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A LABORATORY COMPARISON OF THREE METHODS OF PERSONAL CONDITIONING

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This Report describes work undertaken jointly with the Royal Air Force Institute of Aviation Medicine. It has also been issued as IAM Report R497.

SUMMARY

Twelve practising aircrew were exposed to a simulated sortie under hot environmental conditions on eight occasions. All combinations of two clothing assemblies, high and low level, and four personal conditioning systems, a water cooled system, a convective air system, a reverse flow system and no personal conditioning were tested. Measurements were made of body temperature (aural), skin temperature, blood pressure, pulse rate, sweat loss and the performance of two cognitive tasks Subjective assessments of thermal comfort were recorded using a 10 cm line technique.

The results show significant increments in thermal stress between the water cooled subjects and the convective air cooled subjects, between the convective air cooled subjects and those with the reverse flow system and between those with the reverse flow system and the unconditioned subjects. The differences between the water cooled and convective air cooled subjects were small compared with the other differences. The performance tests showed advantages to the water cooled subjects compared with all other groups and the water cooled suit was preferred on subjective grounds. It is pointed out that the results of this laboratory trial may not necessarily transfer to realistic operating conditions and that field testing both in flight and using appropriate ground equipment will be required before it can be shown whether these advantages can be realised.

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* Replaces RAE Technical Report 70212 - ARC 32961

CONTENTS

1 INTRODUCTION

With improvements in the performance of modern military aircraft, the maintenance of thermal comfort and pilot efficiency becomes increasingly difficult. The increased cabin heat loads from high speeds and avionics and the insulation of complex clothing assemblies, place severe demands on the performance of cabin conditioning systems if thermal comfort is to be achieved by this means alone. Meeting these demands imposes serious weight, bulk and performance penalties on the aircraft which are likely to become increasingly unacceptable.

At the same time the necessity of maintaining thermal comfort, as opposed to merely limiting thermal discomfort, is becoming more important. The pilot's task is more complex and so performance is likely to be affected by smaller departures from comfort than was formerly the case. Under these circumstances the role of personal conditioning will become more important and improvements over existing systems are essential.

Much previous work has been devoted to the study of air (evaporative and convective) and water cooled systems. However they have usually been assessed in isolation and mostly in laboratory environments which have simulated only some of the activities associated with flying. The literature contains little information on how the systems compare with one another on physiological and subjective grounds when used throughout complete sortie simulations. The aim of the work reported here was to obtain such direct comparative information on three types of personal conditioning systems under conditions representative of the complete thermal experience of a sortie in a modern aircraft.

The results indicate that adequate personal conditioning can be achieved in moderately severe laboratory conditions either by a water cooled suit system or by a convective cooling air system. On physiological, behavioural and subjective grounds the differences between these two systems were small but generally favoured the water cooled suit.

2 METHOD OF TEST

2.1 General experimental plan

Twelve subjects each completed eight experimental sorties, testing all combinations of two clothing assemblies (high and low level) and four personal conditioning systems (three cooling systems and an unconditioned control). The sortie simulation consisted of representative phases for the crew-room, walk-out to aircraft, pre-flight checks and flight. The crew-room phase was preceded by a warm-up period (see below) and the flight phase included a period of simulated high-speed low level flight and ended with a period representing pre-landing conditions. During the sortie, measurements were made of the performance of the supply systems, a variety of physiological parameters and the behaviour of the subjects. Subjective assessments of thermal comfort were made by the subjects at intervals throughout the sortie.

2.2 Statistical design

The subjects completed the experiments in groups of four. The order in which the various combinations of personal conditioning system and clothing assembly were tested was designed to prevent the onset of acclimatisation or other 'order effects' influencing the comparison between the conditioning systems. Details of the statistical design are given in Table 1.

Table 1

Statistical design

Subject	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8
1	A_2C_1	A_1C_2	A_1C_4	A_2C_3	A_1C_3	A_2C_4	A_2C_2	A_1C_1
2	A_1C_3	A_2C_4	A_2C_2	A_1C_1	A_1C_4	A_2C_1	A_2C_3	A_1C_2
3	A_2C_4	A_1C_1	A_1C_3	A_2C_2	A_2C_1	A_1C_2	A_1C_4	A_2C_3
4	A_1C_2	A_2C_3	A_2C_1	A_1C_4	A_2C_2	A_1C_3	A_1C_1	A_2C_4
5	A_1C_4	A_1C_1	A_2C_3	A_2C_2	A_1C_2	A_1C_3	A_2C_1	A_2C_4
6	A_1C_3	A_2C_4	A_1C_2	A_2C_1	A_2C_3	A_1C_4	A_2C_2	A_1C_1
7	A_2C_2	A_2C_3	A_1C_1	A_1C_4	A_2C_4	A_2C_1	A_1C_3	A_1C_2
8	A_2C_1	A_1C_2	A_2C_4	A_1C_3	A_1C_1	A_2C_2	A_1C_4	A_2C_3
9	A_1C_3	A_1C_4	A_2C_2	A_2C_1	A_2C_3	A_2C_4	A_1C_2	A_1C_1
10	A_2C_1	A_2C_2	A_1C_4	A_1C_3	A_1C_1	A_1C_2	A_2C_4	A_2C_3
11	A_2C_4	A_1C_1	A_2C_3	A_1C_2	A_2C_2	A_1C_3	A_2C_1	A_1C_4
12	A_1C_2	A_2C_3	A_1C_1	A_2C_4	A_1C_4	A_2C_1	A_1C_3	A_2C_2

C_1 = No personal conditioning; C_2 = Water cooled system;
C_3 = Convective air system; C_4 = Reverse flow system;
A_1 = High level clothing; A_2 = Low level clothing.

2.3 Subjects

The 12 subjects were all practising aircrew from the Royal Air Force. None was heat acclimatised although all had experience of flying in hot countries. Their physical details and a brief note of their experience are given in Table 2.

Table 2

Physical details and experience of subjects

Subject	Height (cm)	Weight (kg)	Surface area (m^2)	Experience of hot climates
1	173	68.7	1.82	Canberra and Jet Provost in Cyprus 3½ years.
2	174	80.5	1.96	Vulcans in Far East 6 months.
3	180	70.3	1.90	Canberra in Far East 3 years.
4	180	84.3	2.06	Victor in Malta and Cyprus with a 2 week trip to Butterworth.
5	177	76.6	1.93	Victors short trips to hot climates over last 3 years.
6	183	84.2	2.08	Shackletons in Far East 2½ years.
7	190	107.0	2.32	Shackletons in Malta with visits to Persian Gulf.
8	178	77.6	1.95	Beaver and Strikemaster in Arabia 2½ years.
9	179	79.9	1.99	Hastings in Cyprus (never used a cooling system).
10	170	70.7	1.82	Victors for 2½ years, 2 months experience of hot climates.
11	180	81.6	2.01	Short attachments to Near and Far East.
12	178	77.4	1.95	Spent 1 year in Laos with VSO 1962-63. Vulcans to hot climates on short Ranger flights.

