the waist at the rear. The laces were covered by material closed with sliding fasteners. The trial was conducted between April and September 1974 at RAF Wildenrath with six Harrier pilots from No. 20 Squadron acting as subjects (Harris and Owen 1974).

The trousers were fitted with care, over the aircrew's normal summer aircrew equipment assembly (AEA), with of course the exception of the Mark 7D anti-G suit. Thigh and lower leg pockets were fitted to the external anti-G trouser for use in place of the aircrew coverall pockets which were occluded by the trouser.

The trial was conducted in a similar fashion to that of the mini anti-G trouser in that the six subjects wore the external trouser for eight weeks, followed by their in-service Mark 7D anti-G trouser for two weeks, and finally completed the trial wearing the external trouser again. Questionnaires were completed by all subjects one week after returning to wearing the external anti-G trouser, and again on completion of the trial.

It can be stated immediately that the garments were greeted with enthusiasm and that the trials team had some difficulty in recovering the garments from the appreciative aircrew.

The questionnaires reflected their opinion:

1. All six preferred the trial garment to their normal Mark 7D anti-G suit.

2. All six thought the external garment more comfortable than the Mark 7D airborne when uninflated, and as comfortable inflated.

3. Subjectively all subjects thought the protection against $+G_z$ accelerations to be equal to that of their Mark 7D suit. (Previous experience at RAF IAM suggests that in fact there will be a reduction in protection of approximately 0.2G.)

4. All subjects found it advantageous to remove the external trouser on the ground though not on all occasions. A particular advantage was the ability to remove the load of the in-flight documents contained in the pockets at the same time as the trousers, and then to be able to quickly don the anti-G trousers and know that all the documents were immediately available.

5. Five of the subjects felt subjectively cooler around the legs and abdomen when wearing the external trousers rather than the Mark 7D suit.

There were a number of criticisms of the trials garment. The most consistent of these was concerning the multiplicity of slide fasteners and suggestions that some might be replaced by velcro. The slide fasteners over the adjusting laces have already been replaced by an elasticated material. Lighter materials for construction of the suit were also suggested and a lightweight external anti-G suit - adjusted by velcro gussets which is in current use by the United States Marine Corps, was demonstrated by an exchange officer.

To summarise - the results of the trial showed that all six subjects preferred the external anti-G trousers to the Mark 7D anti-G suit which they are currently wearing and that their preference was strong. The main advantage of the external trouser is the facility to remove them between sorties and don them immediately prior to walking out to the aircraft thus relieving the aircrew of some weight and thermal discomfort.

These advantages apply in the main to tropical and temperate summer conditions. However, in temperate winter conditions British aircrew normally wear an immersion coverall, often over insulating undergarments. It would seem unlikely that an externally worn anti-G trouser would provide adequate protection against +G_z accelerations in such circumstances. The combination would also be very bulky. The trial report recommended that the acceptability of the use of the external anti-G trouser under or over an immersion coverall, be carried out.

A preliminary aircrew clothing integration exercise wearing the external trouser under a Mark 10 immersion coverall suggested that it might be possible to wear the trouser in such a fashion if minor improvements to reduce its bulk were carried out. A study of the external anti-G trouser worn over a prototype single layer immersion coverall which is to be carried out on the centrifuge at the RAF Institute of Aviation Medicine, has just commenced. Meanwhile the trial of the external anti-G trouser in the Harrier aircraft has been considered sufficiently successful to initiate further trials of its use in other aircraft. This may in turn give rise to the need for further studies on the centrifuge of the use of the external anti-G trouser at high levels of +G_z acceleration and in combination with various AEA's.

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THERMAL PROBLEMS IN MILITARY AIR OPERATIONS

by

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REVIEW AND INTRODUCTION

Military air operations may be conducted over the full range of natural environments from extreme arctic cold to tropical heat. The present emphasis on mobility, with a strong tendency to reduce the number of overseas bases, has diminished the extent of direct experience of environmental extremes. The result is that physiological acclimatization is less widespread among military forces and behavioural adaptations, so markedly affected by experience and training are less readily available.

The effects of natural environment extremes are most pronounced on the ground activity side of air operations and in the survival situation. In contrast to the effort expended on behalf of aircrew the problems of ground crew have received relatively little study. The situation may be with us soon in which the overall effectiveness of air power in operations under adverse environmental conditions is limited more by the ability of ground crews to maintain, refuel and rearm aircraft than by the ability of aircrew to fly them. The imposition of chemical protection techniques is likely to reinforce this position.

Nevertheless the present course is primarily concerned with tne problems of aircrew and the present session on thermal problems will be mostly concerned with the flight environment. The three papers deal with operations in cold environments, thermal problems in high performance aircraft and personal conditioning. It would not be possible in the time available to deal comprehensively with the whole thermal research programme at the Institute and the three papers selected concentrate heavily on the applied problems in the RAF. Our basic research is mostly published in the open literature and therefore available for those with a special interest.

Thermal problems in the flight environment are only partly and mostly indirectly caused by the external ambient environment. In high performance aircraft, for example, kinetic heating of the cockpit is largely dictated by speed and altitude and differences in ambient temperature of the order of 20°C between temperate and tropical countries have only a small effect. Another potent contributor to the thermal load in the cockpit is the increasing amount of avionic equipment in modern aircraft. However, perhaps the most significant cause of thermal problems arises from the necessity to protect the pilot from a whole range of aviation hazards. Such protection involves the use of complicated multi-layer clothing assemblies including several impermeable garments such as anti-G suits and partial pressure jerkins. These clothing assemblies significantly increase the insulation between the pilot and his environment and diminish the effectiveness of his normal thermoregulatory responses. The recent introduction of chemical protection adds a further dimension to this aspect of the problem. This matter and its influence on the design of cabin and personal conditioning systems is dealt with in some detail in the other papers.

The end result of many investigations into thermal stress problems is a statement of the relevant environmental conditions and of the pilots' body temperature responses to these conditions. The difficulty often lies in the interpretation of these findings in terms of their likely effects on operational efficiency. Usually, the levels of stress observed fall well short of those associated with physiological collapse, but they frequently come within the range where adverse effects on performance might be expected. Herein lies one of the major problem areas in the thermal field since existing literature concerned with the performance effects of thermal stress is far from adequate to enable confident definition of what is acceptable and what is not. For the time being this Institute uses a deep body temperature limit of 38.0°C as the upper acceptable limit beyond which serious performance decrements are likely to occur. The evidence for this limit is only tentative and much detailed work is required to substantiate or modify it. It might be useful to outline some of the problem areas:

(a) Much of the existing literature relates performance directly to environmental parameters. It is very difficult to apply this work to aviation because of the overriding influence that factors such as work rate and clothing have on the pilot's response to defined environmental conditions. It is more useful in practice to relate performance to specific levels of thermal strain in terms of deep body and skin temperatures and heart rate.

(b) There is insufficient evidence to enable us to distinguish performance effects that are directly due to increments in the temperature of blood perfusing the brain from those that arise from unpleasant sensory stimulation at the periphery.

(c) Little is known of the performance effects of transient thermal stress which is, of course, common in high performance aircraft. High rates of increase of body temperature might have greater adverse effects than absolute levels.

(d) Almost nothing is known of the effects of duration of body temperature elevation on performance.

(e) It is unknown whether those whose routine experience includes frequent elevations of body temperature are less effected by them than those for whom such stresses are only occasional. Most of the existing experimental results are for individuals in the latter category whereas pilots of

high performance aircraft are probably in the former.

(2) There is some information available on the interactions of different stresses insofar as performance effects are concerned.   In some cases these may be additive such as when thermal stress is combined with loss of sleep or acceleration.   In other cases, such as thermal stress and noise or vibration, the combined effect may be less than that of thermal stress alone.   However, with the present lack of detailed knowledge on the performance effect of individual stresses, it is doubtful whether the current vogue for work on multi-stress environments will do much to clarify the problem.

I have mentioned this problem in my introduction because you will hear little more of it in the remainder of our presentations in the thermal field.   Nevertheless it remains an important problem area and one which merits more attention than it is currently getting in the various aviation medicine research centres.

by

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Summary

The incidence of cold stress in military aviation is discussed together with methods for overcoming the problems it poses, by cabin conditioning or by the use of insulating or heated garments. Protective clothing is also required by aircrew to aid survival in emergencies and the principles of its design are considered. Lastly, an account is given of the RAF's permanent cold climate detachments and of cold weather operational and survival training.

Introduction

The flexibility of modern military air power makes it common for aircrew to operate at short notice from bases with cold climates quite different from those with which they are familiar. Cold stress occurs on the ground in these situations. It may also occur in the air even after take off from a temperate air-field as the performance characteristics of modern aircraft subject them to gross temperature changes in a single sortie. Aircrew cannot fly efficiently and safely unless protected from low temperatures. Severely cold conditions interfere with unskilled tasks and may even give rise to illness but much less drastic alterations in the environment, perhaps in combination with other flight stresses, can cause decrements in skilled tasks involving fine manipulation, judgement and memory. Aviation requires the exercise of these skills in large measure.

In an emergency the aircrew member may have to survive on land or sea in a hostile climate. There will usually be little time in which to prepare and the survivor will be forced to 'make do' with a minimum of equipment and protective clothing.

This paper will consider some of the problems of low temperature stress in military aviation. Additionally, it will summarise the cold weather training with which the RAF is associated. This training is intended to ensure efficient operations in the cold climate and to enhance the chances of survival of an emergency in such an environment.

Cold Stress in Aviation

One characteristic of aero engines is that they produce much hot air and nowadays some of this can usually be used for cabin conditioning. In the past 10 years this has not always been the case. For example, in World War II the tail gunners in large bombers became especially cold. In some cases it was possible to keep them warm with electrically heated clothing but in Flying Fortress bombers the USAF had more casualties from frostbite than from enemy action. Even now there is a cold problem in many aircraft in certain conditions and in a few routinely.

Ground stand-by for long periods in low ambient temperatures with the cockpit open can cause chilling of the crew, the more so because they cannot move around to keep warm. Light aircraft with small power plants, for example Sioux and Wasp helicopters, where air is often just drawn over the oil cooler, have poor cabin heating performance. In the Chipmunk there is no cabin heating at all. Search and Rescue heli-copters fly with their doors off as do some helicopters in an anti-submarine role. Other helicopters must be flown doors-off for visibility when deck landing or to ensure escape in the event of ditching. Another aircraft with a bad cabin conditioning system is the Canberra especially when used for high-altitude slow-speed photo-reconnaissance or target-towing duties. Cold stress also exists in certain test flights with the hatch off or canopy open and in this situation will be altitude dependent. In an emergency when the fuselage is breached at altitude, cold is likely to become a problem, although with the modern emphasis on low level flight this is not likely to be so serious.

Overcoming Cold Stress

Broadly, any environmental stress can be attenuated in its generation, its transmission or its effect on the man. There is little that can be done to avoid climatic extremes in aviation and protection from cold commences with interruption of transmission. The cockpit may be shielded from low ambient tempera-tures whilst the aircraft is on the ground by the use of heated hangars. Fuselage insulation and paint-work which absorbs solar radiation may help. Care must be taken to avoid exposure of the aircrew them-selves to cold stress before they enter the cockpit.

Despite such measures it is often necessary to protect aircrew from low temperatures during flight. There are two possible approaches to the problem; to heat the aircraft cabin and to provide insulating clothing or personal heating. For many reasons the latter measures are commonly taken even when some cabin heating is available. Cabin conditioning plant is heavy and the penalty in performance or payload associ-ated with an efficient system often forces a compromise when a new aircraft is being built.

In a cold aircraft the body tries to maintain its deep temperature against a gradient due to the reduced air temperature. Vasoconstriction soon becomes maximal. Reducing the surface area of the body by huddling up is not possible in an aircraft and a person strapped into a seat cannot produce more metabolic heat except by shivering, which interferes with fine co-ordination. Loss of heat from the body stores acts as a buffer to some extent but too great a loss is difficult to regain. Increase in clothing insulation is the best available protection but this is limited by the thickness and insulation of materials. It is not possible to wear more than about 1" of clothing, that is about 3 Clo, or the use of controls, and flotation and ejection characteristics are interfered with.

It is a basic principle that the man and his oxygen equipment should be protected against cold by such measures as shielding and insulation if possible. Sometimes it may not be practical to protect by insulation alone and it may be necessary to supply heat as hot air, hot water or electrical power. The limit to the temperature of surfaces in contact with the skin is 45°C. Above this tissue damage can occur. Since the temperature gradient is so small the flow rates of fluid warming media must be high. The hands are particularly vulnerable to cooling. It is very difficult to supply enough warmth and still allow manual dexterity except by electrical heating and in certain military aircraft electrically heated gloves are used. Socks or insoles for flying boots can also be heated. Electricity is a convenient form of heating since distribution and control are relatively easy and the source of supply is readily available in most aircraft.

Oxygen equipment must also be protected from cold and freezing of moist expirate is particularly troublesome. Mask valves must be made of neoprene rubber to stay pliable at low temperatures. Ice build-up on the inspiratory valve is prevented by a nylon ice guard and shrouding prevents it on the expiratory valve. Occasionally electrical heating of valves and visors is needed for equipment to meet its low temperature specification.

Clothing worn every day in the cockpit must protect on the ground in an emergency and this dual requirement poses difficult problems. A good maxim that is rarely followed is to dress for the environment and set cockpit temperatures accordingly. Even in routine use clothing insulation must be flexible as heat production can vary so greatly. Either layers of clothing must be taken off as required or there must be fasteners which can be opened to increase heat loss. The layer system is made use of when possible; a number of thin layers of clothing are worn rather than a concentration of insulation in a few thick layers. This ensures versatility but for the system to work the succeeding layers must be appropriately designed and sized. Unfortunately in high performance aircraft partial pressure, anti-g and air ventilated suits must often be worn so that extra thermal protection, when required, is added as a one-piece coverall to avoid further complication. As well as providing insulation, clothing must be permeable to water vapour. 500 ml per day of insensible perspiration are produced and evaporated at rest and during sweating much larger quantities are secreted. Unless the clothing is permeable all the sweat will collect inside.

For even the shortest exposure to severe climates protective clothing is necessary. The precise nature of this will depend upon the environment against which the man must be protected; whether cold/dry or cold/wet and whether windy or not. The ultimate of the cold/wet survival situation is immersion in the sea. The open sea around Britain is cold even in summer and the uninsulated man will quickly succumb to hypothermia. A completely waterproof outer layer is essential in this situation but as stated above such a garment would cause sweat accumulation in routine wear. This clash of requirements is overcome by the use of ventile fabrics.

Because of its vascularity heat loss from the head can be considerable. In flying, because helmets are worn for other reasons, the head is adequately protected and suitable emergency head gear is carried in the personal survival pack.

The Occurrence of Cold Stress at RAF Permanent Bases

The RAF has few bases where severe cold and large amounts of snowfall can occur. There are two permanent detachments; one at Goose Bay, Labrador and one at Offut Air Force Base, Nebraska. In addition, as described below, temporary detachments are carried out to North Norway.

At Goose Bay, from November to May, an average of 4-5 feet of snow cover occurs. Vulcan bomber training takes place from here; very low level flights over undulating terrain which are not possible over UK training areas. No aircraft are kept here permanently, they are sent over from UK for short periods, but there is a small detachment of ground personnel. At Offut, Vulcan aircraft undergo integration training with the American Strategic Air Command.

The severely cold conditions dictate certain changes in handling aircraft on the ground. If for any reason the aircraft have to stand out on the hard pan overnight, before flight they must be dug out of the snow and towed into a heated hangar. Pre-flight checks are carried out here. They are then towed out just before take off and the engines started up at once. The ground crew's living accommodation is somewhat overheated and the rapid transition from this to conditions of -20°C with blowing snow can be very stressful. A heated bus stands by while the ground crew are operating to provide immediate rewarming facilities. Clothing indoctrination is essential and is handed on from one detachment to the next. There is a good overlap period for this purpose. Aircrew on detachment carry out a one-day survival exercise; learning to cope with snow shoes, survival camping, fires and rations. However they do not sleep out of doors.