2.4 Sortie simulation and climatic conditions

The simulated sortie was devised to include periods representative of the various phases of a typical operational sortie. After an initial pre-conditioning period the phases simulated were a crew-room phase, walk to aircraft, pre-flight phase, and a flight phase. The details of each of these are discussed below and summarised in Table 3.

Table 3

Details of sortie phases

Activity	Pre-conditioning	Dressing	Briefing	Walk out	Checks	Sitting	Work	Sitting	Pre-landing
Duration	10 min	30 min	30 min	10 min	15 min	45 min	30 min	35 min	10 min
Climate									45/27/53 rising to
DB/WB/GT C°	38/27/38	33/26/33		45/27/45	45/27/58	45/27/53			50/32/58
Air movement (ft/min)	Not measured	Not measured		300	300	300			300
Personal conditioning equipment									
Convective AVS (cu ft/min)	Nil	Nil	12.4* (reverse flow)	7.5* 9°C	12.4* 15°C	24.8* 10-35°C			12.4 15°C
Liquid cooled suit (kg/hr)	Nil	Nil	54* approx. 24°C	54* approx. 24°C	46* 15-30°C	46* 15-30°C			46 15-30°C
Reverse flow AVS (cu ft/min)	Nil	Nil	12.4*	7.5* 9°C (direct flow)	12.4*	12.4*			12.4
Unconditioned	Nil	Nil	Nil	Nil	Nil	Nil			Nil

* Uncorrected rotameter readings.

2.4.1 Pre-conditioning. The object of this was to bring the subjects to the sort of thermal condition in which they would be on arrival at a crew-room on a tropical station. Normally subjects arriving at the laboratory from the outside conditions of a UK winter have had a variable 'cold soak' and the first part of any hot exposure would be a rather pleasant means of warming up. To avoid this situation the subjects performed a mild exercise (stepping 15 times per minute on and off a one foot high stool) for 10 minutes in a warm environment (globe and dry bulb temperature 38°C, wet bulb temperature 27°C) prior to the commencement of the crew-room phase.

2.4.2 Crew-room phase. This phase represented the period spent dressing and briefing before walking to the aircraft. The total duration was 60 minutes and the climatic conditions were 33°C dry bulb and globe temperature and 26°C wet bulb temperature. These conditions were selected as representative of internal temperatures in an unconditioned building during the hot season in

Cyprus. During the early part of the phase the subjects were instrumented and dressed in the appropriate clothing assembly, taking about 30 minutes, and then sat comfortably for the remainder of the 60 minutes. During this period each subject drank 250 ml of squash. Clothing that would not normally be donned until immediately before leaving the crew-room, for example the life-preserver, helmet and gloves, were put on at the end of this phase.

2.4.3 Walk-out phase. This phase represented the walk from the crew-room to the aircraft. In practice this involves a variable time depending on local layout and the period of 10 minutes used in this study probably represents a maximum. The climatic conditions (dry bulb and globe temperature 45°C, wet bulb temperature 27°C, air movement 300 ft/min) were dictated by the necessity to conduct this phase in the same climatic chamber as the subsequent in-flight phase. However in view of the absence of a solar radiation simulator, the conditions are probably representative of those in Cyprus in full sun during the hot season. The walk was at 2.5 miles/h over a measured circuit with some subjects carrying portable conditioners as appropriate to the experimental plan (see below).

2.4.4 Pre-flight phase. In this phase which lasted 15 minutes from the end of the walk-out, subjects initially strapped themselves into Mk.3 ejection seats, the instrumentation and personal conditioning systems were connected and adjustments made. Climatic conditions (globe temperature 58°C, dry bulb temperature 45°C and wet bulb temperature 27°C, air movement 300 ft/min) were more severe than during the subsequent in-flight phase as is the case in practice due to hot soak conditions on the ground. Personal conditioning supplies during this phase are discussed below.

2.4.5 Flight phase. The total duration of this phase was 120 minutes representing a rather long sortie for a fighter aircraft. The phase was divided into 4 sections, 45 minutes sitting at rest, 30 minutes of work*, 35 minutes sitting at rest and 10 minutes at the end during which the climate was made more stressful as often occurs in practice prior to landing. Climatic conditions for all except the last 10 minutes were globe temperature 53.5°C, dry bulb temperature 45°C, wet bulb temperature 27°C and air movement

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* The 30 minute work period in this phase was intended to represent a period of high-speed low level flight. In the absence of measurements of in-flight oxygen consumption a work rate was chosen approximately to double the resting oxygen consumption, this being the best available estimate based on measurements of pulmonary ventilation. The work consisted of a simple lever exercise performed with the legs.

300 ft/min. In the absence of accurate measured climatic conditions for high performance aircraft in Cyprus the climate was based on information from the American tropical trial of the Phantom, (Aeronautical Systems Division - US Air Force Systems Command, 1965). During the final 10 minutes of the flight the air and globe temperatures were increased progressively and the personal air supplies were downgraded (see below) since this would normally occur in practice during pre-landing circuits with low engine revolutions.

2.5 Personal conditioning systems

2.5.1 The water cooled system. The water cooled personal conditioning system consisted of a modern prototype suit with a portable conditioner for use during the crew-room and walk-out phases and a fixed laboratory supply during the pre-flight and flight phases. The suit was a Type 1 Series 5 model, internally tunnelled, with approximately 400 ft (120 m) of pipework. The portable conditioner was a Normalair-Garrett chip ice model (Type 1112, F000, RNA YR-A). It measures 15 in × 17½ in × 12 in and weighs approximately 20 lb (9 kg) when charged with ice (about 10 lb of ice). The pump unit provides a flow of about 120 lb/hr (54.5 kg/hr) through the suit and the inlet temperature is controllable down to about 23°C. The conditioner used during the crew-room phase was replaced by one charged with 5 lb of ice for the walk-out. The laboratory supply provided a fixed flow of water at 100 lb/hr (46 kg/hr) at a temperature controllable (by the subjects) between 15 and 30°C. The water cooled system was identical for the high and low level clothing runs.