Winter Training in Norway

Allied Command Europe maintains a Mobile Force, the AMF (Land), using troops from the UK, Italy and Canada. An AMF (Air) is also provided for close support, ground attack, reconnaissance, trooping logistic support and airfield protection. Aircraft from UK, USA, Belgium and Holland are involved. The RAF supplies fighters for close support and also helicopters for the other roles. From January to March the

AMF (L) deploys in Norway for training the ground forces in winter conditions. AMF (A) accompanies them. The helicopters are transported by air to Sola, near Stavanger. They are rebuilt here and then flown to Bomoen, near Bergen. AMF (A) personnel travel by air via Bergen. The helicopter aircrew carry out an intensive flying programme including soft snow landings, flying in "white-out" conditions, training in depth perception in snow covered terrain, flying in recirculating snow, packing, transporting and delivering loads, night flying, navigation exercises, troop drills and casualty evacuation of ground troops. Where possible the aircrews carry out Winter Survival School Training first.

The aircrew and ground crew live in tented accommodation. They wear the RAF's Arctic Scale of clothing, designed on the layer principle. The tents used are 12 x 12s which can be arranged in tandem when necessary. Ground crew training is also an important part of the exercise. Herman-Nelson heaters are used to blow hot air directly over the part of the aircraft worked on in the open; in addition a temporary shelter can be erected around the repair.

Fixed wing aircraft training is carried out at the same time to familiarise aircrew with Winter flying. Operating from snow-covered strips, aircraft concealment in snow and operating from detached sites are all practised.

The ground forces involved are essentially snowshoe troops but about a third of them train extensively on skis. They stay at Nurfelt Youth Hostel. They operate in 5-10 man sections and are given speed, fire support and flexibility by the use of Volvo over-snow vehicles. Logistic support is carried out by various other army units and army helicopters are also operated from the Bomoen District air strip.

Certain subsidiary exercises are carried out whilst the above training is in progress. For example, the Defence NBC School often mounts an exercise to test chemical procedures in the cold, usually during February.

Each Winter a Naval exercise is carried out in Norway under the aegis of SACLANT and includes training of Marine Commandos at Narvik, helicopter squadrons at Bardufoss and small boat squadrons at Tromso. The land forces are essentially ski-troops, operating in small groups, who would expect to be landed by helicopter from a commando carrier. Normally a forward operating base would be established so that the Naval helicopters would be independent of their ships. For the purposes of the exercise, because of the inconvenience of having a ship stand-by off the coast of Norway for two or three months at a time, the aircraft are now landed by ship at Sorreisa and fly to Bardufoss. The squadron personnel live in huts but carry out survival training in tented accommodation. The purpose of the exercise is to train aircrew and ground crew to operate a Forward Base in Arctic conditions, to carry out a flying training programme similar to that of the RAF helicopter squadrons and to perform survival training.

The Winter Survival School

A WSS is set up each year by RAF Germany in Bavaria. There are five fortnightly courses for aircrew which take place in the first three months of the year. The school accepts approximately 50% of its students from UK and 50% from Germany. Most students are from the RAF but other arms are catered for as well. The School of Combat Survival and Rescue, RAF Mount Batten, supplies instructors. The students undergo ski-training in the first few days to toughen them and then spend 4 days living out in the woods with snow underfoot, in survival shelters. Next, there is an escape and evasion exercise. They travel across country for a distance depending on the prevailing conditions, hunted by German paratroopers and then undergo tactical questionning when caught. Each course carries a volunteer medical officer. The last few days of the course are again spent ski-ing.

THERMAL PROBLEMS IN HIGH PERFORMANCE AIRCRAFT

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This paper is intended to give a general review of current thermal problems in high performance aircraft, their origins and current design trends in their solution. It will deal in principles rather than detailed design since the latter is usually specific to type.

THE ORIGINS OF THERMAL STRESS

It might be thought that modern engineering skills should be capable of providing a thermally comfortable cockpit. However, the rate of improvement of aircraft performance, both in low level speed and manoeuvrability, and the enthusiasm of avionic engineers to instal more and more black boxes within or near to the cockpit, increasing both the heat input to the cockpit and demands for cooling air, has resulted in the design of cabin conditioning systems scarcely keeping up with the demands placed upon them. Indeed it is true to say that there is not a single military high performance aircraft flying today that is wholly thermally comfortable in all flight conditions. Complaints are frequent, even from the European theatre and diminished only by the fact that aircrew have come to accept that they have to sweat it out as their predecessors did.

Looking at the problem in more detail and taking the input side first the main sources of heat are aerodynamic heating, solar radiation, electrical heat load from avionic fits and the aircrew's own metabolic heat production.

Aerodynamic heating

The end result of aerodynamic heating is a raised aircraft skin temperature, the equilibrium level being a function of the ambient environmental temperature and the speed of the aircraft. During high speed low level flight aircraft temperatures may be as high as 110°C. This results in a high heat input into the cooler cabin air by convection and directly to the pilot's clothing, helmet and skin surfaces by radiation.

Solar radiation

Inspite of the increasing use of avionic aids, all round visibility from the cockpit remains a prerequisite for flying. Thus modern aircraft retain large cockpit transparencies which do little to filter the high radiant loads on the cockpit structure and pilot from the sun.

Electrical heat loads

The increasing use of sophisticated avionic aids influences cabin temperatures in two ways. Firstly, most of these equipments are highly temperature sensitive and place high demands for cooling air from the main conditioning plant. Secondly, they generate hot surfaces within the cockpit area which exchange heat with the cabin air and further increase the radiant load on the pilot.

Aircrew heat production

A pilot at rest generates approximately 80 watts of heat from his internal metabolic processes. This can be raised by a factor of 2 or 3 during high performance flying and the greatly improved manoeuvrability of modern aircraft at speed increases the physical work on the pilot.

A modern example

To place these various heat sources into perspective Table 1 gives figures derived from theoretical calculations for the Multi-Role Combat Aircraft:

MRCA flying at Mach 0.9			At Sea Level in ISA +35
Aerodynamic heat load	9.0	Kw)	
Solar radiation load	2.5	Kw)	Total direct heat
Electrical heat load (cockpit instruments)	1.2	Kw)	input to cockpit = 12.9 Kw
Pilot metabolic heat production	0.2	Kw)	
Electrical heat load (equipment bays)	9.5	Kw)	

Table 1. Cabin Heat Loads for MRCA

From this short consideration it may be seen that thermal problems are not confined to aircraft operations in tropical climates since many of the most potent heat sources are present in temperate climate flying though some of them are obviously less severe.

CURRENT DESIGN TRENDS IN CABIN CONDITIONING

At the start of this section the author makes no apology for excursions into the systems engineer's province since so much of the end result represents a compromise between what is physiologically desirable and what is practical from the engineering and operational point of view. In arriving at this compromise it is desirable that the biologist and the engineer should each have a proper appreciation of the other's problems.

Thermal comfort

To deal first with the physiologically desirable end-point, this is thermal comfort. For practical purposes, that is to enable the engineer to make calculations, a definition of thermal comfort is required. A suitably simple definition is to state that a thermally comfortable man has a mean skin temperature of 33°C with a range of skin temperature of not greater than 6°C from the trunk to the peripheral parts of the limbs. This definition can be greatly complicated and qualified by the academic physiologist but it has the practical merit of simplicity.

Design calculations

With this end point in mind the systems engineer can calculate the requirements for cabin conditioning air in terms of mass flow and inlet temperature and techniques for doing so have been described by Hughes (1968). In doing so he will take into account all the sources of heat input in representative flight conditions including the pilot's own heat production.

Aircrew clothing

In making these calculations one very important factor influencing heat exchange between a pilot and his environment is the insulation of his flying clothing assembly. The requirement to provide protection against the whole range of aviation hazards with anti-G suits, pressure clothing, chemical protective clothing, life preservers and so on, places a considerable layer of insulation between the pilot's skin surface and the cabin air. To achieve adequate heat exchange across this insulation places greater demands on the cooling system than would be the case if "shirt sleeve" flying were possible. The fact that several of the garments worn include water impermeable layers considerably embarrasses the effectiveness of the pilot's thermoregulatory sweating mechanism by restricting sweat evaporation should thermal comfort not be maintained throughout flight. The increased demand on cabin cooling systems arising from the effect of complex aircrew clothing is among the more important reasons for a serious consideration of personal conditioning systems which can achieve the desired physiological end point more economically.

Typical cabin conditioning performance

To illustrate the type of information that should emerge from preliminary design calculations of the type described Table 2 gives the data derived for the Multi-Role Combat Aircraft.

Mach No	-	Taxy	.3	.9	.75	1.8
Altitude	Feet	0	0	0	36000	50000
Ambient temperature	°C	40	40	40	-65	-40
Humidity	g/kg	22	22	22	0	0
Ram Temperature	°C	40	46	91	-42	111
Cabin Heat Load	kW	4.5	7.0	10.5	-3.3	11.7
Cabin Air Flow	kg/S	0.13	0.39	0.40	0.23	0.27
Required cabin temperature for comfort	°C	-	14.4	13.8	-	6.7
Cabin inlet temperature	°C	15	2	6	39	-20
Cabin outlet temperature	°C	43	15	27	27	23
Cabin temperature	°C	36	12	22	30	12
Selector setting		FULL COLD			FULL HOT	FULL COLD

Table 2.   Cabin Conditioning Predicted Performance Calculations

System design rules

Having outlined the various factors determining the required performance of the cabin conditioning system, insofar as the pilot is concerned, a number of general design rules may be stated. Before doing so a brief description of a typical aircraft cabin conditioning system will aid the reader to follow subsequent discussion.

Fig. 1 is a diagram of such a typical system. High temperature, high pressure air is tapped from the engine compressors and after preliminary ram air cooling by a primary heat exchanger the air is expanded through a turbine with a marked drop in pressure and temperature. The physical work done by this turbine is used to drive a compressor in the upstream side which raises the pressure and temperature at this point and enables further cooling to be achieved in a secondary heat exchanger (inter cooler). This type of Cold Air Unit, which forms the heart of the system, is known as a Bootstrap Cold Air Unit. Water droplets which condense out during this cooling are removed by a water separating device and the air is then ducted to the cockpit and equipment bays. Fig. 1 so illustrates the several subsidiary functions of the cabin conditioning system including rain dispersal, wing sealing, demisting and CAU bearing cooling.
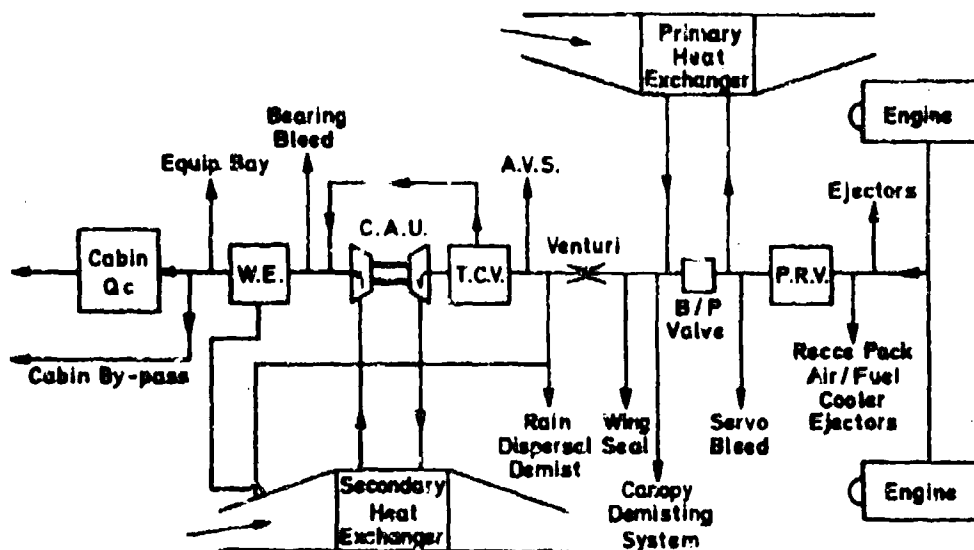
FIG. 1. TYPICAL AIRCRAFT CABIN CONDITIONING SYSTEM

Distribution ductwork and outlets

In determining the mass flow and temperature requirements for cabin cooling air the design of the distribution system downstream of the cold air unit is vital. A poor distribution system will make inefficient use of available cold air. In the past it has generally not been possible to produce a mean environmental temperature immediately surrounding the pilot that is cooler than about the cabin outlet temperature. Thus if inlet temperature is say 10^0C and outlet temperature 30^0C, the mean temperature surrounding the pilot will be in the region of 30^0C. Meticulous design can reduce this temperature to a point more like three fourths of the gradient from inlet to outlet temperature, ie nearer 25^0C in the quoted example.

The distribution system should be designed to produce the coolest conditions immediately surrounding the pilot. This is achieved by careful positioning of the cabin air outlets in relation to the pilot and by the use of nozzle outlets specially designed to reduce air entrainment (Hughes - personal communication). The latter is a feature of poor nozzle design in which warm cabin air is drawn into the outlet cold air jet immediately downstream of the nozzle and substantially downgrades the quality of cooling air reaching the pilot. The system should also allow personal adjustment by the pilot, particularly with regard to face ventilation.

Insulation

The contribution of high aircraft skin temperatures has already been mentioned. Clearly this can be reduced by careful attention to insulation of the cockpit walls from the cabin air with reduction in both the convective and radiative inputs to the cockpit.

It is also important to insulate the distributive ductwork between the cold air unit and the outlets to reduce the heat input to the cabin cold air supply before it reaches the pilot.

Noise generation

Whilst not strictly relevant to the subject matter of this paper it should be mentioned that cabin conditioning systems are important contributors to the cockpit noise problems. Again careful design can minimise noise generation in ductwork and outlets.

Water separation

As a result of the substantial temperature drop across the cold air unit, considerable quantities of water are condensed out of the cabin air supply either as water droplets or ice. Without an adequate system for removal, these droplets or particles of ice can be carried through the distributive ductwork and be blown onto the pilot. This is a common occurrence on several existing aircraft. Even if this does not happen the lack of effective water separation will lead to reabsorption in the ductwork and a rise in humidity of the cabin air supply.

Reduction of radiant heat loads

Mention has already been made of the value of cockpit wall insulation in reducing the radiant load on the pilot from high temperature aircraft skins. This leaves the more difficult problem of reducing the solar radiation load through the canopy. The difficulty lies in the requirement to maintain external visibility particularly in twilight conditions, but some success can be achieved by the use of filters such as gold film.

Demisting systems

A secondary function of most cabin conditioning systems is to provide a transparency demisting facility. This has often taken the form of a hot air supply to outlets which direct it over the trans-parencies. Such a system introduces large quantities of hot air into the cockpit. Use of the de-misting system is common during the later stages of descent to low altitude at a time when it would be of considerable advantage to prolong the advantages of cold soak at altitude for as long as possible. In some aircraft, for example the Phantom, the ductwork is common to the demisting system and the cabin conditioning. This has the added disadvantage that use of the demisting system heats up much of the distributive ducting which then has to be recooled on reversion to normal cabin conditioning. There is considerable advantage in using electrical methods in the primary demisting system, with a hot air system as a back-up. The latter should have ductwork entirely separate from the cabin conditioning distribution system.

Design limitations

The huge demands for cooling air both for maintaining pilot comfort and for avionic cooling have now reached the point in modern military aircraft where they represent the maximum that can be achieved within the limits of present technology. Already the extent of air bleed from engine compressors is beginning to have important effects on engine thrust performance. Tapping air from late compressor stages in modern jet engines results in very high temperature bleed air which in turn produces problems in the design of heat exchangers. Thus the position has been reached where further increments in cabin conditioning performance are hardly possible and this has led to an increasing interest in personal conditioning for the pilot and in alternative means for avionic cooling.

GROUND FACILITIES

However effective cabin conditioning systems may be all are engine dependent and work less effect-ively during taxying and not at all during ground pre-flight checks or stand-by. This is particularly unfortunate since many thermal stress problems are associated with the pre-flight period when aircraft may have been hot-soaked. Palliation can be obtained by the use of fixed ground facilities and ground air trolleys.