2.5.2 The convective air cooled system. In determining the supply specification for this system some compromises were made on an 'ideal' system so that its performance would not exceed limits achievable in practice. Thus for the crew-room phase a reverse-flow supply (see below) was used at a flow rate of 1 lb/min since fully conditioned convective supplies in crew-rooms are not likely to be available in practice. For the walk-out a conventional supply of 0.6 lb/min at 9°C was provided representing the likely performance of the Normalair-Garrett portable air conditioner now under development. Since these conditioners were not available the supply was piped from laboratory sources and the subjects carried mock conditioners of appropriate weight (15 lb). For the flight phase supplies were provided at 2 lb/min with the temperature controllable down to 10°C. This performance is representative of that available in the Buccaneer S Mk.2 (RAF) (Hawker Siddeley Aviation Ltd., 1968). For the preflight and pre-landing (last 10 minutes) phases this performance was downgraded to 1 lb/min at 15°C to represent supplies that might be available from a ground air ventilated suit (AVS) trolley or from the aircraft system during low engine speeds. A Mark 3 convective AVS was used for all runs using the convective cooling supply. It is appreciated that this suit is not ideal for evaporating sweat and that a suit supplying equal volume flow to equal skin areas would have been better during the crew-room phase when reverse flow (evaporative) supplies were used. However, it is clearly not practicable to change suits halfway and, in the absence of a variable distribution AVS, the compromise was made in favour of the longer flight phase.

2.5.3 The reverse flow air system. The potential merits of this system have been pointed out for some time by the Institute of Aviation Medicine. When ambient air conditions are the same as those of the AVS supply air, a system sucking air through the AVS in the reverse direction from normal is very nearly as effective as the conventional blown supply (Morrison, 1969). The potential advantage of a reverse flow system is that it avoids the compression and frictional heating effect of electrically driven fan supplies, which can give rise to temperature increases of 15-20°C in the supply air, and thus removes the overriding disadvantage of these extremely simple and engine independent systems. Flight tests in a Vulcan (Allan *et al.*, 1969) have demonstrated some of the practical advantages of reverse-flow systems but the overall potential of the system has yet to be fully appraised (Allan, *et al.*, 1970). In the interest of obtaining further information on reverse flow systems one was included in the present trial. A reverse flow of 1 lb/min was provided during the crew-room, pre-flight and flight phases which was not downgraded at any stage since the system in practice would be independent of the engines. During the walk-out the subjects used the same supply as those on the convective air system since this type of supply could be available regardless of the aircraft installation. A portable reverse flow ventilator is now under development but accurate performance and weight data were not available at the time of this trial. A reverse flow supply will generally require a low back pressure equal distribution AVS and for this trial a prototype air ventilated air-crew coverall was used throughout for low level runs and an AVS Mark 4 (Type 3a), which is a low back pressure evaporative suit for the high level runs.

2.5.4 Unconditioned control. To provide comparative data each subject completed control runs with no personal conditioning. For these runs, of course, personal conditioning garments were not worn.

2.5.5 Other clothing items. In addition to the conditioning garments detailed above the subjects wore the following items of clothing:

(a) Low level assembly. Jockey type underpants, anti-G suit Mark 7, aircrew coverall Mark 7 (except for reverse flow subjects who wore the air ventilated coverall), socks terryloop, flying boots 1952 pattern, cape leather gloves, life preserver Mark 9b, inner 'G' helmet, protective helmet Mark 1a and P or Q mask.

(b) High level assembly. All items were as for the low level runs except for the anti-G suit which was replaced by a combined partial pressure anti-G suit. This was a prototype garment without integral ventilation (developed for Lightning 3).

Oxygen was not used; warm ambient air was breathed throughout the tests.

3 MEASUREMENTS

3.1 Supply systems

The water suit supply flow and inlet and outlet temperature at the suit connector were recorded continuously during the flight phase. No in-sortie performance measurements were recorded from the portable water conditioners but these were checked before and after use. Air flow in both air systems were controlled at the intended level by monitoring the supply pressure measured at the suit inlet. This was converted to flow by reference to standard pressure-flow curves for the suit. The temperature of the convective cooling supply (adjustable by the subject) was measured at the suit inlet and recorded continuously. The 'portable' air supplies were controlled at the intended flow and temperature by continuous monitoring and manual adjustment by observers.

3.2 Physiological measurements

3.2.1 Body temperature. Deep body temperature was measured by aural thermistor at the start of the experiment and at the end of each phase. During the flight phase it was recorded continuously. Skin temperatures were recorded separately from five sites, using thermocouple sensors, during the flight phase only. The sites used were the forehead, chest, back, upper arm laterally and medial thigh.

3.2.2 Pulse rate. Pulse rate was counted manually at the end of each phase and recorded electrocardiographically at 10 minute intervals throughout the flight phase.

3.2.3 Sweat rate. Overall sweat loss was measured by nude body weighing at the start and end of the sortie simulation and adjusting the weight loss for the measured drink given during the crew-room phase.

3.2.4 Blood pressure. Blood pressure was measured with a sphygmomanometer during the in-flight phase - 15 minutes before work, midway through work, at the end of work, approximately halfway through the second rest period and at the end of the experiment. These measurements were only made on the last group of four subjects.

3.3 Behavioural measures

3.3.1 Two tasks were used to assess behaviour and to simulate the cognitive work-load associated with a flight. As complete simulation of the flying task was not technically possible, performance assessment was confined to short-term memory and calculation ability, two of the many cognitive processes involved in flight.

The constraints provided by the system, the small amount of space for apparatus, group testing, and limited practice time necessitated simple self-paced, repeatable tests with a small learning component. A further constraint was that the difficulty level of the task had to be increased for the last 10 minutes of the flight in order to simulate the landing phase. In addition to the performance measure, the subjects' confidence in each response was also recorded.

Behavioural testing occupied the last 40 minutes of the sortie, the time-course of the events in this period being:

0 to 15 minutes - memory test
15 to 20 minutes - physiological and subjective measures
20 to 30 minutes - calculation task Part 1
30 to 40 minutes - calculation task Part 2 .

The display, response and recording apparatus were the same for all tasks:

3.3.2 Display. Four digital display tubes connected to an Actan programmer, viz:

A	B	C	D

(for the purpose of discussion these are labelled alphabetically).

3.3.3 Response. Each subject had a panel containing two sets of buttons. There were 10 response buttons labelled 1 to 10 and three confidence buttons labelled, 'Almost certain', 'Fairly confident', and 'Complete guess'.

3.3.4 Recording. A Hewlett-Packard recorder provided a printed record of all responses.

3.3.5 Memory task. Digits appeared on the 4 display tubes according to a prearranged sequence. The display changed at intervals of 7½, 10 and 12½ seconds on a continuous cycle. The subject was required to memorise both the first and second group of 4 digits and, when the third group appeared, he noted the position of the highest number in this group and responded by pressing in the digit from the first group which had appeared in this position. This process was repeated so that the subject was always having to remember the numbers which had appeared two groups before those which were currently being displayed. Confidence in the correctness of each response was recorded.

3.3.6 Calculation task. In this task the subject added digits A and B (see Display). If this sum was even he added, and if it were odd he subtracted, digits A and B and digits C and D. He then reduced this total to a single number by adding the component digits until only a single figure remained. Confidence in each response was recorded. For the first part of the task the digits changed in a cycle of 7½, 10 and 12½ seconds and for the second part, the simulation of the landing phase, the timing was 5, 7½ and 10 seconds.

3.4 <u>Subjective assessments</u>

3.4.1 User opinion as to the thermal comfort provided by the conditioning systems was assessed using a 10 cm line technique (Gedye, *et al.*, 1961). Three types of measure were used and examples of all the scales are shown in Fig.1. The assessments were obtained as follows:

3.4.2 In-sortie. At five times in the sortie, (crew-room, walk-out, end of exercise, mid-test, and end of flight), each subject assessed his thermal comfort <u>at that time</u> on a 10 cm line, the end points of which were labelled 'intolerably cold' and 'intolerably hot'. Separate cards were used for each assessment so that there could be no back reference. All three methods of subjective assessment are illustrated in Fig.1.

4 DEBRIEFING

4.1 Daily

At the daily debrief immediately after the completion of the sortie, each subject rated the thermal comfort of various body parts as he remembered them as having been during the pre-landing phase. The body areas were:

head, chest, back, arms, legs and whole body.

4.2 End of trial debrief

At the end of the trial each subject made a direct comparison of the thermal comfort provided by the various systems. This was made on a vertical 10 cm line where the best and worst systems were assumed to occupy the two endpoints of the line and the position of the other two systems was to be marked at intervening points on this line, the distance between the points being a reflection of the relative merits of the systems.

5 RESULTS

5.1 Supply systems performance

5.1.1 Portable air supplies. The two air systems used a laboratory source of air during the walk-out phase and no information is therefore available as to the performance of an actual portable air conditioner. The air flow and temperature was maintained close to the planned supply of 0.6 lb/min at 9°C.

5.1.2 Convective air system. For the flight phase the supply was a fixed rate of 2 lb/min except during the pre-flight and pre-landing phase when the flow was decreased to 1 lb/min. Inlet temperature was controlled by the pilot down to 10°C during the flight phase but only down to 15°C during the pre-flight and pre-landing phase. The mean choice of inlet temperature during the flight phase is given in Table 4. The results in Table 4 show that subjects wearing high level clothing selected slightly lower temperatures (mean 11.5°C) than those wearing low level clothing (mean 13.3°C). Immediately before the pre-landing phase 6 of the 12 subjects had selected maximum cooling (10°C) when wearing low level clothing and 8 of the 12 when wearing high level clothing. These results suggest that several would have selected colder inlet temperatures had they been available.

Table 4

Mean choice of inlet air temperature °C

Phase	Pre-flight	Flight									Pre-landing
Time (min from start of phase)	14	12	24	36	48	60	72	84	96	108	
High level AEA temperature °C	15.0	13.0	12.5	11.7	11.3	11.0	11.0	11.0	10.9	10.9	15.0
Low level AEA temperature °C	14.7	15.1	14.3	14.7	12.8	12.3	12.4	12.6	11.7	11.8	15.0

5.1.3 Reverse flow. This system was fixed at the planned flow of 1 lb/min.

5.1.4 Portable water conditioners. These were used during the crew-room and walk-out phases, and their mechanical performance has been reported (Beeny, 1970). Temperatures and flow rates were not measured directly but performance was estimated from running times and ice consumption. During the crew-room phase conditioners removed about 110 kcal/hr, while during the simulated walk to aircraft this rose to 180 kcal/hr. All subjects stated that additional cooling capacity was desirable.

5.1.5 'Aircraft' water cooled suit supply. The coolant supply for the 'in aircraft' phases was derived from a rig which gave a flow of 46 kg/hr. The supply temperature was infinitely variable in the range +15°C to 34°C with a time constant of about 8 minutes. The mean values of temperature selected and resultant gross heat pick-up are given in Tables 5 and 6 and are plotted in Figs.2 and 3.

Table 5

Mean choice of inlet water temperature °C

Phase	Pre-flight	Flight			Pre-landing	End
Time (min from start of test)	14	30	60	90	135	145
High level AEA	20.96	21.17	21.19	21.10	20.90	19.91
Low level AEA	19.97	19.23	19.40	19.07	18.68	18.26

Table 6

Mean values of heat pick-up kcal/hr

Phase	Pre-flight	Flight			Pre-landing	End
Time (min from start of test)	14	30	60	90	135	145
High level AEA	271.4	245.5	248.4	235.7	229.4	264.8
Low level AEA	262.3	263.2	249.3	260.8	251.9	280.1

When high level clothing was worn the inlet temperature tended to be constant over all but the last 10 minutes of the exposure and to be 1 to 2°C higher than the corresponding temperature when wearing the 'low level assembly'. Heat pick-up tended to fall probably due to a progressive fall in mean skin temperature which decreased the gradient between the skin and coolant and hence reduced the quantity of heat transferred. This probably indicates a tendency for the subjects to select an inlet temperature which was slightly too low to maintain thermal balance without vasoconstricting.

With low level clothing there was a slight fall in inlet temperature throughout the test, associated with a fall in heat pick-up over the first 90 minutes, followed by an increase during the remaining 45 minutes. This suggests that the subjects were choosing a heat removal rate very close to that required by their metabolism and the environmental heat leak into the man/suit system through the relatively thin clothing worn.

The most extreme values of temperature chosen as a cooling requirement, rather than a temporary setting to explore the available temperature range of the system, were 16.5°C and 25.4°C with high level aircrew equipment assembly (AEA) and 15.2°C and 22.9°C with low level AEA. Three subjects probably had full cold selected for a significant period during their exposure and may have chosen a lower temperature had it been available. However, when asked to comment on the degree of cooling obtainable from the rig, none of the subjects said that it was inadequate.

5.2 Physiological measurements

5.2.1 Ear temperature. The mean ear temperatures for the 12 subjects at the end of each phase of the sortie simulation are shown graphically in Figs.4 and 5 for the low level and high level clothing assemblies respectively.