Fixed ground facilities

From time-to-time the use of such aids as sun-shades and thermal blankets usually special to type, has been demonstrated to be effective in reducing solar radiant heating of aircraft on the ground. Unfortunately these devices present logistic problems, particularly at dispersal airfields.

A spin-off from the increasing use of hardened sites for aircraft parking will be the reduction of solar loads.

Ground cooling trolleys

When available the use of ground trolleys to provide cold air supplies to cockpits during the pre-flight period is a highly effective method for reducing pre-flight thermal stress. Again, these can present logistic problems and increase the work of ground crews. However, where effective personal conditioning is not available pre-flight, their use is strongly advocated.

SUMMARY

From this short review it may be seen that the causes of thermal problems in modern military aircraft are well understood and the solutions, though they stretch the conditioning engineer's technology to the limit, are known. Nevertheless the position has been reached when considerable design and operational advantages might accrue from the use of effective personal conditioning systems rather than by trying to achieve comfort solely through the cooling of cabin air supplies.

The fact that so many current aircraft are not thermally comfortable reflects the acceptance by aircrew that high performance aircraft have always been uncomfortably hot with the result that this part of the weapon system has often received inadequate attention.

Several factors suggest that a more positive attitude may have to be taken in the future. Firstly, the provision of chemical protective clothing will add a further increment to existing thermal strain and secondly, the overall increase in the complexity of the pilot's task makes the acceptance of even minor discomforts more difficult. Perhaps the time has come to abandon the position in which the question usually asked is "can pilots tolerate these conditions?" and ask in its place "how much more effectively will pilots perform if conditions are wholly comfortable?"

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PERSONAL THERMAL CONDITIONING

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SUMMARY

The inadequacy of cabin conditioning systems in high performance aircraft has resulted in aircrew being exposed to severe heat stress situations within the cockpit environment during certain flight profiles. To alleviate the physiological strain imposed upon the man, methods of thermally conditioning the micro-environment within flying clothing assemblies have been investigated and applied to operational situations. The cooling agents used in the "personal thermal conditioning" role have been air or water. The former has been utilised either as an evaporative agent or convective cooling agent. In this paper the relative merits of the different personal conditioning systems have been discussed and a case made for the development of a practical liquid-cooled suit system for use in present and future high-performance aircraft.

INTRODUCTION

It has been established that man's fatigue is increased and his efficiency of task performance reduced when he is exposed to thermal stress. The efforts to offset the ever increasing thermal input to the cabin environment of recent generations of high performance aircraft, by improving cabin thermal conditioning systems, have not been wholly successful. In the immediate future further improvements in man's thermal environment in high performance aircraft cockpits depend upon the ability to condition the micro-environment within the flying clothing assembly.

THE REQUIREMENT FOR PERSONAL CONDITIONING

During the last two decades rapid advancement in the development of aircraft engines and structures has permitted equally rapid changes in the flight envelopes of high performance aircraft. This has increased the thermal stress within the cockpit environment in the following ways:

1. Increasing the speed of flight at low level raises the thermodynamic heating of the aircraft's structure to levels where aircraft skin temperatures substantially exceeding 100°C are frequently encountered.

2. Inclusion of more sophisticated avionic back-up equipment within the cabin results in an increased number of radiant heat sources both in close proximity to the pilot, and in sites where they produce an additional thermal input to the cockpit environment and increase the demand for cooling air from the environmental control system.

3. The increased manoeuvrability of modern aircraft during high speed low level flight increases the workload of the pilot and therefore his metabolic heat production.

4. The flying clothing assemblies worn by aircrew operating high performance aircraft have high insulation values. Some flying garments are of course impermeable to water and will thus inhibit man's most useful thermal regulatory mechanism for increasing his heat loss to the environment, namely sweat evaporation. Recent proposals for protecting aircrew from chemical agents using specific items of clothing, involve additional insulation and a fully enclosed headgear system. It can be predicted that this will further increase the heat strain upon the man.

It is desirable that aircrew be maintained in thermal comfort throughout the entire sortie. This period extends from the time the man leaves the crewroom, through the walkout, taxy and flight stage, to the time he re-enters the crewroom. Engine powered cabin conditioning systems provide no cooling before take-off. This problem can be alleviated by providing ground cooling trolleys to condition cockpits whilst the aircraft is still on the pan without engines running. Although this is a relatively simple facility to provide on permanent flying stations, it becomes an increasingly difficult logistic problem when aircraft are obliged to operate from dispersal sites, where back-up facilities may be of a very limited nature. Even when the engines are running and the aircraft is taxying, the cabin conditioning system is inadequate to cope with any large thermal load, because the output from the cabin conditioning system is proportional to the engine power. The latter is of course operating at a low output during the taxy phase. This is also true during certain other phases of most flight profiles, such as idling descents, when a marked increase in cockpit temperatures can be noted.

Even if these problems were soluble, it is doubtful if cabin conditioning systems alone could provide a cockpit environment where man could be maintained in thermal comfort. This stems from the large insulating values of the flying clothing assemblies. Because of these large insulating values, the man requires a greater temperature gradient between his skin and the cockpit environment to lose sufficient heat to maintain thermal equilibrium. To achieve this the cabin air temperature is required to be considerably cooler than would be necessary to maintain a lightly clothed man in thermal comfort. However, in achieving this situation an increased gradient between the cabin air and the aircraft's skin temperature results,

producing a greater heat input from the aircraft structure to the cabin environment. Therefore, to produce an acceptable thermal environment within the cockpit requires a high level of performance from the conditioning system to provide the mass of variable temperature air needed to cope with the diverse inflight conditions encountered. Such systems impose considerable size and weight penalties on the aircraft. Also the air used for the cabin conditioning system is obtained by tapping the engine compressors. The mass of air bled from the engine for this purpose has at the present time reached a level where any further increase would result in significant reduction in engine performance.

It would seem therefore that major improvements of cabin conditioning systems in both present and future generation high performance aircraft are unlikely. Since it is increasingly difficult to condition the cockpit environment satisfactorily, attention has been orientated to conditioning the micro-environment within his flying clothing assembly.

DESIGN REQUIREMENTS OF PERSONAL CONDITIONING SYSTEMS

The ideal being aimed at when considering thermally conditioning aircrew is the achievement of thermal comfort in all phases of the sortie. This includes pre-flight, in-flight and post-flight situations. The definition of thermal comfort used in this context is:

1. A mean skin temperature of 33°C.

2. An evaporative heat loss equivalent to 20% of the metabolic rate.

3. A relatively higher skin temperature in the central body region than in the extremities (preferred distribution of skin temperature).

Methods available for personal thermal conditioning at present utilise either air or water as the medium for exchanging heat between the man and his environment. Air can be used as a heat transfer agent in two modes; either using its evaporative capacity, or utilising its convective power. When water is used as the cooling agent the heat transfer mechanism is more complicated, both conductive and convective elements being present.

AIR VENTILATED SYSTEMS (AVS)

1. MECHANISM OF ACTION

a. Evaporative

Although there are several engineering advantages to this method of using air ventilation, it is the least acceptable method of personal thermal conditioning, in terms of both physiological and subjective assessments of thermal comfort. The mechanism by which heat is transferred from the man is by removal of latent heat of vapourisation of sweat. However, before man begins to sweat a degree of thermal strain must exist. Therefore, although a thermal steady state situation may be arrived at by using evaporative air ventilation in a heat stress situation, it will be accompanied by an elevation in deep body temperature and some loss of thermal comfort.

b. Convective

The use of air ventilation for removal of sensible heat in this mode offers the obvious advantage that the heat transfer mechanism does not require the man to sweat before it begins to work. Thus it is possible to maintain thermal comfort without any elevation in deep body temperature. This is a more acceptable method of maintaining thermal comfort both in terms of objective physiological responses and subjective criteria. However, this advantage is offset by several disadvantages in terms of the penalties on the aircraft of providing the quantities of cold air needed for the system to function adequately.

2. SUPPLY REQUIREMENTS

When utilising air as the cooling agent for personal thermal conditioning systems the mechanism of heat transfer, i.e. evaporative or convective, has important implications on both the design of the air supply systems and of the garments utilising the supply systems. The temperature of the air for evaporative cooling need not be lower than that of the mean skin temperature. What is important is that the water content of the air is minimal so that maximum evaporation from the wet skin to the air can take place. Air temperatures of up to 40°C with low humidity will still provide sufficient cooling power to maintain a thermal steady state, albeit at an elevated deep body temperature. This means that the inevitable heat pick-up by the ventilating air supplies, from the pipework system between the cold air unit, water extractor, and the man, is of less importance than in convective cooling. In the latter system the temperature of the air supply to the man must be less than the mean skin temperature for comfort, i.e. 33°C. However, humidity is less important than for evaporative air ventilation. Greater quantities of air are necessary for removal of a given quantity of heat by convection than evaporation. An inadequacy of both types of AVS is that the temperature control for all aircrew members in an aircraft is set by a master control switch which the pilot operates. All other crew members can only control the flow rate to their individual garments. Illustrations of the air supply systems for evaporative and convective personal thermal conditioning are shown in Figures 1 and 2. It can be seen from these figures that the convective air supply system may incorporate a turbo-fan cold air unit. The additional cooling power available from this unit means that less load is placed on the primary heat exchanger utilising environmental control system air. This results in a lower heat load being passed to the cabin conditioning air than in the evaporative AVS.

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3. GARMENT DESIGN

When considering the garments used in conjunction with air supplies in both evaporative and convective modes, substantial differences are again encountered. Since different skin sites sweat at approximately equal rates, evaporation is most efficiently achieved by providing equal volume flows of air to equal skin surface areas. If this equal flow to equal skin area distribution is not achieved, sweat will not be evaporated adequately from some regions and therefore a higher sweat rate from the supplied areas will be required to maintain sufficient heat extraction. Also in those areas where the distribution of air is inadequate, wetting of the garments will take place producing discomfort. In the past this equal volume flow to all skin areas has been achieved by a complicated ducting system comprising a large number of equal bore tubes supplying air jets within the garment (Figure 3). Although at the present time it is felt that the air distribution system might be simplified, the necessity to provide equal air flows to equal skin areas does limit design improvements. For convective air cooling a relatively greater amount of cooling must be provided to the periphery than the central body area to maintain preferred skin temperature distribution. The design of these garments has allowed a simpler pipework system than that used in evaporative garments to be developed (Figure 4).

A summary of the advantages and disadvantages of these two systems is shown in Table 1. It can be seen from the comparison of the two air ventilation methods that in terms of maintaining the aircrew in thermal comfort, the convective principle is the method of choice. However, the penalty on the aircraft of the bulk of equipment to provide the ventilating supply is considerably less using the evaporative principle. It is for this reason that at the present time in the Royal Air Force, only the Buccaneer has the facility for providing the aircrew with convective AVS cooling. However, the multi-role combat aircraft (MRCA) in its present Phase 1 development is being produced with the facility to provide convective cooling to the crew if required. Even if future generations of aircraft are manufactured with this type of cooling system there still remain several problems to be solved. Firstly, the pre-flight heat stress which can result from either the climate or from a high workload. To date it has been found impossible to provide a practical portable conditioning unit to supply ventilating air whilst the individual is mobile in the pre or post flight phase. The only prototype portable units produced have been of such bulk and mass (more than 10 kilograms fully charged) that initial assessments suggested that the cost of carrying the item, in terms of workload and subjective discomfort, outweighed its useful cooling properties. In the absence of ventilation to the suit, the air ventilated garments become yet another layer of thermal insulation, adding to the total thermal stress on the individual. Secondly, since personal thermal conditioning systems utilising air ventilation are engine dependent, then in all situations where low engine power is being applied, i.e. idling descents, and taxy, cooling is likely to be inadequate and an increase in thermal strain will occur. In ground standby, with no engine power available, no air supply will be available unless it is supplied from an auxiliary ground cooling unit. Finally the policy to protect aircrew from chemical agents requires suitable filters for the air supplies to these garments. These filters reduce the performance of the cooling system.

LIQUID CONDITIONED SYSTEM (LCS)

In principle this process involves the exchange of heat between the man and the liquid flowing in small plastic pipes mounted within the fabric of a stretch material garment (Figure 5). The mechanism of heat transfer is a combination of both conduction and convection. To date, the liquid used has been a mixture of water and ethylene glycol (the latter to prevent freezing in the supply system). The present proposal is for a 50/50 water glycol mixture which will meet the most adverse operating conditions, but will allow freezing of the coolant during ground cold soak to $-60^\circ C$. Any further increase in the fraction of ethylene glycol in the mixture will both reduce the cooling properties of the medium, by lowering the thermal conductivity and specific heat, and also increase the specific gravity and viscosity of the mixture requiring a greater power source to maintain a given flow through the system. In order to maintain the preferred skin temperature distribution, the liquid after entering the garment at an inlet manifold, flows firstly to the peripheral parts of the limbs, and then flows proximally towards the central trunk area to an outlet manifold.

The liquid cooled system works on a fixed flow principle. At present design requirements demand a flow rate of approximately $1.L.min^{-1}$. The temperature of the coolant to the suit inlet can be varied from $15^\circ C$ to $45^\circ C$ and is controlled by individual crew members. This is achieved by mixing hot and cold streams of coolant to a value selected by the crew member on his temperature controller. The suit inlet temperature is prevented from varying outside the range quoted above, by sensors in the supply system which produce an error signal and cause the by-pass valve to work, cutting off the suit supply. Cooling is achieved using a vapour cycle refrigeration system (Figure 6).

Field and laboratory assessments of different personal thermal conditioning systems, including liquid conditioned systems, convective air ventilated systems and evaporative air ventilated systems, have furnished evidence that both on physiological objective measurements and subjective criteria, the liquid conditioned suit system is the most acceptable. The use of water as a cooling agent offers several advantages over air. The specific heat of water being considerably higher than that of air, a much larger quantity of heat can be accepted by a unit mass of water. The liquid system provides a closed loop system and this has two advantages. Firstly, because recirculation of the heat transfer fluid takes place, only the heat picked up by the coolant from the man and the cockpit environment has to be eliminated from the system. Secondly, protection of the cooling medium from chemical agents is far easier than with that of an open circuit system using air ventilation. The smaller power requirements and reduced flow of the cooling medium facilitates the development of a practical portable conditioner. To date prototypes have been produced wearing approximately 5 kilograms fully charged (Figure 7). All crew rooms where LCS are being used by the aircrew can be provisioned with a supply of readily charged portable conditioners. The user only requires to disconnect a conditioner from its charging source and connect it to his inlet/outlet suit manifold. The endurance of a fully charged conditioner varies with the heat input from the man and environment, but under normal operating procedures, i.e. walk-out to aircraft phase endurances of 60 min have been recorded. The LCS, unlike the AVS, is independent of engine power requiring only electrical output from the aircraft's system. This, in conjunction with a practical portable conditioning unit means that personal thermal conditioning is

available to the aircrew throughout the whole sortie. The comparative advantages of the LCS are summarised in Table 1 with those of the AVS systems.

To date no aircraft have been developed with an integral liquid conditioned suit system, despite the opinions of most investigators in the field of personal thermal conditioning that the LCS offers considerable net advantages over air ventilated systems. However, at the present time discussion is proceeding on the feasibility of incorporating a liquid conditioned suit system in the UK variant of the MRCA.