The differences between conditioning systems are small and insignificant until the end of the first resting period of the flight phase in the low level clothing assembly (Fig.4). Thereafter the results diverge until at the end of the sortie the unconditioned subjects (38.2°C) are significantly hotter than the reverse flow (37.9°C) who are significantly hotter than the convectively cooled (37.3°C) who are significantly hotter than the water cooled (37.1°C). In the high level assembly (Fig.5) the unconditioned subjects are significantly hotter at the end of the walk than those with the convective air and water supplies. Thereafter the body temperatures diverge more markedly than in the low level assemblies, those of the unconditioned subjects reaching intolerable levels by the mid-flight stage. The body temperatures of the two groups of subjects with conditioned supplies are no higher with high level clothing than with low level clothing and they do not constitute unacceptable thermal stress in either case.

5.2.2 Skin temperature. The mean skin temperatures excluding the head are shown in Fig.6 (low level clothing) and Fig.7 (high level clothing). The skin temperatures of the two groups of subjects with conditioned supplies are similar and near to the required 33°C. Those of the unconditioned and reverse flow subjects are always higher, by up to 4°C with low level clothing and 6°C, with high level clothing. Skin temperatures of the reverse flow subjects are similar to those of the unconditioned subjects in low level clothing but significantly lower than unconditioned subjects (by about 1.5°C) in high level clothing.

5.2.3 Forehead temperature. The mean forehead temperatures are shown in Fig.8 (low level clothing) and Fig.9 (high level clothing). In contrast to the other measurements of skin temperature, the forehead temperatures of the subjects with water or convective air supplies are higher than those of the unconditioned and reverse flow subjects. This result probably reflects the disadvantages of suppressing sweating by conditioning garments that do not cool the head. The observed differences agree quite closely with the differences in overall sweat loss (see below).

5.2.4 Pulse rate. The mean pulse rates throughout the sortie are given in Figs.10 and 11 for the low and high level clothing assemblies respectively. In general the results follow the measurements of ear temperature. An exception is that significant advantages of conditioned supplies appear rather earlier, i.e. at the end of the walk-out. In the case of the water cooled subjects this would be expected and indeed these subjects had lower pulse rates at the end of the crew-room phase in high level clothing. However, the convective air and reverse flow subjects had identical supplies up to the end of the walk and the difference between them in low level clothing is difficult to explain.

5.2.5 Blood pressure. The mean systolic, diastolic and pulse pressures are shown diagrammatically in Figs.12 and 13 for the low and high level clothing assemblies respectively. The results show significantly higher systolic blood pressures and pulse pressures in the unconditioned subjects in both clothing assemblies. In low level clothing, systolic pressure is higher in the unconditioned subjects than the other 3 groups at all measurements after the start of work. Systolic pressure of the reverse flow group is higher than the water or convective air cooled group at the end of the sortie. Up to and including the midwork measurement, the water cooled and convective air cooled subjects had higher diastolic pressures than the unconditioned group. Thereafter the analysis of results was difficult due to the unavailability of data for some subjects in high level assemblies and no conclusions can be reached although the water cooled subjects still tended to have higher diastolic blood pressures. Taken together with the measurements of pulse rate, the general trend of the blood pressure measurements indicate the severe load placed on the cardiovascular system of the unconditioned subjects. The fact that high systolic blood pressures were maintained without significant falls in diastolic pressure probably reflects the high physical fitness and cardiac reserve of the subjects. It is likely that the widespread cutaneous vasodilation is partly compensated by vasoconstriction in the splanchnic bed and in resting muscle. Nevertheless the contribution of personal conditioning towards reducing cardiovascular strain is clearly very valuable.

5.2.6 Sweat rate. The mean total sweat loss under each set of circumstances is given in Fig.14 which also summarises the final measurements of ear temperature and pulse rate. The sweat losses generally reflect the ear temperatures, with those for the water cooled group significantly lower than the convective air cooled group whose sweat rates were significantly lower than the reverse flow group in both clothing assemblies. The reverse flow group had significantly lower sweat rates than the unconditioned subjects in high level clothing but not in low level clothing.

5.3 Behavioural tests

The results of the behavioural tests are summarised in Table 7 and Fig.15.

Table 7

Behavioural tests*

		Low altitude clothing	High altitude clothing
1	Memory test	$C_2C_3 > C_4C_1$	$C_2 > C_3C_4$
2	Calculation Part 1	NS	NS
3	Calculation Part 2	$C_2C_3 > C_4C_1$	$C_2 > C_3C_4$

$>$ = significantly better score than (5 per cent level)

C_1 = unconditioned; C_2 = water cooled suit;

C_3 = convective AVS; C_4 = reverse flow AVS.

* Based on the performance of the last 8 subjects. Difficulties with the apparatus meant that the results from the first 4 subjects had to be abandoned.

Analyses of variance revealed substantial inter-subject effects, but no effect due to the type of clothing assembly (low or high).

The results from the confidence measures were inconclusive, there being very large inter-subject differences.

5.4 Subjective measures

5.4.1 In-sortie. The subjective ratings (10 cm line) made five times during the sortie are illustrated in Figs.16 and 17 and summarised in Table 8.

Table 8

In-sortie subjective ratings

	Low altitude	High altitude
Crew-room	$C_2 > C_3C_4C_1$	$C_2 > C_3C_4C_1$
Walk-out	$C_2 > C_3C_4C_1$	$C_2 > C_3C_4C_1$
End of work	$C_2 > C_3 > C_4 > C_1$	$C_2 > C_3 > C_4$
Mid-test	$C_2 > C_3 > C_4 > C_1$	$C_2 > C_3 > C_4$
End of flight	$C_2 > C_3 > C_4 > C_1$	$C_2 > C_3 > C_4$

$>$ = rated as being 'significantly COOLER than' (1 per cent level).

5.4.2 End of sortie. The end of sortie subjective ratings (10 cm line) by body part are shown in Fig.18. The ratings on the six body parts (head, front trunk, back trunk, arms, legs, and whole body) gave very similar results, the order, in terms of the thermal comfort provided by the system always being liquid conditioned suit, convective air suit, reverse flow suit and unconditioned. Analyses of variance showed these 'between conditioning' effects to be very highly significant.

The only significant diversion from this very consistent pattern was for the head where the ratings under the reverse flow and unconditioned systems were very similar to those made for all other body parts, whereas under the water cooled and convective air suits the ratings were very significantly higher than they were for all other body parts.

5.4.3 End of trial. On the measure of thermal comfort, all 12 subjects placed the conditioning systems in the order liquid conditioned, convective air, reverse flow, unconditioned, this rating holding for both high and low altitude assemblies. The mean 'distances' (cm) between the conditioning systems were:

Low altitude - LC ← 2.2 → CA ← 5.6 → RF ← 2.2 → UC
High altitude - LC ← 2.6 → CA ← 5.3 → RF ← 2.1 → UC
LC = liquid conditioned; CA = convective air;
RF = reverse flow; UC = unconditioned,

i.e. the liquid conditioned system was rated as being a little better than the convective air system which was rated as being considerably better than the reverse flow system which was rated slightly better than the unconditioned system.

6 DISCUSSION

6.1 Physiological data

The results in detail reveal none of the problems found during the trials with earlier prototype water cooled suits. In particular there appeared to be no difficulty in pilot selection of appropriate inlet temperatures within the limits set on the supply system performance, body temperatures were controlled at acceptable levels and there were no adverse changes in blood pressure. Similarly, there were no physiological objections to the degree of thermal control achieved with the convective air system, although this was slightly less effective than the water cooled system. The measurements of forehead temperature, however, revealed a possible difficulty where effective conditioning systems are used without head cooling. The general suppression of sweating also applies to the uncooled face which therefore reaches higher skin temperatures than in subjects less adequately cooled. In the light of existing evidence it is not possible to say categorically whether or not this could have adverse effects on the performance of skilled tasks but the matter should be kept under review and the inclusion of head cooling in a personal conditioning system may be desirable if it can be achieved without other disadvantages such as noise.

The performance of the reverse flow system in this experiment showed a valuable reduction of thermal stress compared with the unconditioned controls but was not comparable with the two 'conditioned' systems. It should be pointed out, however, that the severe climatic conditions used during the flight phase represented the upper limits of conditions commonly met in practice and that, under less severe conditions, the reverse flow system performance would be expected to be nearer that of the conditioned systems. As a simple and cheap means of lessening thermal stress in existing aircraft, it clearly has something to offer. In new aircraft in which it may prove possible to effect considerable improvements in the performance of cabin conditioning systems and the distribution of conditioned air, the reverse flow system has considerable potential advantages (Allan, *et al.*, 1970).

The measurements taken at the end of the crew-room phase show only small differences between any of the conditioning systems and the controls when low level clothing was worn (Figs.4 and 10). In high level clothing the unconditioned subjects were clearly more stressed with respect to heart rate (see Fig.11) than any other groups but there was little to choose between the water cooled and reverse flow systems. In these circumstances the system installed in an unconditioned crew-room will be determined by the usual factors of complexity, reliability and cost, and by the need to be consistent with the supply systems used in aircraft.

The end of walk results give some indication as to the practical use of portable conditioners, subject of course to the acceptance of the trial conditions as being realistic. This particularly applies to the duration of the walk (10 minutes). In low level clothing there were no differences of significance between the groups with respect to body temperature but pulse rates were lower in the water cooled and convective air groups. The fact that the 'reverse flow' group, who at this stage had had the same conditioning as the 'convective' group, did not show this pulse rate advantage is not readily explained but may be attributable to the different ventilating garments. In high level clothing there was again little difference in body temperature (aural) at the end of the walk between the four groups but again the pulse rate measurements showed a marked advantage to the water cooled group with a smaller advantage to the 'convective' and 'reverse flow' groups. The general conclusion from these results is that portable conditioners are probably only worth while when high level clothing is worn but the matter should be resolved by definitive trials with fully developed conditioners.

6.2 Behavioural data

Two of the three behavioural measures used in this trial revealed significant differences between the conditioning systems. On the short-term memory task performance was significantly better with the liquid conditioned suit and the convective air suit than with either the reverse flow or unconditioned systems for the low altitude assembly, whereas, for the high altitude assembly the difference was between the liquid conditioned suit and the two remaining conditioning systems (Table 7).

The effects of heat on short-term memory are not well known, but the results from this trial do not conflict with those of Wing and Touchstone (1965) who found impairment of short-term recall at an effective temperature of 35°C. With the low altitude assembly, the big drop in performance was between the convective air suit and the reverse flow suit, whereas with the high altitude assembly it was between the liquid conditioned suit and the convective air one.

The calculation test did not show differences between the various conditioning systems until the pace (and presumably the difficulty level) of the task had been increased for the last 10 minutes of the sortie. As the ambient conditions were increased at the same time it is impossible to attribute this change solely to the difficulty level of the task. The differences between the conditioning systems on this task were very similar to those shown on the memory task and are comparable with a decrement in calculation ability shown by Wilkinson, *et al.* (1964). Confidence has been shown to increase under raised body temperature (Colquhoun and Goldman, 1968) but this finding was not confirmed in the present trial, there being very large inter-subject differences.

Although it can be argued that short-term memory and calculation ability are components of any flying task, statements as to the effect of these conditioning systems on the performance of an actual flying task must be made with extreme caution.

6.3 Subjective assessments

The subjective ratings produced clear, perhaps surprisingly clear, results. The in-sortie ratings showed that the liquid conditioned suit was judged to provide a more comfortable environment all through the sortie (under both altitude assemblies) whereas the differences between the other systems only became large at, and following, the end of work phase of the sortie; a finding borne out by the physiological data. It would appear that it is the whole body rather than any specific area which is felt to be hot, for the ratings of the various body parts were very similar. The highly significant exception to this finding was the rating for the head which was adjudged to be hotter than the other parts of the body under the liquid conditioned suit and convective air systems. This finding is not surprising as the physiological data confirm a consistent difference in forehead temperature (see Figs.8 and 9).

At the debriefing at the end of the trial the subjects gave a very clear indication as to their assessment of the degree of thermal comfort provided by the various systems. This quantitative rating showed that, regardless of the altitude assemblies, the 'difference' between the liquid conditioned system and the convective air system and that between the reverse flow system and no conditioning were similar and about half that between the convective air system and the reverse flow system (see page 22). Thus on the subjective rating of thermal comfort a large distinction is made between these two types of air flow systems.

Subjective rating methods (10 cm lines) are a more rigorous method of assessing thermal comfort than is the often-used casual interview technique. However the authors' are very conscious of the dangers inherent in the use of subjective measures, for example in the biases and prejudices about systems which are present either at the beginning of the trial or develop early in the trial and are communicated between the subjects. However there was no opportunity for back-checking of subjective ratings which were very consistent both within and between subjects and it is felt that these ratings are a valuable addition to the physiological and behavioural measures which were taken.