TABLE 1. CHARACTERISTICS OF EVAPORATIVE AVS, CONVECTIVE AVS AND LCS

| ITEM	EVAPORATIVE AVS	CONVECTIVE AVS	LCS
1. Mechanism of action.	Removes heat by latent heat of vaporisation of sweat. Requires man to be actively sweating before it can function. Therefore requires a heat strain situation to exist before effective. Cannot maintain ideal thermal comfort.	Removes heat by convection. Therefore no necessity for heat strain situation to exist prior to functioning. Theoretically can maintain ideal thermal comfort.	Removes heat by convection/conduction. Theoretically can maintain ideal thermal comfort. Closed loop system removes heat only from man and micro-environment within flying clothing. Also uses cooling agent with high specific heat. Therefore only small power requirement.
2. Cooling agent characteristics.	Air. Temperature not critical, up to 40°C can produce net heat loss from man. Low water vapour content of air essential. (Design requirements - approx 350 l min⁻¹ at 35°C.)	Air. Temperature must be below mean skin temperature to produce net heat loss from man. Water vapour content not important. (Design requirements approx 730 l min⁻¹ at 10°C.)	Water/ethylene glycol mixture. Temperature of coolant must be below mean skin temperature. (Design requirements approx 1 l min⁻¹ at 15°C to 45°C.)
3. Garment characteristics.	Equal flow of air to equal skin areas. More complex ducting system than for convective.	Greater flow of air to peripheral skin areas than central region to maintain preferred skin temperature distribution. Simpler ducting system than for evaporative.	Complex multiple small pipework system mounted in fabric tunnels within stretch-fabric garment. Flow of coolant directed first to periphery and then proximally to trunk region to maintain preferred skin temperature distribution.
4. Pre-flight conditioning.	Engine dependent system. Requires ground cooling trolley for cockpit standby. Inadequate during low engine power, eg taxy. No satisfactory portable conditioner available.	As for evaporative.	Engine independent. Functions adequately during cockpit standby and all flight configurations. Practical portable conditioner available.
5. Protection from chemical agents.	Requires rain-fic filter for air supply. Degrades cooling performance of system.	As for evaporative.	Closed loop system. Not readily contaminated. Cooling performance not downgraded in a chemical warfare environment.
6. Effects on equipment cooling.	Air cooling power for equipment bay reduced.	Worse than evaporative since requires greater mass flow.	More air-cooling available for equipment than with AVS.
7. Effect of high altitude.	Mechanism of action depends on volume flow, easily maintained at altitude.	Mechanism of action depends on mass flow. More difficult to maintain at altitude.	Unaffected by altitude.
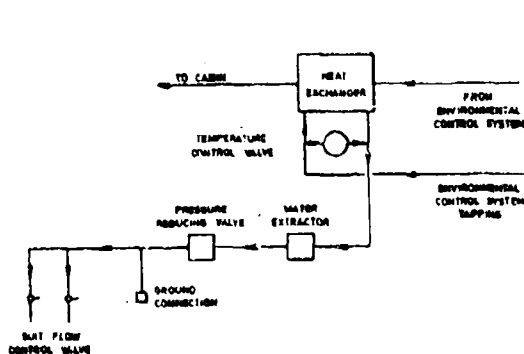
Figure 1. Typical air supply system for evaporative air-ventilated suits
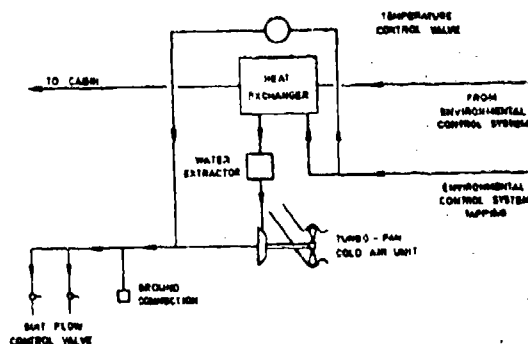

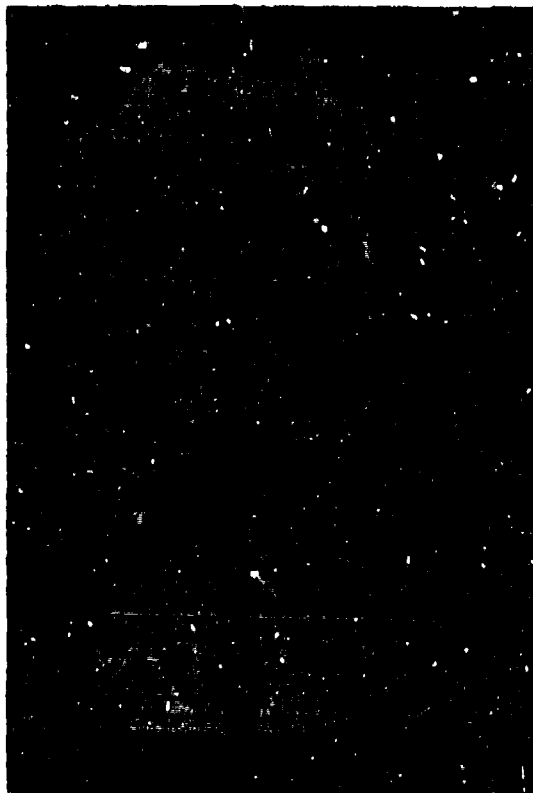Figure 2. Typical air supply system for convective air-ventilated suits

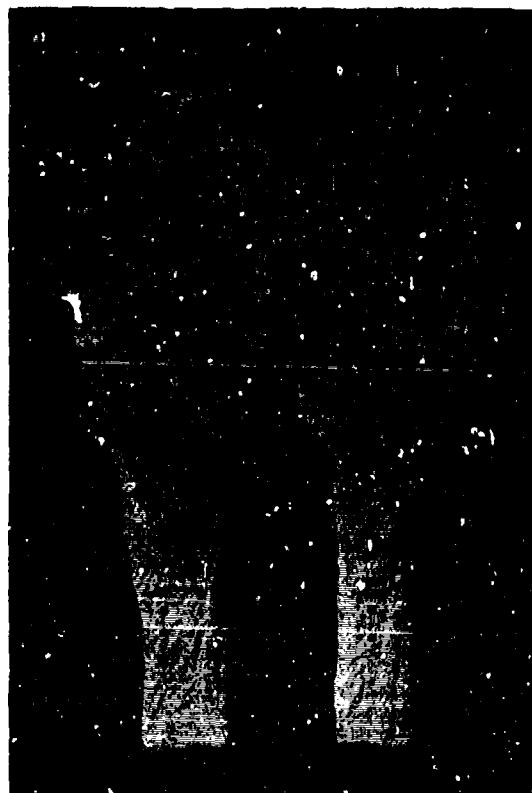Figure 3. Evaporative air-ventilated suit
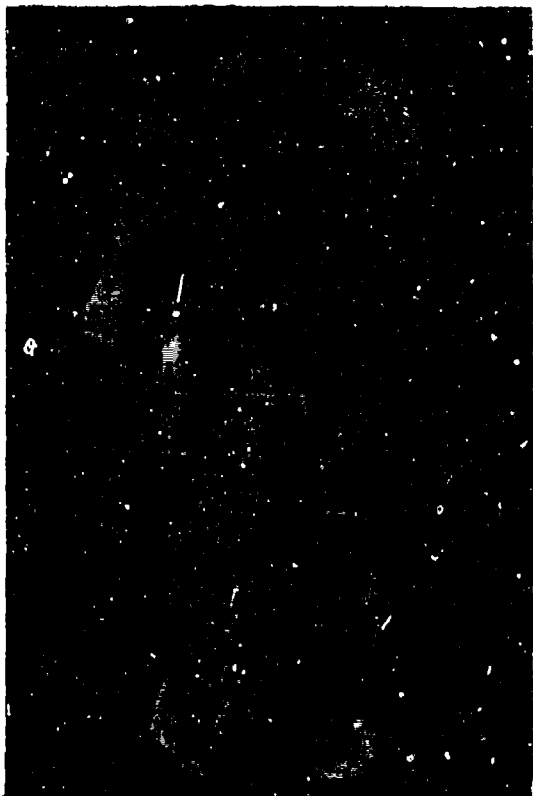

Figure 4. Convective air-ventilated suit
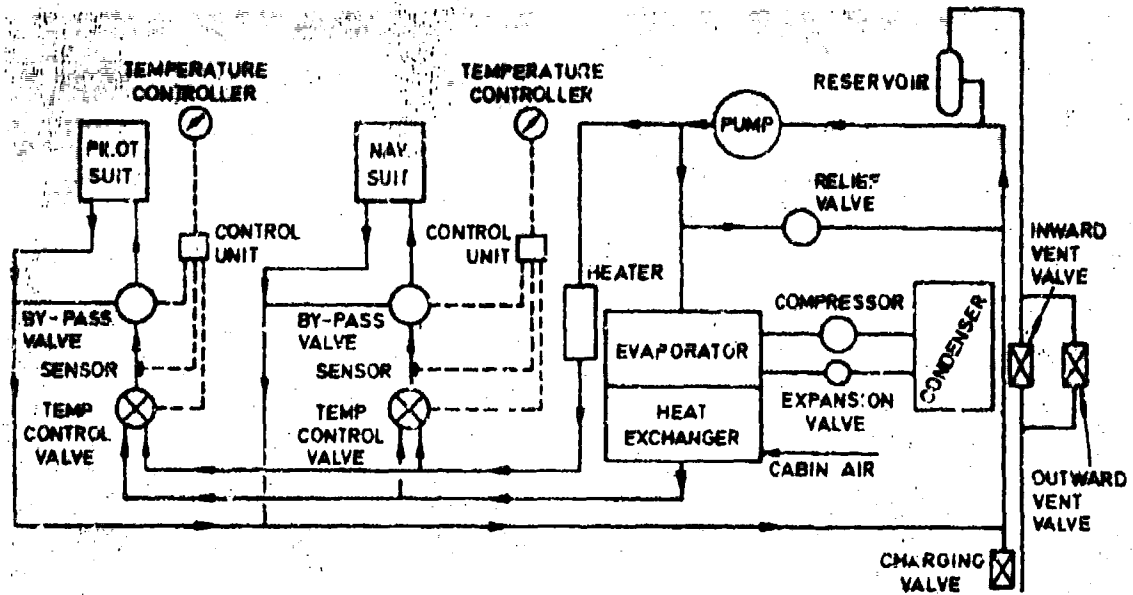

Figure 5. Liquid conditioned suit

Figure 6. Vapour cycle system (standby) combined with cabin
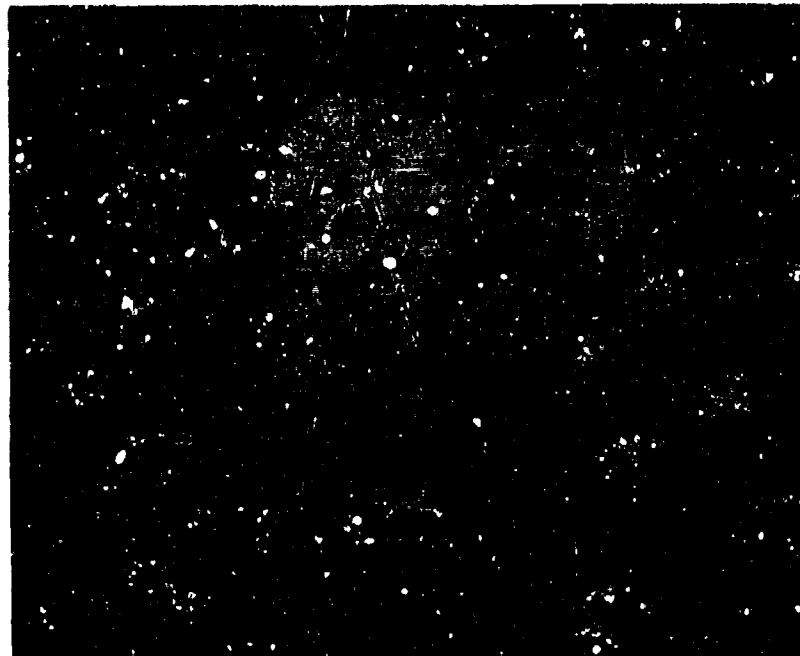air heat exchanger (flight) for liquid cooled suits

Figure 7. Portable supply unit for liquid conditioned suit

CABIN PRESSURISATION AND OXYGEN SYSTEMS-REQUIREMENTS

by

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SUMMARY

The considerable interactions between the physiological requirements for cabin pressurisation and the relationship between concentration of oxygen and cabin altitude required of oxygen delivery systems for aircrew in flight are explored in this paper. Although work performed until 1960 suggested that hypoxia induced by breathing air at altitudes of up to 8000 feet was acceptable, investigations performed more recently at RAF IAM and elsewhere suggest that the maximum acceptable degree of hypoxia for aircrew in flight is that associated with breathing air at 5000 feet. The incidence of hypoxia due to malfunction of oxygen delivery equipment and of decompression sickness at altitudes above 20,000 feet is such that the maximum cabin altitude in combat aircraft should not exceed 20,000-22,000 feet. The concentration of oxygen which must be breathed to avoid transient hypoxia on sudden failure of a pressure cabin even when 100% oxygen is delivered to the respiratory tract immediately the decompression occurs is generally greater in high differential pressure aircraft than that required to prevent significant hypoxia with the pressure cabin intact. Even in modern combat aircraft this consideration requires a higher than "5000 feet equivalent" breathing mixture at aircraft altitudes greater than 35,000 feet.

INTRODUCTION

Although the basic physiological requirements for cabin pressurisation and the performance of oxygen systems are well established the interactions between these two essential life support systems have only been explored in detail over the last 15 years. Some of these interactions and the way in which they affect the physiological aspects of the requirements for cabin pressurisation and oxygen systems are considered in this paper.

The crew and passenger compartments of virtually all modern high performance combat and transport aircraft are pressurised with air in order to prevent the occupants being exposed to the low pressure of the environment in which the aircraft may fly. At first sight there would appear to be great advantages in maintaining the absolute pressure in the cabin at one atmosphere (760 mm Hg) throughout flight. Such a requirement would however impose considerable penalties with regard to the weight of the pressure cabin and the pressurisation equipment, and hence the performance of the aircraft. Furthermore, the larger the pressure differential across the wall of a cabin the greater is the risk of damage to the aircraft and its occupants in the event of a failure of the structure. Thus, in practice, compromises are made between the physiological ideal of a cabin pressure of 1 atm absolute, the weight and performance penalties of a high cabin pressure differential and the risk of explosive failure of the cabin. A clear recognition of the effects of low environmental pressure upon man in particular hypoxia, decompression sickness, expansion of gastro-intestinal gas and the effects of rate of change of pressure upon the middle ears and sinuses is essential to the derivation of the best compromise cabin pressurisation schedule for an aircraft. The form of the cabin pressurisation schedule can affect the ideal relationship between the concentration of oxygen delivered by the oxygen system and the cabin altitude. The cabin pressurisation schedule also determines the pressure differential applied to the oxygen and respiratory systems in the event of a decompression of the cabin.

HYPOXIA DURING ROUTINE FLIGHT

The intensity of hypoxia which is acceptable in aircrew operating aircraft has important implications for the design of both pressure cabins and aircraft oxygen systems. It sets the maximum cabin altitude in aircraft in which air is breathed during flight and the minimum concentrations of oxygen delivered by an oxygen system.

The results of numerous studies of the effects of acute hypoxia carried out before and during World War II suggested that psychomotor and mental performance is unimpaired by breathing air at altitudes up to about 12,000 feet (McFarland (1); Ernsting (2)). The one exception was the light sensitivity of the dark adapted eye which is significantly reduced by the hypoxia associated with an inspired P_{O_2} of 110 mm Hg (3). It was accepted as a result of these studies and practical experience gained in flight that the hypoxia induced by breathing air at altitudes of up to 8000 feet was acceptable for flight deck crews. In 1962 however, Ernsting, Gedye and McHardy (4) found that the ability of subjects to reproduce a sequence of eight digital operations learnt whilst breathing air at 8000 feet was significantly impaired as compared with their performance when the task had been learnt whilst breathing 100% oxygen at 8000 feet. This finding led to two further studies at the RAF Institute of Aviation Medicine of the effects of mild hypoxia upon performance during the learning of a task (5 and 6). The performance of matched groups of subjects was measured during the learning of a complex orientation task whilst breathing air at ground level, 5000 and 8000 feet. The subject carried out mild exercise on a bicycle ergometer and was also required to maintain a constant pedalling speed. Performance at this complex orientation task was impaired by mild hypoxia whilst the test was being learnt but not after the subjects had practised it. Impairment during the learning phase was only just detectable at 5000 feet (22% increase in mean reaction time (p < 0.05)) but considerable at 8000 feet (mean reaction time twice that obtained at ground level (p < 0.02)). Several other independent studies have shown that breathing air at 8000 feet produces a significant impairment of performance during the learning phase of a vigilance task (7), a complex psychomotor task (8) and a complex choice reaction task (9). Other investigations in which subjects performed two-dimensional tracking (10), mental problem solving and auditory vigilance (11) confirmed that the hypoxia associated with breathing air at altitudes up to 8000 - 10,000 feet has no detectable effect on performance if the task has previously been well learnt at ground level.

In summary, therefore, recent studies have shown that the hypoxia induced by breathing air at altitudes of up to 10,000 feet (inspired P_{O_2} = 99 mm Hg) has no effect upon well learnt tasks but does prolong the time taken to learn a new task. This impairment of learning increases with the complexity of the task but even choice reaction times are significantly prolonged by breathing air at 8000 feet. Impairment of learning even of a complex task is only just detectable at 5000 feet. Although routine flying consists primarily of the practice of thoroughly over-learnt tasks, unpractised emergency situations do occur in both military and civil operations and novel combinations of complex tasks occur repeatedly in combat flying. Thus reduction of the inspired P_{O_2} to 108 mm Hg (equivalent to breathing air at 8000 feet) should not be accepted for aircrew employed in air operations because it produces a very significant impairment of the ability to respond to novel complex situations. It is concluded that a practical compromise with regard to the degree of hypoxia acceptable when oxygen economy or the magnitude of the cabin differential pressure are of concern is that inspired P_{O_2}s down to 122 mm Hg i.e. breathing air at altitudes up to 5000 feet are acceptable for aircrew operating both combat and transport aircraft. Thus the cabin altitude of an aircraft in which the aircrew breathe air should not exceed 5000 feet. The engineering and aircraft performance penalties of applying this physiological requirement to current transport aircraft over the whole range of operating altitudes is however significant. The current practical compromise set in the UK is that the cabin altitude shall not exceed 6000 feet at the maximum cruising altitude of the aircraft. The minimum oxygen concentration-cabin altitude relationship for current UK crew oxygen delivery systems is a ground level equivalent (inspired P_{O_2} = 159 mm Hg). The use of a minimum concentration of oxygen which produces hypoxia equivalent to that induced by breathing at 5000 feet (inspired P_{O_2} = 122 mm Hg) has however been used for many years in North America.

MAXIMUM ACCEPTABLE CABIN ALTITUDE BREATHING OXYGEN

In combat aircraft the weight and hence aircraft performance penalties of a high differential pressure cabin such that the crew may breathe air throughout flight, are unacceptable. Furthermore it is usually considered that the threat to the integrity of the pressure cabin by enemy action and the possible ensuing decompression should be taken into account in this type of aircraft. Thus, it is generally accepted that the crew of combat aircraft will wear oxygen equipment throughout flight so that the magnitude of the cabin pressure differential in this type of aircraft can be considerably less than if the maximum cabin altitude is limited to the 5000 to 8000 feet required by air breathing.

The early post war combat aircraft designed and built in the UK had a maximum cabin pressure differential of 3.5 Lb./sq.in. (180 mm Hg) so that cabin altitude was of the order of 25,000 feet when the aircraft altitude approached 45,000 feet. It was believed that this cabin pressure differential represented the best compromise between the risk of hypoxia and decompression sickness during flight at high altitude on the one hand and of damage in the event of a sudden decompression on the other. As experience was gained of the reliability of pressure cabins and the altitudes at which service flying was carried out approached and exceeded 50,000 feet and the maximum cabin pressure differential for combat aircraft was increased to 4.0 Lb./sq.in. (210 mm Hg).

By progressively enriching the inspired air with oxygen it is possible to maintain the alveolar oxygen tension at the value associated with breathing air at sea level at altitudes of up to 33,000 feet. However, the rate at which the function of the central nervous system is impaired by an interruption of the oxygen supply so that the aircrew man reverts to breathing air increases progressively as the altitude is raised above 15,000 feet. The time available at an altitude of 20,000 feet for an individual to recognise that his oxygen supply has ceased and for him to carry out the appropriate corrective action is approximately three times greater than the time available at an altitude of 25,000 feet. Furthermore, the reduction of the inspired oxygen tension produced by a given fractional inboard leak of air due to an illfitting oronasal mask increases with increase of altitude. Thus, although it is theoretically possible to maintain a normal sea level alveolar oxygen tension at altitudes of up to 33,000 feet by increasing the concentration of oxygen in the inspired gas these considerations suggest that both the incidence of hypoxia and its severity will increase with increase of altitude above 15,000 feet. The incidence of hypoxia accidents in unpressurised aircraft in World War II was 6 times greater for flight at 25,000 feet as for those at 20,000 feet whilst when the altitude of flight was 30,000 feet the incidence was nearly 70 times that at 20,000 feet. The experience of the Royal Air Force over the last 20 years has amply confirmed these wartime observations, with the incidence and severity of hypoxia accidents rising markedly with increase of cabin altitude between 20,000 feet and 25,000 feet.

Other aeromedical consequences of the use of maximum cabin pressure differentials of 3.5 and 4.0 Lb./sq.in. gauge have been a significant incidence of decompression sickness and, associated particularly with the introduction of aircraft capable of very high rates of descent, the occurrence of otitic and sinus barotrauma. There has been, therefore, over the last 10 years an increasing tendency to advise that the maximum cabin altitude in strike aircraft should be reduced from 25,000 feet towards 20,000 feet. The most recent UK requirement for cabin pressurisation which in this respect is in agreement with the United States MIL specification for the pressurisation of the cabins of strike aircraft requires that the maximum cabin pressure differential shall be 5.25 Lb./sq.in. (275 mm Hg). This requirement provides a cabin altitude of 16,000 feet when the aircraft altitude is 40,000 feet and a cabin altitude of 19,500 feet at an aircraft altitude of 50,000 feet.

CABIN PRESSURISATION SCHEDULES - COMBAT AIRCRAFT

The relationship required between cabin pressure differential and aircraft altitude in a combat aircraft depends upon a number of considerations. At first sight it may appear highly desirable that pressurisation of the cabin should commence at the lowest possible aircraft altitude and that the cabin altitude should be held constant as the aircraft ascends until the maximum cabin pressure differential is reached. This is the form of pressurisation schedule required by United States MIL specification. In practice, in order to avoid pressurisation of the cabin when the aircraft is on the ground it is necessary to delay the altitude of onset of pressurisation to a pressure altitude which exceeds the lowest atmospheric pressure which may occur when the aircraft is on the ground. A reasonable compromise would appear to be that the pressurisation of the cabin of a strike aircraft should commence at an aircraft altitude of 5000 feet. With a maximum cabin pressure differential of 5.25 Lb./sq.in. it is possible to maintain a cabin

altitude of 5000 feet between aircraft altitudes of 5000 and 19,000 feet (Table 1, MIL specification).

Table 1. The relationship between cabin altitude and aircraft altitude for strike aircraft

Aircraft Altitude (feet)	Cabin Altitude (feet)	
	MIL Specification	UK Requirement
0	0	0
5,000	5,000	5,000
10,000	5,000	6,500
15,000	5,000	8,500
20,000	5,500	10,250
25,000	8,500	12,250
30,000	11,250	13,500
35,000	13,750	14,750
40,000	16,000	16,000
45,000	17,750	17,750
50,000	19,500	19,500

A pressurisation schedule of this type ensures that the cabin altitude is maintained at the lowest practical level over the whole flight envelope. However, from the points of view of structural fatigue of the pressure cabin and the risk of damage to the occupants arising from a structural failure, it is highly desirable that the proportion of the flight envelope in which the maximum cabin pressure differential is operative should be kept to a minimum. These considerations result in the type of cabin pressurisation schedule employed in UK combat aircraft in which the maximum pressure differential is not operative until the aircraft altitude exceeds a value, depending upon the magnitude of the maximum pressure difference, between 25,000 feet and 40,000 feet. At altitudes between that at which cabin pressurisation commences and that at which the maximum pressure differential becomes operative the absolute pressure in the cabin varies linearly with the external atmospheric pressure. The latest UK requirement for strike aircraft requires that the maximum cabin differential of 5.25 Lb./sq.in. is only operative at and above an aircraft altitude of 40,000 feet (Table 1 - UK requirement).

Although the UK pressurisation schedule results in higher cabin altitudes at aircraft altitudes between 5000 and 40,000 feet than those given by the MIL specification schedule (Table 1) the difference is of little significance with respect to the potential occurrence of hypoxic incidents since the difference only arises at cabin altitudes below 16,000 feet. Indeed the differences between the cabin altitudes produced by the two schedules is greatest at the lower aircraft, and hence cabin altitudes where the possibility of significant hypoxia occurring in flight can be virtually discounted.

Of considerably greater practical importance however is the difference in the rate of change of cabin altitude with a given rate of descent of the aircraft produced by the MIL specification and UK types of schedule. The MIL specification schedule provides a constant cabin altitude on descent from an altitude of 19,000 feet until the aircraft passes through 5000 feet below which cabin pressurisation ceases and the rate of decrease of cabin altitude equals the rate of descent of the aircraft. With the UK requirement however the cabin altitude decreases progressively as the aircraft descends from 19,000 feet to 5000 feet. On the other hand, descent from aircraft altitudes greater than 19,000 feet gives a progressive decrease of cabin altitude with either schedule. For a given rate of descent of the aircraft however the rate of increase of cabin absolute pressure produced by the MIL specification is about twice that produced by the UK pressurisation schedule. Thus with high rates of descent from altitudes considerably above 19,000 feet the MIL specification schedule requires a more frequent venting of the middle ear cavities and sinuses and with very high rates of descent of the aircraft would be expected to cause a greater incidence of otitic and sinus baratrauma than that associated with the UK pressurisation schedule.

It may be concluded therefore that aeromedically for a strike aircraft which operates primarily at altitudes below 20,000 feet the MIL specification schedule of cabin pressurisation is more suitable than the UK schedule. On the other hand the UK pressurisation schedule is more desirable than that given by the MIL specification when the aircraft is expected to spend a significant proportion of its flight time at altitudes in the 20,000 feet to 50,000 feet range. Engineering considerations related to the increased structural fatigue produced by the MIL specification pressurisation schedule could give an overall advantage to the UK requirement even for a strike aircraft which operates predominantly at altitudes below 20,000 feet.

HYPOXIA INDUCED BY RAPID DECOMPRESSION

A rapid decompression of the pressure cabin of an aircraft flying at altitude produces an equally rapid fall of the P_{O_2} and P_{CO_2} of the alveolar gas. Thus rapid decompression whilst breathing air from 8000 feet to 40,000 feet in 1.6 sec produces a virtually instantaneous fall of alveolar P_{O_2} from 65 to 15 mm Hg and the alveolar P_{O_2} remains below 18 mm Hg for as long as air is breathed at 40,000 feet (4). If the subject does not start to breathe 100% oxygen until 8 - 10 sec after the beginning of decompression unconsciousness supervenes approximately 5 - 7 sec later. Even when 100% oxygen is delivered to the respiratory tract at the beginning of the decompression there is a very significant impairment of performance during the period from 13 sec to 40 sec after the decompression.

Extensive studies at the RAF Institute of Aviation Medicine of the effects of rapid decompression (times of decompression varied between 1.5 and 90 sec) whilst breathing air from 8000 feet to final altitudes between 25,000 feet and 43,000 feet in which 100% oxygen has been delivered to the respiratory tract

at various intervals after the decompression have led to the conclusion that there is a significant impairment of performance and detectable changes in the eeg if the alveolar P_{O_2} is reduced to below 30 mm Hg even for a very short period. Performance has been measured by testing the ability of the subject to reproduce a recently learnt sequence of operations of a set of three keys (12) and the reaction time to a rapidly repeated spatial orientation task (13). The intensity of the changes of the eeg and the degree of impairment of performance have been found to be proportional to the magnitude of the hypoxic pulse as expressed by the area on an alveolar P_{O_2}-time plot below a P_{O_2} of 30 mm Hg. The intensity of the hypoxic pulse increases as the final altitude is raised progressively above 30,000 feet and as the interval between the beginning of the decompression and the delivery of 100% oxygen to the respiratory tract is lengthened.

Any impairment of performance as detected by the two tests used in these studies is considered to be unacceptable in aircrew who are required to perform skilled tasks during and following a rapid decompression in flight. It follows therefore that the alveolar P_{O_2} should not fall below 30 mm Hg during or immediately after a rapid decompression. Thus, whilst with decompressions to an altitude of 25,000 feet the delivery of 100% oxygen can be delayed for up to 15 sec, oxygen must be breathed immediately when the final altitude is 30,000 feet. At final altitudes greater than 30,000 feet the concentration of oxygen in the gas breathed at 8000 feet before the decompression must be greater than 21% even if 100% oxygen is breathed immediately the decompression occurs. The concentration of oxygen which must be breathed before a decompression to prevent alveolar P_{O_2} falling below 30 mm Hg assuming that 100% oxygen is delivered to the respiratory tract as the decompression occurs will depend upon the initial and final altitudes (and to a smaller extent upon the duration of the rapid decompression). The relationships between the concentration of oxygen required in the inspired gas and cabin altitude to prevent significant impairment of performance (i.e. the alveolar P_{O_2} falling below 30 mm Hg) following rapid decompression to various final altitudes are depicted in Figure 1. Analysis of this relationship shows that even in combat aircraft with a 5.25 Lb./sq.in. cabin pressure differential the concentration of oxygen required to prevent significant hypoxia on a rapid decompression (assuming 100% oxygen is delivered immediately the decompression occurs) exceeds that required to maintain an inspired P_{O_2} of 149 mm Hg during routine flight at cabin altitudes above 16,000 feet i.e. aircraft altitudes greater than 40,000 feet. It can also be calculated that the concentration of oxygen required to prevent hypoxia following rapid decompression exceeds that necessary to maintain an inspired P_{O_2} of 122 mm Hg (equivalent to breathing air at 5000 feet) at cabin altitudes above 14,000 feet i.e. an aircraft altitude of about 35,000 feet. These requirements with regard to the prevention of hypoxia following rapid decompression assume that 100% oxygen is breathed immediately the decompression occurs. A delay in the delivery of 100% oxygen beyond the beginning of the rapid decompression can induce severe hypoxia (14). The design of the oxygen delivery system should ensure the delivery of 100% oxygen to the mask cavity within 2 sec of the beginning of a rapid decompression to an altitude in excess of 30,000 feet.

RELATIONSHIP BETWEEN OXYGEN CONCENTRATION AND CABIN ALTITUDE

The ideal relationship between concentration of oxygen in the inspired gas and cabin altitude is set by a number of physiological and operational factors. As has been seen the minimum concentration is determined by the need to prevent significant impairment of performance during routine flight and following a rapid decompression. The actual relationship between the minimum acceptable concentration of oxygen in the inspired gas and cabin altitude necessary to meet the physiological requirements is set by the cabin pressurisation schedule and the flight altitude of the aircraft. In aircraft with high differential pressure cabins the minimum acceptable concentration of oxygen in the inspired gas is determined principally by the requirement to prevent hypoxia on rapid decompression. Thus in aircraft with high differential pressure cabins (8 - 10 Lb./sq.in. gauge) in which the cabin altitude during routine flight does not exceed 6000 - 8000 feet the concentration of oxygen in the inspired gas must exceed that in air if hypoxia is to be avoided following rapid decompression to a final altitude above 30,000 feet. When the final altitude after sudden decompression is 40,000 feet about 40% oxygen (Figure 1) must be breathed before the decompression if transient hypoxia is to be avoided (assuming that 100% oxygen is breathed immediately after the decompression).

In aircraft with low differential pressure cabins (4 - 5.25 Lb./sq.in.) the concentration of oxygen required in the inspired gas is determined at cabin altitudes of up to about 15,000 feet by the need to prevent hypoxia with the pressurisation system intact whilst at higher cabin altitudes it is set by the need to prevent hypoxia on a rapid decompression. The heavy solid line in Figure 1 shows the minimum concentration of oxygen required in the inspired gas in a typical combat aircraft (cabin pressure differential of 5.25 Lb./sq.in.). The maximum concentration of oxygen acceptable in the inspired gas is determined by the need to avoid lung collapse on exposure to sustained accelerative forces ($+G_z$) and to prevent delayed otitic barotrauma (15).