6.4 Extension of test results to real aircraft conditions

This discussion would be incomplete without giving some indication as to how the present results affect the general problem of which type of personal conditioning to use in future generations of aircraft. It can now be stated clearly that in laboratory simulations of severe aircraft operating environments using laboratory supply systems, the water cooled suit is the method of choice. This is not to say that the same conclusion would necessarily be reached under actual operating conditions. To clarify this situation the general aircrew acceptability, including comfort, reliability, freedom from leaks etc. and the convenience of supporting ground equipment, must be assessed under realistic field operating conditions over a reasonable period of time. To achieve this a water cooled suit system will have to be installed either in a Squadron aircraft or in a trials aircraft attached to an operational Squadron in a hot country.

Prior to this it is necessary to know that a water conditioning system suitable for aircraft installation and of the required performance is acceptable in terms of weight, bulk, and power consumption, in comparison with alternative systems.

7 CONCLUSIONS

Under severe laboratory conditions simulating the thermal time-course of a typical operational sortie the water cooled suit is more effective than a convective air ventilated suit at maintaining thermal comfort. The differences are small, however, and both systems produce acceptable control of thermal stress.

The reverse flow system is less effective than 'conditioned' systems under severe ambient conditions but produces a worth while reduction in thermal stress when compared with unconditioned subjects.

Under simulated crew-room conditions (unconditioned) there was little to choose between the water cooled and reverse flow air systems.

The results indicate some advantages in using portable conditioners, particularly with the water cooled suit, but these require confirmation by definitive tests with developed hardware.

Acknowledgements

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Note to readers

This Current Paper is based on an RAF/IAM report which cites references by authors' and then lists them alphabetically as above. To avoid further changes to the text this arrangement has been left unaltered here as only ten references are listed.