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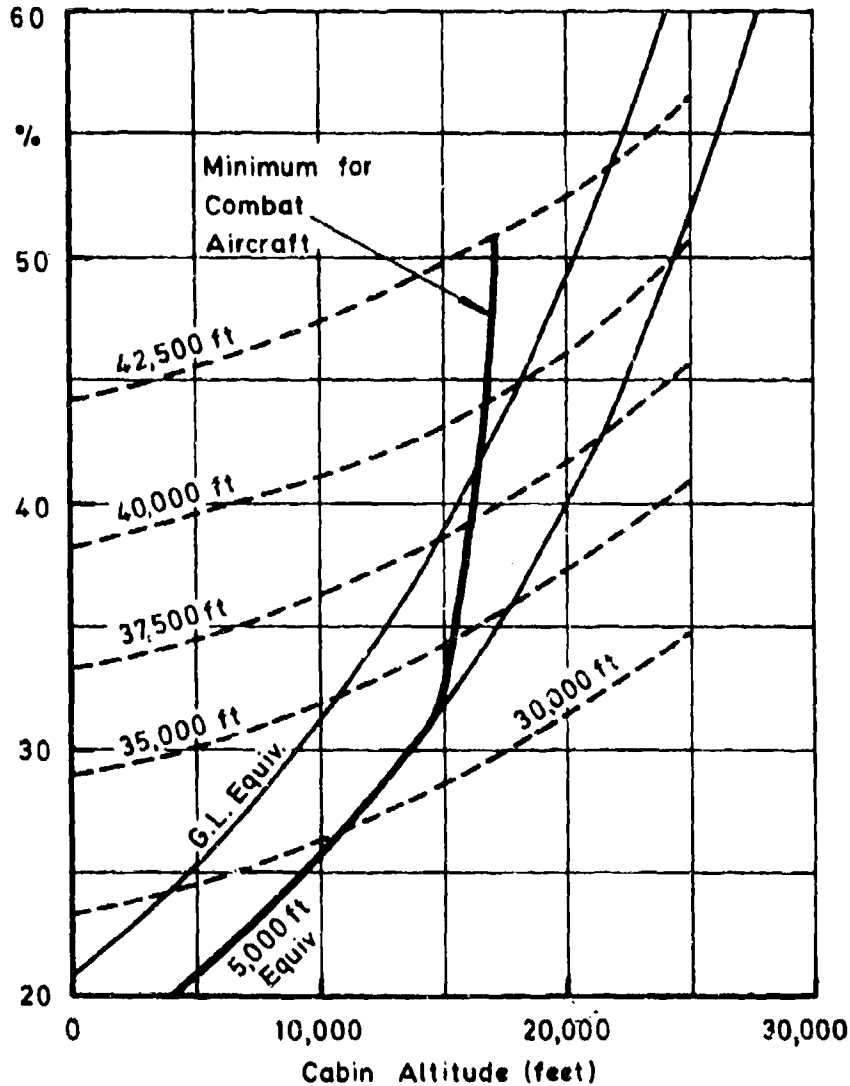   altitude.   Aerospace Med. 34, 991.

Figure 1. Relationships between concentration of oxygen in the inspired gas and cabin altitude required (i) to maintain alveolar PO_2 at 103 mm Hg (curve marked G.L. Equiv.), (ii) to maintain alveolar PO_2 at 75 mm Hg (curve marked 5,000 ft Equiv), (iii) to prevent significant hypoxia on rapid decompression to final altitudes between 30,000 and 42,500 feet providing 100% oxygen is breathed immediately the decompression occurs (dotted curves marked 30,000 ft, 35,000 ft .... 42,500 ft) and (iv) depicting minimum concentration of oxygen required at various cabin altitudes in a combat aircraft with a maximum cabin differential pressure of 5.25 Lb./sq.in. gauge (solid curve marked minimum for combat aircraft).

SEAT MOUNTED OXYGEN REGULATOR SYSTEMS IN
UNITED KINGDOM AIRCRAFT

by

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SUMMARY

The rationale for mounting a demand oxygan regulator assembly on the ejection seat of combat air-craft has been described. The special facilities which have been incorporated in systems used in the Royal Air Force by utilising the advantages of seat mounting are discussed and it is considered that the system provides true duplication of essential components, allows very simple crew drills and reduces aircraft servicing penalties in the event of malfunction of the regulator package.

INTRODUCTION

In recent years, a variety of sites within aircraft cockpits have been used for mounting the demand regulator which controls the composition, flow and pressure of the gas delivered to the crewman.

Many of the aircraft currently operated by the Royal Air Force incorporate oxygen systems in which the regulator is torso mounted. Mounting in this site has many advantages over panel mounted regulators, including ease of servicing, and ready accessibility but suffers severe disadvantages because of vulner-ability to damage and many more regulators than aircraft are required to meet the service needs.

A review of the available sites for mounting a demand regulator conducted within the United Kingdom, concluded that the most desirable position is on the side of the ejection seat. This paper describes the advantages embodied in these systems and the special features of these systems used in United Kingdom aircraft.

ADVANTAGES OF SEAT MOUNTED OXYGEN REGULATOR SYSTEM

1)   Miniature man mounted oxygen regulators in present systems are sited on the crewman's torso harness. The introduction of improved harness restraint systems has led to withdrawal of the torso harness thus the convenient location on the crew member's chest is no longer available. Therefore positioning the regulator elsewhere in the cockpit is required.

2)   A chest-mounted regulator is extremely susceptible to damage. Experience has demonstrated that a high proportion of the unserviceability associated with man mounted regulators has been caused by blows to the regulator either during donning or doffing the torso harness, or entry and exit from the cockpit.

3)   A seat mounted regulator reduces the amount of equipment carried by the crewman. Aircraft equipment assemblies are bulky and any reduction in the equipment carried by the crewman has advantages. Further-more there is more space available on the seat than there is on the man.

4)   Since there is more space available on the seat it is possible to make the regulator package larger than that which can be comfortably mounted on the crewman so that more comprehensive protection for component failures including duplication of regulators can be provided.

5)   Duplication of regulators increases the flexibility and operational capability of the system so that either the main or emergency oxygen supplies may be used through either of the regulators. The outlets of the two demand regulators being connected via a single hose to the crew member's oro-nasal mask.

6)   The total number of regulators required on au aircraft fleet is considerably less than the number required when demand regulators are issued personally to all aircrew.

SPECIAL FEATURES OF UNITED KINGDOM SEAT MOUNTED OXYGEN SYSTEMS

1)   Oxygen supply

Two separate stores of oxygen are provided, main and emergency. The main supply is used throughout routine flight and the emergency only in the event of failure or contamination of the main supply or following ejection. The main oxygen supply may be stowed either in liquid or gaseous form, but in order to achieve optimum regulator performance the pressure at which the gas is delivered to the regulator is maintained within narrow limits (70-80 Lb/sq in). It is carried to the seat mounted regulator assembly by a flexible pipe through a quick release self-sealing coupling.

The emergency oxygen supply enters the regulator assembly through the same port as the main supply. The on/off valve at the outlet of the emergency oxygen cylinder can be operated manually by the crew member by means of a control on the front of the seat pan. It is also turned on automatically on ejec-tion. The pressure at which the gas from the emergency oxygen supply is delivered to the regulator assembly is reduced by a valve to 45 Lb/sq in. This arrangement ensures that if both the main and emergency supplies are turned on, the main supply is used in preference to the emergency supply. The crew member can determine whether or not the emergency supply is being consumed as a pressure gauge

indicating the contents of the emergency supply cylinder is mounted on the front of the seat pan at a position where he can see it in flight.

2) Regulator Assembly

Consideration of the essential components of the oxygen delivery system which it is estimated are the most likely to malfunction during flight has resulted in the decision to employ two demand oxygen regulators in the seat mounted regulator assembly. The regulator to be used is brought into operation by switching the common oxygen supply (from the main and emergency stores) to that regulator.

However complete duplication of the regulators would require that each of the regulators provided all the facilities, namely airmix and 100% oxygen with automatic safety pressure and pressure breathing, However, the provision of both air dilution and 100% oxygen in the same miniaturised regulator imposes certain compromises on performance and it was decided that one of the two regulators would provide airmix whilst the other provided 100% oxygen. Selection of airmix or 100% oxygen during flight then becomes simply a matter of switching the oxygen supply to the appropriate regulator. Thus the valve in the oxygen supply line becomes the airmix/100% oxygen selector switch. The airmix regulator is then the primary regulator which is used throughout flight whilst the 100% oxygen regulator (the secondary regulator) is used only in the event of a failure of the airmix regulator or when 100% oxygen is required, This arrangement does not provide air dilution with its attendant economy of the use of oxygen in the event of failure of the primary (airmix) regulator. The crew member can however continue to use the aircraft oxygen supply through a demand regulator and the only penalty of failure of the primary (airmix) regulator is a reduced endurance and the physiological disadvantage associated with breathing 100% oxygen. It is necessary to fit an oxygen pressure opening valve to the air inlet of the airmix regulator in order to ensure that air cannot enter the system when the 100% oxygen regulator is selected, This air shut off valve only opens when there is an adequate oxygen supply pressure to the inlet of the airmix regulator. This feature also provides a warning to the crewman in the event of failure of the main supply when the airmix regulator is selected. The air-inlet would shut and he would experience difficulty breathing in.

The primary airmix regulator provides all the necessary facilities, namely oxygen diluted with air, automatic safety pressure at cabin altitudes above 15,000 feet and pressure breathing above 40,000 feet. It also has a press-to-test facility whereby the mask pressure can be raised to 20-30 mm Hg in order to test the function and the integrity of the system before (and during) flight.

Minimal reduction of operational capability is imposed on selection of the secondary 100% oxygen regulator following a failure of the primary airmix regulator because the former also provides automatic safety pressure and pressure breathing. Safety pressure is required when 100% oxygen is selected in order to ensure adequate protection of the respiratory tract against toxic material in the cockpit atmosphere. Thus the secondary 100% oxygen regulator provides a fixed safety pressure from ground level to 40,000 feet and pressure breathing above 40,000 feet.

The masks used with the seat mounted system are fitted with conventional inlet non return and compensated outlet valves. Such a mask valve system has the disadvantage that a rise of pressure in the delivery hose relative to that of the cockpit environment due to; head movement causing hose pumping, overshoot by the regulator, a leak across the demand valve of the regulator or a rapid decompression, produces excessive resistance to expiration. This disadvantage is overcome in the seat mounted regulator assembly by fitting a compensated dump valve between the outlet port of the regulator and the cockpit. The datum pressure for this dump valve is obtained from the reference chamber for the breathing diaphragm of the regulator in use.

The two regulators are built into a single assembly which has a single inlet port and a single outlet port. The regulator assembly is attached to the forward surface of the personal equipment connector (PEC). The regulator-PEC combination can be easily and rapidly removed from and replaced on the side of the pan of the ejection seat.

3) Emergency control

There is a mechanical link between the emergency oxygen control on the front of the seat pan and the airmix/100% oxygen selector switch of the regulator assembly. This link is such that whenever the emergency control is pulled to turn on the emergency oxygen supply the selector level switches the oxygen supply from the primary (airmix) regulator to the secondary (100% oxygen) regulator. Thus, in turning on the emergency oxygen supply the crew member automatically selects the secondary regulator, ie under normal flight conditions pulling the emergency oxygen control not only turns on the emergency supply but also selects the secondary regulator. Should the main oxygen supply be intact the crew member will continue to use oxygen from it. If however the main supply has failed he will suffer no interruption to his oxygen supply. He will however be aware that he is using the emergency oxygen supply by the cessation of operation of the flow indicator (which is contained in the main supply line) and the progressive fall in the contents of the emergency oxygen cylinder.

The mechanical linkage between the control operating the emergency supply and the valve switching the oxygen supply (main and emergency) from the primary to the secondary regulator greatly simplifies the drills to be carried out by a crew member in the event of an actual or suspected malfunction of his oxygen delivery system. The drill is the same for all malfunctions namely check the integrity of connections and pull the emergency oxygen control. If the emergency oxygen cylinder remains full then the crew member can continue the sortie at altitude. It is also possible for him to reselect the primary (airmix) regulator after operating the emergency oxygen control and determine whether the primary regulator is still performing correctly.

The possibility of linking the emergency oxygen control with the primary/secondary regulator inlet valve which markedly simplifies emergency drills is one of the major advantages of mounting the regulator on the ejection seat.

ABSORPTION, METABOLISM AND EXCRETION OF HYPNOTIC DRUGS

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Summary

Absorption, metabolism and excretion are the processes which govern the growth
and decay of plasma concentrations of all drugs, including hypnotics.
Variations in plasma concentrations lead to corresponding variations in effect,
although the exact detail of the relation between level and effect is more
complex than is implied by this statement. Existing data on absorption,
metabolism and excretion for the various hypnotic drugs are of variable detail.
Total absorption of oral doses is generally believed to occur, although when
systematically examined, absorption has sometimes been found to be incomplete.
Metabolism occurs by a variety of reactions, but only occasionally to
pharmacologically-active compounds. Excretion is of both unchanged drug and
metabolites in bile and urine. These events and processes as they relate to
hypnotic drug actions are considered in detail in this paper.

Introduction

For an orally-administered drug to exert a hypnotic effect it must first be absorbed from the
gastrointestinal tract. It must then be transported from the portal circulation to the central nervous
system, and it must be capable of penetration to its site of action in its target tissue, the brain.
For its effect to wear off when no longer required, the drug concentration in the brain must fall, and
this will generally occur by metabolism and/or excretion. The processes of absorption and tissue
distribution comprise drug disposition. The processes of metabolism and excretion are important in the
fate of the drug. Drug disposition and fate are conveniently studied by measurement of drug concentrations
in body fluids, principally plasma. The study of drug concentrations in plasma is sometimes termed the
science of pharmacokinetics (1).

Basic Pharmacokinetic Phenomena

Standard reference data is most readily obtainable from experiments with intravenous doses. When
a drug is administered rapidly by this route (injection time less than one circulation time) a number of
clearly definable pharmacokinetic phases appear to occur in sequence: (i) a phase lasting less than one
minute when the dose is unevenly distributed through the plasma volume; (ii) a phase of variable length
during which distribution in the plasma is basically uniform, and during which equilibrium distribution
into tissues of high vascularity such as liver, lungs and brain (in spite of restrictions imposed by the
blood-brain barrier) is gradually achieved; (iii) a further phase, also of variable length, during which
distribution in the plasma and tissue of high vascularity is at equilibrium, and during which distribution
into body areas of low vascularity such as voluntary muscle and fat, is gradually achieved; and (iv) a
final phase during which equilibrium concentrations (but not necessarily even distribution) have been
reached throughout the body. There is obviously some overlap of these phases, as, for example, the
relatively slow penetration of fat commences as soon as any molecules reach plasma. However, generally
speaking, these various events affect drug concentrations in plasma as if they occurred sequentially.
Ignoring the initial phase, which has no relevance to current usage of hypnotic drugs, concentrations of
drugs decline most rapidly during the second phase and most slowly during the final phase. The final
phase indicates the rate of release from tissues for metabolism and excretion once equilibrium has been
reached.

When intravenous doses are given relatively slowly (e.g. over five minutes) there is an increased
degree of overlapping of the pharmacokinetic phases, with the initial phase disappearing completely. A
further mode of intravenous injection, infusions, is designed to balance exactly the declining concentration
with continuous input.

Oral (and intramuscular) administration adds a new dimension, in that the dose requires a finite
time for absorption into the blood. A definable phase of rising concentration in plasma thus occurs.
Absorption apparently never occurs in less than one circulation time, so the initial phase seen following
intravenous dosage disappears. The second and third phases are commonly still evident following the peak
concentration (which indicates the point beyond which absorption is of minimal importance), as absorption
clearly must occur more rapidly than does tissue penetration (otherwise the concentration in plasma might
never rise). Even so, when absorption occurs relatively slowly, the second and third phases recorded
during the intravenous study may disappear, leaving only a rise in concentration (with absorption as the
major influence) followed by a fall (with metabolism and excretion as the major influence).

Additionally, oral doses (and intramuscular doses more rarely) are subject to: (i) delay before
absorption commences; and (ii) incomplete absorption. The former will lead to a lag before the rise in
concentration commences. The latter will lead to the recording of a reduced area under the curve of a
graph of concentration against time, compared with that following an intravenous dose.

The most important pharmacokinetic measurement is the time for a drug concentration to fall by half (the half-life or half-time). It must be appreciated that this time will he relatively short if measured in any phase of a declining concentration-time curve other than the final one.

In considering individual examples in this paper I shall ignore the initial phase following intravenous doses. I shall refer to half-times during the second and third phases together as pre-equilibrium half-times. I shall refer to half-times during the final phase as elimination half-times. I shall also refer to absorptive phases and to areas under the curve when assessing rates and degrees of absorption.

Pharmacokinetic Data for Various Actual or Potential Hypnotics

This section should be read in conjunction with an examination of the data in Table 1 (2-15). These data are provided for reference purposes, rather than commitment to memory. The various compounds now in use, or potentially useful, as hypnotics, have been studied in various ways, although few have been adequately assessed. For example, not all have been studied following intravenous doses, and without such studies, conclusions about half times and absorption are inevitably tentative. Of those compounds which have been assessed following intravenous doses, only one (chlordiazepoxide), failed to show a pre-equilibrium half-time and an elimination half-time. In contrast with this, sophisticated mathematical analysis of diazepam data following intravenous doses has apparently demonstrated subdivision of the pre-equilibrium phase into two distinct lesser phases (the second and third phases discussed earlier).

With some examples, it has been claimed that a pre-equilibrium phase and an elimination phase are detectable after the concentration peak following oral doses. While these phases are undoubtedly detectable at times, any such claim must be considered very carefully, as continuing absorption can greatly distort the falling phases, even though the peak plasma level may have passed. This may be the reason for apparent discrepancies, for example, that between oral and intravenous pentobarbitone.

Absorption of Oral Doses

As implied earlier, very few hypnotics have been studied systematically in regard to their absorption. Systematic study would involve determination of mechanisms, and quantitative assessment by means of intravenous and oral doses of the rate and extent of absorption from plasma level data. As regards mechanisms, it may be presumed that absorption occurs by diffusion, down concentration gradients from the gastrointestinal lumen to the blood, and that active transport plays virtually no part. Absorption will occur to some extent from the stomach, but principally from the intestine, being influenced by the chemistry of the drugs concerned and by a wide variety of non-specific factors, including gastric emptying time and surface areas available for absorption.

Only with diazepam, chlordiazepoxide and nitrazepam has a reasoned comparison between data following intravenous and oral doses has been made. With diazepam, the ratio of area under the curve (oral/i.v.) ranged from 0.901 to 1.205 (mean 1.002). These data indicate that oral doses of diazepam are completely absorbed. In contrast, examination of similar data for nitrazepam revealed a mean figure of 78 (range 53-94)% absorption, and for chlordiazepoxide 81% (single subject).

Certainly with most, perhaps with all of the other compounds in Table 1, it is generally supposed that the entire oral dose is absorbed, and there is no evidence to suggest that this supposition is incorrect in any particular case. Nevertheless, caution is necessary, as systematic examination of absorption often reveals anomalies. This occurred, for instance, with chlorpromazine, which is extensively metabolized in the intestinal wall (16). In particular, claims of full absorption based solely on oral data must be viewed with suspicion. Such claims are often made following a common abuse of pharmacokinetics, involving estimation of the time at which absorption apparently ceases, and calculation of relative absorption at times up to this point, which inevitably provides a 100% asymptote in any graphing of the data obtained.

Metabolism and Excretion

Metabolic reactions of drugs are relatively uninteresting unless they are involved in some way with the pharmacological actions of the compounds in question. Generally speaking, drug metabolism, which occurs principally in the liver, leads to relatively polar drug metabolites. These polar metabolites are more likely than the parent drugs to be actively excreted in bile and in the renal tubule. Additionally, they are less likely to be reabsorbed by diffusion in the renal tubule after filtration at the glomerulus. Thus drug metabolism facilitates drug excretion by mechanisms common to a wide variety of examples.

Barbiturates are principally metabolized by oxidation of the alkyl side chains, producing inactive compounds.
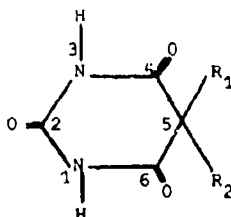

(A)

The side chains are R_1 and R_2 in formula A. For example, phenobarbitone (R_1 = phenyl; R_2 = ethyl) is metabolized to p-hydroxyphenobarbitone. Additionally, thiobarbiturates (in which C-2 is replaced by S) are converted by substitution to conventional barbiturates (e.g. thiopentone to pentobarbitone). Also, hydrolysis to urea and a malonic acid derivative is possible. This last reaction removes activity (17).

The major route of metabolism of methaqualone (B) in man is by hydroxylation of the tolyl substituent. Little unchanged drug is excreted. Additionally, an N-oxide has been isolated as an intermediate in the formation of 2-nitrobx o-o-toluidide. These reactions are not considered likely to lead to active products (18).

(B)
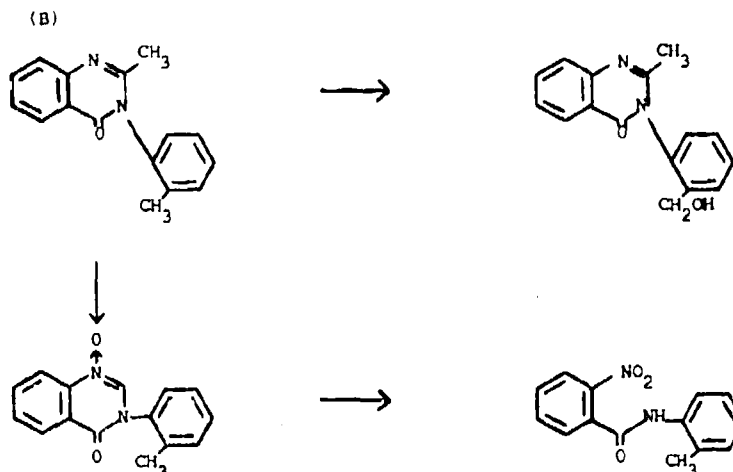
Ethinamate (C) is metabolized by hydroxylation and glucuronidation (19).

(C)
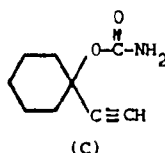
Glutethimide (D) is also metabolized by this route, but there are several isomers possible, and there is a suspicion that 4-hydroxyglutethimide is pharmacologically active (20). The hydroxylation reactions are shown below.

(D)
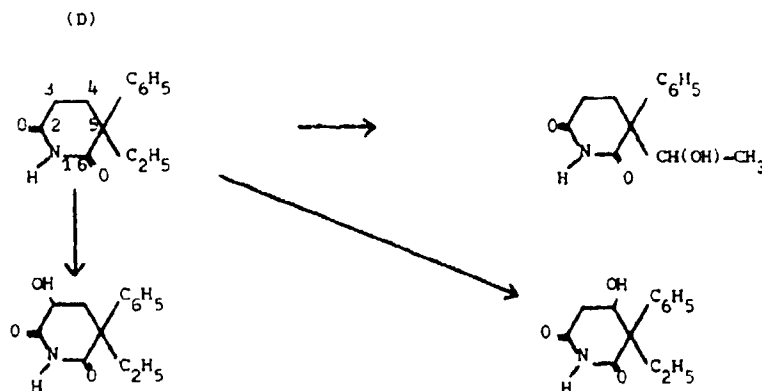
The metabolism of the benzodiazepines is of considerably greater interest. The major reactions occurring are: (1) demethylation and deamination; (2) oxidation; and (3) reduction of N-oxides. This makes possible a wide range of related compounds. For example, the compounds in Fig. 1 are all related metabolically, and many of them are marketed drugs. Generally speaking, however, the only compound found as a metabolite (as opposed to following its own administration) is N-desmethyldiazepam. The major benzodiazepines not shown in Fig. 1 are nitrazepam (E) which is metabolized by reduction of the nitro group, in addition to the oxidations mentioned above, and flurazepam (F), which is metabolized to N-desalkyl derivatives analogous to those arising from diazepam (21, 22).

(E) (F)
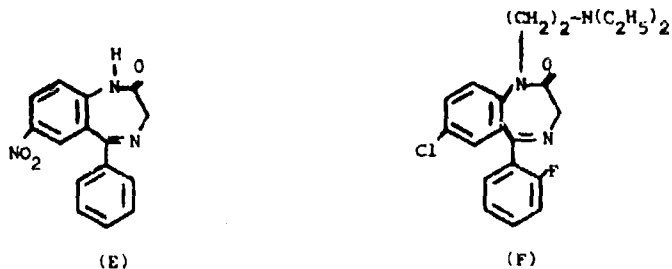
General Considerations

Generally speaking, the time course of onset and duration of drug effect relates closely to the disposition and fate of the drug in question. There are, of course variations in human sensitivity, influences from tolerance, metabolite phenomena, and other reasons for this general principle to appear to fail on occasions, but its value as a rule of thumb is undoubted.

Most of the drugs used as hypnotics appear to show a two or three-phase plasma level pattern during oral dosage, with a rising phase and one or two phases of fall in concentration. These phases of fall have the pre-equilibrium and elimination half times mentioned earlier. Induction and wear-off of depressant effects can be presumed to occur at points on either side of the peak concentration, not necessarily at identical concentrations in each case. Induction or onset of effect will clearly occur on the rising phase, and will thus relate to degree and speed of absorption. In the field of hypnotics, there is little evidence for any dramatic differences in degrees of absorption, but rates of absorption vary enormously. At a first approximation, the time of the peak concentration assesses the moment when absorption has virtually ceased. Mean times recorded for this peak vary from 1.1 hours after the dose (diazepam) to 6 hours after the dose (heptabarbitone). Within the data for each compound, variation can be as much as from 2-12 hours (mean 3 hours) after the dose (quinalbarbitone). Since intensity of effect relates closely to the overall level, and since the height of the peak is inversely related to the time taken to reach the peak, the rate of absorption is also capable of exerting a dramatic effect on the overall level of effect. Similarly, pre-equilibrium and elimination half times will both be of importance to the time course of drug action, and elimination half times will also be the most obviously useful indicators of rates of loss of drugs from the body. These half times can also be used to indicate levels of drug localization in tissues.

(I) (IV)
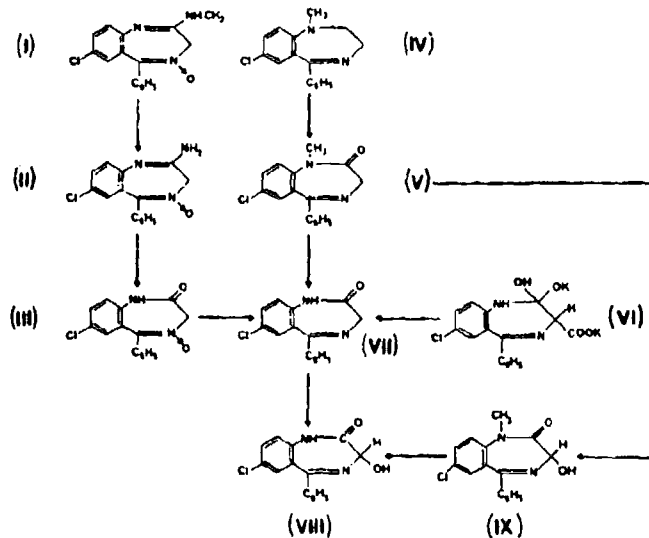
(II) (V)

(III) (VII) (VI)

(VIII) (IX)

Fig. 1. Metabolic relation of various benzodiazepine drugs. I, chlordiazepoxide; II, metabolite of I; III, demoxepam; IV, medazepam; V, diazepam; VI, clorazepate; VII, N-desmethyldiazepam; VIII, oxazepam; IX, temazepam.

It is with wear-off of effect that difficulties with hypnotics arise, and it should be immediately obvious that the wear-off time will be dramatically affected by the position of the level at which wear-off occurs on the falling concentration pattern i.e. whether it is on an early rapidly falling section or a later slowly falling section, on those occasions when two phases occur. This is shown most clearly with the anaesthetic barbiturate thiopentone, which has been given in various doses to human subjects, and a detailed examination of the data is worthwhile at this point. The doses given were 0.4, 1, 2, and 3.8 g. The times of regaining consciousness were 0.25, 0.5-1, 1½-2½ and 4-6 hours later respectively, the duration

of action being disproportionately long at the higher doses (23). The rate of metabolism was the same in each case. Consciousness was regained when the blood concentration was about 8 µg/ml. This was reached on the early rapidly-falling phase at low doses, and on the later slowly-falling phase at higher doses. The disproportionately long action at high doses thus related to the fact that effects were still obtainable in the post-equilibrium period when decline was slow, after high doses. Thus, if a drug effect wears off during the rapidly falling phase, it is likely to be of brief duration, but if it wears off later, it is likely to be of disproportionately long duration, and low doses may be of one type while high doses may be of the other. It is of interest in this regard that the pre-equilibrium phase has been noticed as persisting for 2 h with amylobarbitone, 3 h with pentobarbitone, and as much as 12 h with diazepam.

It is probably true that a good hypnotic will have rapid onset of effect, and slow and/or irregular absorption (e.g. longer than 2 hours to the peak) will be a disadvantage. Another requirement is complete wear-off of effect within 8 hours of induction of sleep. The exact requirements will of course depend on the reasons for the sleep disorder, but a drug with, particularly, any residual effect on waking will be a bad hypnotic. In fact, most hypnotics actually come into this latter category. Thus amylobarbitone, nitrazepam, and flurazepam have been shown to cause specific impairment of function during the days following single nightly doses (24, 25). Of these compounds, nitrazepam and amylobarbitone have long second phase half-times, and the persistence of effect is not surprising in view of earlier comments on concentrations in plasma. However, heptabarbitone and methaqualone have been found to be devoid of residual effects, in spite of half-times which will still leave a considerable residue in the body at 8 hours (see Nicholson, A. N., these proceedings). It may be that these compounds, unlike nitrazepam and flurazepam, are sufficiently potent as hypnotics for onset and wear-off of effect to occur within the rising and rapid-fall phases, while they are devoid of potency in the small amounts persisting in the slow-fall phase. Conceivably, they might cause residual impairment if doses larger than necessary were to be given for a hypnotic effect. Quite obviously, much more work relating impairment of function to pharmacokinetic factors is required.

Although the benzodiazepines have been extensively investigated as hypnotics, and their potential and known advantages are obvious, little attention has been paid to the prototype compound in this series, diazepam, as a hypnotic. This may have resulted from the quite early discovery of its long half-time. However, small doses of diazepam do have hypnotic action, and this is quite possibly exerted at doses leading to no residual effects. In our department, we recently tested diazepam as a hypnotic in 11 anxious medical students. In a double blind comparison of diazepam (10 mg, one hour before retiring) and placebo, it was shown that the diazepam group experienced significantly superior sleep, with no residual effects, and alleviation of anxiety during the day following. It has already been shown that the metabolite of diazepam, N-desmethyldiazepam, which has minimal sedative properties, is superior to diazepam as an anxiolytic. Since diazepam (10 mg) improves sleep without causing residual effects, it would appear that diazepam in this dosage exerts a hypnotic effect which wears off on the rapidly falling concentration phase, at an early stage (even though this phase persists for as much as 12 hours), while producing its anxiolytic metabolite for exertion of a psychomotor effect during day time. As such, it may be the best hypnotic of all for both anxious and non-anxious patients, (26).

I have not thus far referred to multiple dosing. Ideally, the use of hypnotic drugs would be considered as a series of single doses, such that the dose each evening was given to the patient in a baseline situation as far as his pharmacological features were concerned. However, as shown by the data already discussed, the previous night's dose is unlikely to be totally removed from the body before bedtime the next night. With fixed dosing, the concentration in the body will then build up and although homeostatic influences will ensure that some form of pseudo-steady-state will eventually be reached, and although enzyme induction may actually reduce the drug concentrations below the predicted level, there will still be a persisting residue, day and night, during multiple dosing, at a level higher than that persisting in the body in the day following a single acute dose. If this higher level is above the threshold level for a particular pharmacological effect, then this effect will occur, night and day, in a way not observable after single doses. It is considerations of this type that make phenobarbitone, with its relatively low lipid solubility, slow absorption, slow penetration of the blood brain barrier, and long half-time, unsuitable as a hypnotic, although, of course, some prescribers consider that its day and night sedative properties are of value in their own right (1, 6).

Conclusion

Although much is now known of the absorption, metabolism and excretion of hypnotic drugs, and sophisticated methods now exist for evaluation of hypnotic effect, the relation between pharmacokinetic factors and effect is still far from clear.

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Table 1. Basic pharmacokinetic data for a selection of actual and potential hypnotic drugs.

Example	Route	Dose g(mg/kg)	Pre-equilibrium half-time(h)	Elimination half-time(h)	Time of peak (h)	Ref.
Barbiturates						
Pentobarbitone	I.v. (7 min)	1 (14.0)	1	50	-	2(a)
	Oral	0.2 (-)	<5	>24	<2	3(b)
Amylobarbitone	I.v. (3 min)	-(3.54)	0.6	21	-	4(a)(b)
Heptabarbitone	Oral	450-654(6.6)	-	12	6(1-9);	5
Quinalbarbitone	Oral	225-265(3.3)	-	27	3(2-12)	5
Phenobarbitone	Oral	0.05	-	200	-	6
Butobarbitone	No data available					
Methaqualone	Oral	0.3(3.65-5.08)	-	2.6	1.6(1-3)	7
	Oral	0.3(3.41-4.41)	0.85	16	2.9(2-3.5)	5
Ethinamate	Oral	1(11.3-14.7)	-	2.5	1.6(1-2)	5
Glutethimide	Oral	0.5(5.1-9.3)	3.9(2.7-4.3)	11.6(5.1-22.0)	2.2(1-6)	8
Benzodiazepines						
Diazepam	I.v.	0.01(0.113-0.157)	0.15(0.03-0.22)	31.3(26.7-36.5)	-	9(g)
	Oral	0.01(0.113-0.157)	-	32.3(21.0-46.2)	1.1(1.0-1.5)	9
N-Desmethyldiazepam	Oral	0.02-0.03(-)	-	51(28-86)	Not recorded	10(b)(c)
Nitrazepam	I.V.	0.01(0.16)	-	21.1(17.8-24.0)	-	11(d)(f)
	Oral	0.01(0.16)	-	25.1(21.2-28.1)	2.3(2.0-4.0)	11(d)(f)
Chlordiazepoxide	I.v.	0.02(0.29)	-	14	-	12
	Oral	0.02(0.234-0.338)	-	13(6.6-28.0)	3.7(2.0-6.0)	12
Clorazepate	Converted quantitatively to N-desmethyldiazepam					
Flurazepam	Oral	0.03(0.385-0.461)	-	Approx. 4	4.5(3.0-6.0)	13
Temazepam	Oral	0.03(0.330-0.461)	2-3	15-20	1.25(1.0-2.0)	14
Medazepam	Oral	0.05(0.649)	<0.5	>24	1.5(1.0-2.0)	15
Demoxepam	Oral	0.02(0.234-0.338)	-	37(14-95)	2-8	12

Notes: (a) min in brackets indicates time taken in injecting dose (b) weights not recorded (c) after multiple dosing
(d) data suggest existence of a pre-equilibrium half-time but quantitation not possible (e) where no limites are given,
data is from a single subject, or mean data from groups in a report in which individual data and limits were not recorded
(f) some older data exists, erroneously indicating a six hour elimination half-time, which was obtained by the use of
unsatisfactory chemical methods (g) a third, intermediate phase, with a mean half-time of 2.21 h has been detected.

RESIDUAL EFFECTS OF HYPNOTICS

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Royal Air Force Institute of Aviation Medicine
Farnborough, Hampshire, United Kingdom.

INTRODUCTION

Many studies have investigated the effectiveness of hypnotics and the changes which they induce in sleep patterns, but less is known about their residual effects on performance. Von Felsinger, Lasagna & Beecher (1953) observed impaired performance on tests of visual perception, attention and computation up to 8h after pentobarbitone sodium (100 mg) and Kornetsky, Vates & Kessler (1959) reported deficits on digit symbol substitution and symbol copying around 14-15h after quinalbarbitone sodium (200 mg). More recently, behavioural impairments have been detected to 13h after amylobarbitone sodium (100 mg) (Malpas, Rowan, Joyce & Scott, 1970) and to 12h after butobarbitone sodium (100 mg) (Bond & Lader, 1972).

Tests which involve motor skill may be more sensitive than tests of cognition to the residual effects of a barbiturate (Bond & Lader, 1972). In this context McKensie & Elliott (1965) observed performance decrements on a visual pursuit tracking task 22h after secobarbitone sodium (200 mg), though no changes were detected after 100 mg of the drug (Hartman & McKensie, 1966). The residual effects of hypnotics after their therapeutic purpose has been fulfilled need careful consideration, particularly if they are given to persons involved in skilled activity. We have studied this problem using the technique of adaptive tracking which demands a high level of skill acquired only by considerable practice.

METHODS

Measurement of performance

Performance was measured using an adaptive tracking task. The task required the subject to position a spot inside a randomly moving circle displayed on an oscilloscope. The movement of the spot was controlled by a hand held stick. An error signal, proportional to the distance between the spot and the centre of the circle, controlled the difficulty of the task by modulating the mean amplitude of the movement of the circle. This technique provided the adaptive component of the task which maintained optimum performance of the operator.

The movement of the circle on the oscilloscope was produced by two independent maximum length binary sequences. Low pass filtering smoothed the output of the binary sequences and the movement of the circle was statistically random. Independent x and y signals derived from high grade potnetiometers mounted on the control stick were fed via an 'aerodynamic loop' to the inputs of the oscilloscope. The loop avoided an artificial one to one relation between the control stick and spot movement and smoothed out any small steps caused by the potentiometer windings.

The oscilloscope (Airmec 383) had a sitrotion free, medium persistence tube and displayed the task over an area of 20 x 20 cm. It was modified by the addition of x axis bean switching and allowed two independent signals to be displayed in each axis. A voltage proportional to the distance between the spot and the centre of the target circle was measured and the radial error signal computed. A voltage proportional to the square of the circle radius was subtracted from the square of the radial error signal. The output from the scoring circuit was fed to a voltage integrator and the output of the integrator, scaled from 0-10, controlled the mean amplitude of the task.

At the start of each experiment the output from the integrator was set at zero and the circle was stationary. The subject positioned the spot inside the circle and the negative error signal made the integrator output increase. The circle tended to move away from the spot and, when the spot could no longer be maintained inside the target circle due to the increasing difficulty of the task, the polarity of the voltage to the integrator reversed and the task became less demanding. The integrator had a long time constant which allowed each subject to 'warm up' gradually.

With zero error the task required about 25s to reach maximum difficulty. A constant displacement between the spot and the centre of the circle of 4 cm would reduce the task to zero difficulty within 6s. As the subjects became aware of the penalty of error signals they tried to avoid all errors, but the task did not permit a performance level of 10 to be reached.

An eight channel pen recorder monitored the equipment and the performance of each subject. The position of circle, spot and radial error signal were recorded for each axis together with the output from the task integrator. Each tracking run lasted 10 min and the subjects reached a plateau level of performance within the first 100s of each run. The mean amplitude of the task over the final 500s was computed using a voltage to frequency convertor and digital counter. The subjects were infromed that this time interval only was used in the assessment of their performance, but they were unaware when this period of time commenced.

Subjective assessment of performance

Each subject was presented after each task with a line 100 mm in length. The question 'What standard of performance did you reach' was asked and the subject made the assessment by crossing the line with a pencil between the extremes of Zero and Perfect. The assessment was quantified by measuring in millimetres the displacement of the mark from the Zero extremity.

Experimental procedure

Healthy male volunteers were used. Instructions were given to all subjects to avoid alcohol and they were not involved in any other form of therapy. There were no restrictions on the consumption of non-alcoholic beverages. The experiments were carried out in a sound attenuated and air-conditioned room.

The subjects were required to reach a plateau level of performance on the task before studies commenced. In subjects familiar with this technique, such as pilots, this level of performance would be reached within about five days, but with laboratory personnel a plateau level of performance was usually reached with daily practice after 2-3 weeks. Training sessions were made available during the preceding week of each experiment to maintain levels of performance which had been reached during initial training.

Assessment of the effect of placebo or each drug was carried out over 3 days. On day 1, before the ingestion of placebo or drug, four assessments of performance were made at 0900, 1200, 1500 and 1800h. The capsule (placebo or drug) was given at 2300h the same evening and the subject slept at home. The subjects attended the laboratory on day 1 at 0830h, but were brought to the laboratory on day 2 between 0800h and 0830h. On day 2 perofrmance was measured at the same time as on day 1, i.e. at 0900h (+ 10), 1200 (+ 13), 1500 (+ 16) and 1800 (+ 19h after ingestion of placebo or drug). On day 3 performance was measured at 0900h (+ 34h) only.

RESULTS

The detailed results of a series of investigations are given elsewhere (Borland & Nicholson, 1974, 1975 a&b, Borland, Nicholson & Wright, 1975), but a summary of the studies is of value.

Barbiturates. Decrements in performance were observed at the 10h interval after 200 mg, at the 10h and 13h intervals after 300 mg and at the 10h, 13h, 16h and 19h intervals after 400 mg of heptabarbitone. Decrements in performance at each interval and the persistence of the effects were dose related. Similar results to the 400 mg dose of heptabarbitone were obtained with the 200 mg dose of heptabarbitone sodium. Subjective assessments of performance correlated with measured performance, but the subjects, as a group, over-estimated their performance after placebo and heptabarbitone. With heptabarbitone (400 mg) highly significant decrements in performance persisted to the 19h interval after ingestion, but subjective assessments of performance to the 19h interval did not differ significantly from subjective assessments of control activity of the day before.

Benzodiazepines. Impaired performance was observed at 10h, 13h, 16h and 19h after nitrazepam (10 mg) and at 10h, 13h, 16h after flurazepam hydrochloride (30 mg). Increased reaction time persisted to 16h after nitrazepam and lfurazepam hydrochloride. During the morning immediately after ingestion, the subjects as a group were able to differentiate correctly between placebo and drugs, but they were not able to assess accurately the persistence of the residual effects of nitrazepam. Flurazepam hydrochloride would appear to be a more promising benzodiazepine than nitrazepam for use as an hypnotic by persons involved in skilled activity. There was a rapid recovery of performance during the afternoon and, unlike nitrazepam, subjects retained the ability to recognize impaired skill.

With diazepam (10 mg) decrements in performance on adaptive tracking were observed only at 0.5h and 2.5h after morning ingestion. Reaction time was slowed at 0.5h and 2.5h after diazepam. The subjects as a group differentiated correctly between performance decrements on adaptive tracking and the persistence of the decrement in performance was accurately assessed. However, these studies were carried out on morning ingestion and the possibility does arise that overnight ingestion of diazepam may still give rise to residual effects.

Methaqualone hydrochloride (400 mg). There was no evidence of impaired performance on adaptive tracking from 10h to 19h after overnight ingestion. With reaction time there was an increase at 10h.

DISCUSSION

These studies suggest that the residual effects of hypnotics on performance vary considerably. It would appear that the benzodiazepines, nitrazepam (10 mg) and flurazepam hydrochloride (30 mg) have residual effects comparable to those of heptabarbitone (400 mg) and pentobarbitone (200 mg), and in this respect do not offer an advantage over the barbiturates. Methaqualone hydrochloride (400 mg) and diazepam (10 mg) may prove to be of value as an hypnotic for persons involved in skilled activity, but more information is required on the effectiveness of these drugs as hypnotics. It is, however, likely that diazepam or a closely related drug will prove to be of particular value in the context of this work. Current studies on the effectiveness of diazepam and various derivatives on sleep in man are being published in the British Journal of Clinical Pharmacology (Nicholson, Stone, Clarke & Ferres, 1976, Nicholson, Stone & Clarke, 1976, Nicholson & Stone, 1976, In press).

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PROGRAMME OF FOURTH ADVANCED OPERATIONAL AVIATION MEDICINE COURSE, FARNBOROUGH, 17–26 JUNE 1975

Opening Remarks

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Aviation Medicine
and
Air Commodore D.W.Atkinson, RAF
Director of Health & Research
Ministry of Defence (Air)
UK National Co-ordinator ASMP

Aviation Medicine Training of Aircrew
Chairman -- Air Vice-Marshal R.J.A.Morris, CB, QHS, RAF
Royal Air Force Strike Command

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Work of the RAF Aviation Medicine Training Centre (AMTC) North Luffenham	Wing Commander G.R.Sharp, RAF
Training in the use of oxygen equipment	Wing Commander G.R.Sharp, RAF Dr A.J.F.Macmillan
Orientation training	Dr A.J.Benson Squadron Leader G.J.Murphy, RAAF
Aircrew anthropometry	Wing Commander J.Ernsting, OBE, RAF Mr G.Turner

texts not available for publication

Naval Helicopter Operations
Chairman — Surgeon Captain W.A.N.Mackie, DSC, RN
Royal Navy, Naval Air Command

Underwater escape from helicopters	Lieutenant G.N.Greener, RN
Helicopter operations in NATO	Commander J.D.W.Husband, RN

texts not available for publication

Helicopter operations on the northern flank of NATO	Surgeon Lieutenant Commander A.P.Steele-Perkins, RN
Medical aspects of operating on the northern flank of NATO	Lieutenant W.J.Blake, RN
The operation of Helicopters from small ships	Surgeon Commander J.W.Davies, RN
The immersion victim	Surgeon Commander F.St.C.Golden, RN

Developments in Personal Equipment
Chairman — Group Captain A.J.Barwood, OBE, RAF
Royal Air Force Institute of Aviation Medicine

Mechanics of head protection	Wing Commander D.H.Glaister, RAF
Auditory communication	Mr R.Green
Eye protection and protective devices	Dr D.H.Brennan
Helmet mounted sights and displays	Mr J.Laycock
Current developments of headgear for military aircrew in UK*	Wing Commander J.Ernsting, OBE, RAF
Warning systems in aircraft: considerations for military operations	Squadron Leader D.C.Reader, RAF

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* AGARD Report No.642 (Supplement) classified NATO CONFIDENTIAL contains this paper, together with seven papers delivered

Developments in Personal Equipment (Continued)

Advances in military cockpit displays   Dr J.M.Rolfe

Map displays   Mr R.Taylor

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requirements

Seat mounted oxygen regulator systems in   Dr A.J.Macmillan
UK aircraft

Use of Hypnotics by Aircrew

Chairman — Air Commodore D.W.Atkinson, RAF
Director of Health & Research, Ministry of Defence (Air)

Absorption, metabolism and excretion of   Dr S.H.Curry
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15. Abstract

During June 1975 the Fourth Advanced Operational Aviation Medicine Course was held at the Royal Air Force Institute of Aviation Medicine, Farnborough. Representatives from nine NATO countries attended the course, and they included doctors from sea, land and air forces.

The course covered in depth some aspects of aviation medicine which are of current concern to the effectiveness of NATO air forces. The topics included the training of aircrew in aviation medicine, medical aspects of naval helicopter operations on the northern flank of NATO, developments in personal equipment with special reference to helmet developments, high speed escape and thermal problems, and the use of hypnotics in air operations.

This publication includes lectures delivered to the Course.

This Course was conducted under the auspices of the Aerospace Medical Panel of AGARD.

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