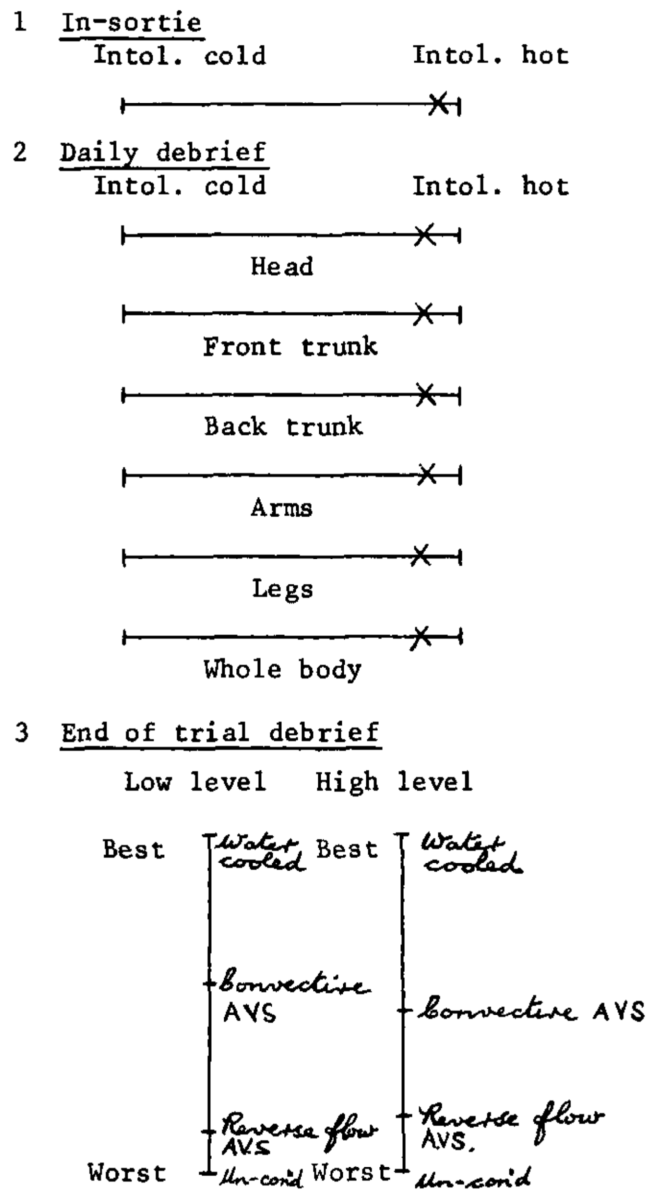

Fig.1 10 cm line scales used for subjective assessments

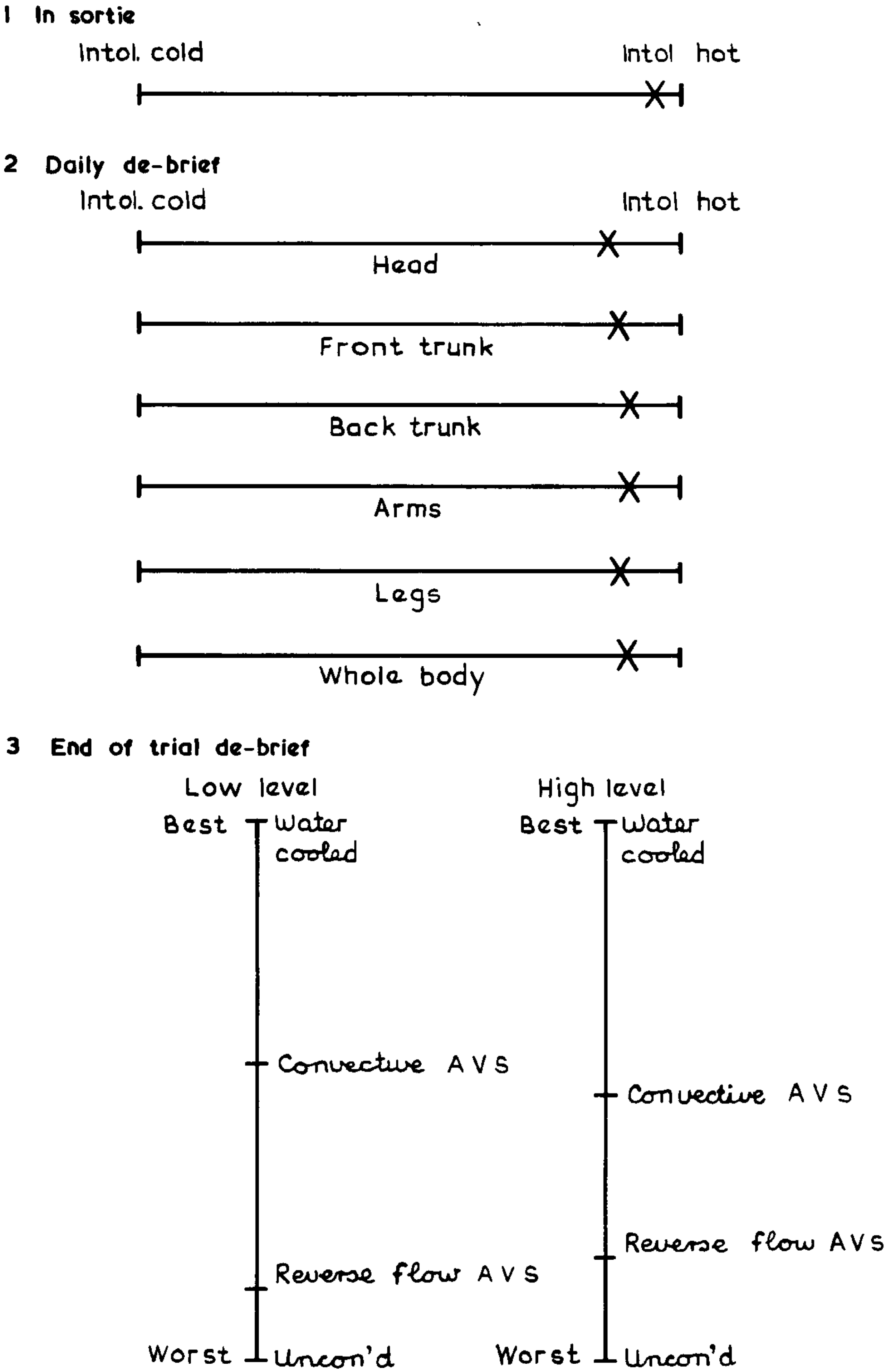

Fig.1 Subjective rating scale

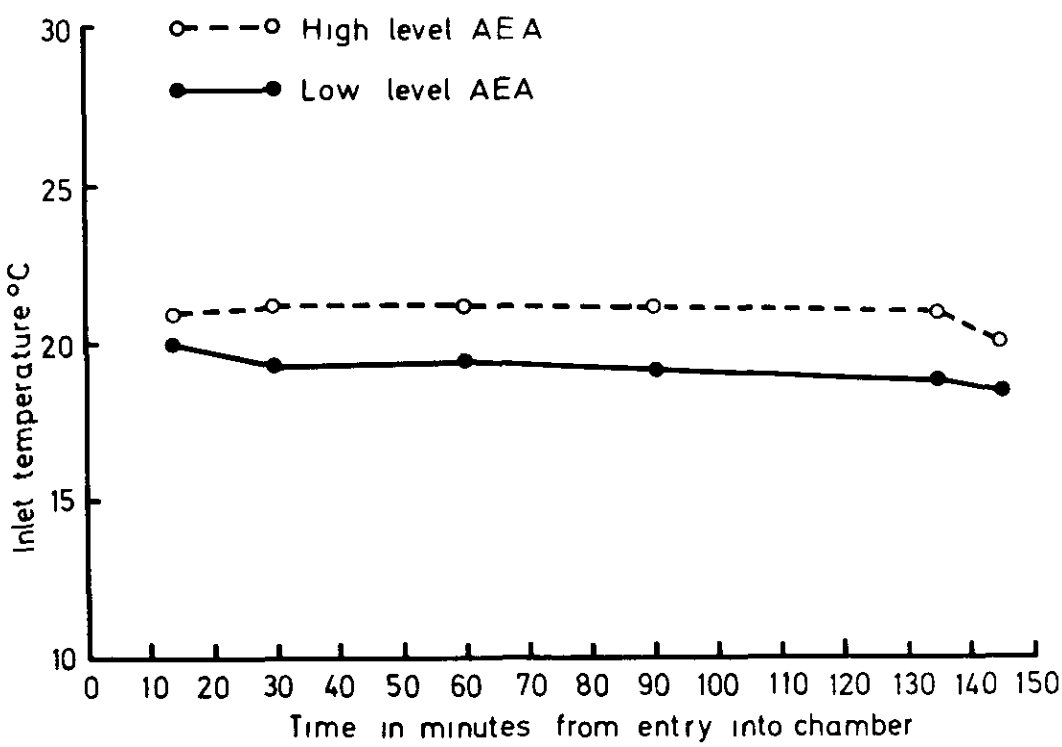

Fig. 2 Mean inlet temperature for water cooled suit with high and low level AEA

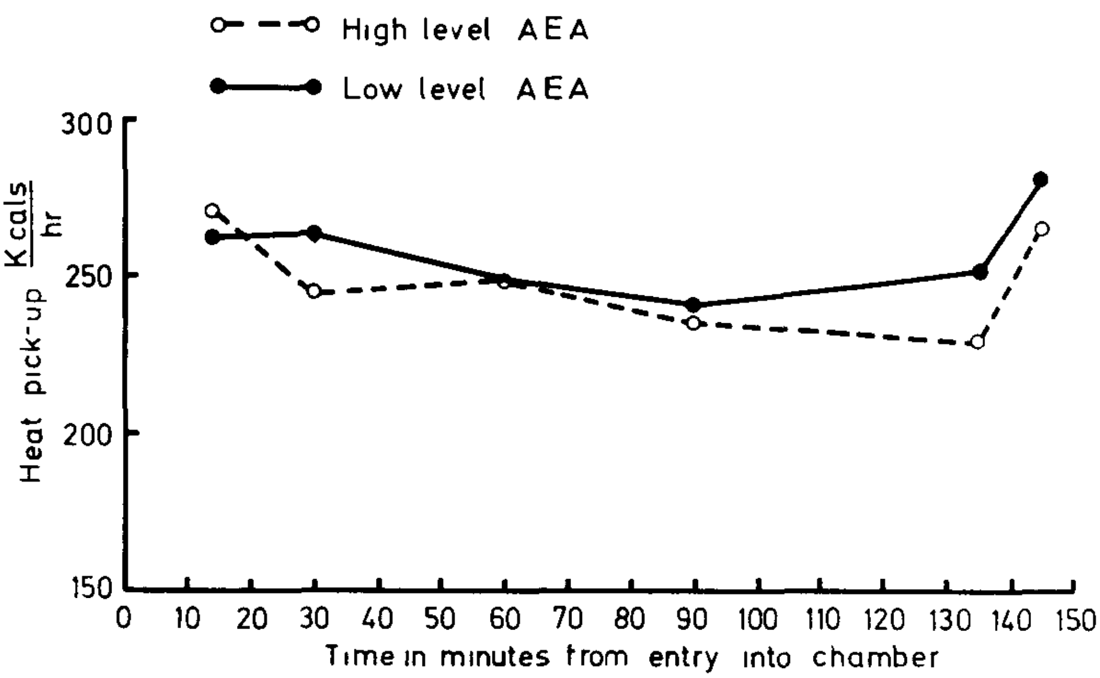

Fig. 3 Mean heat pick-up for water cooled suit with high and low level AEA

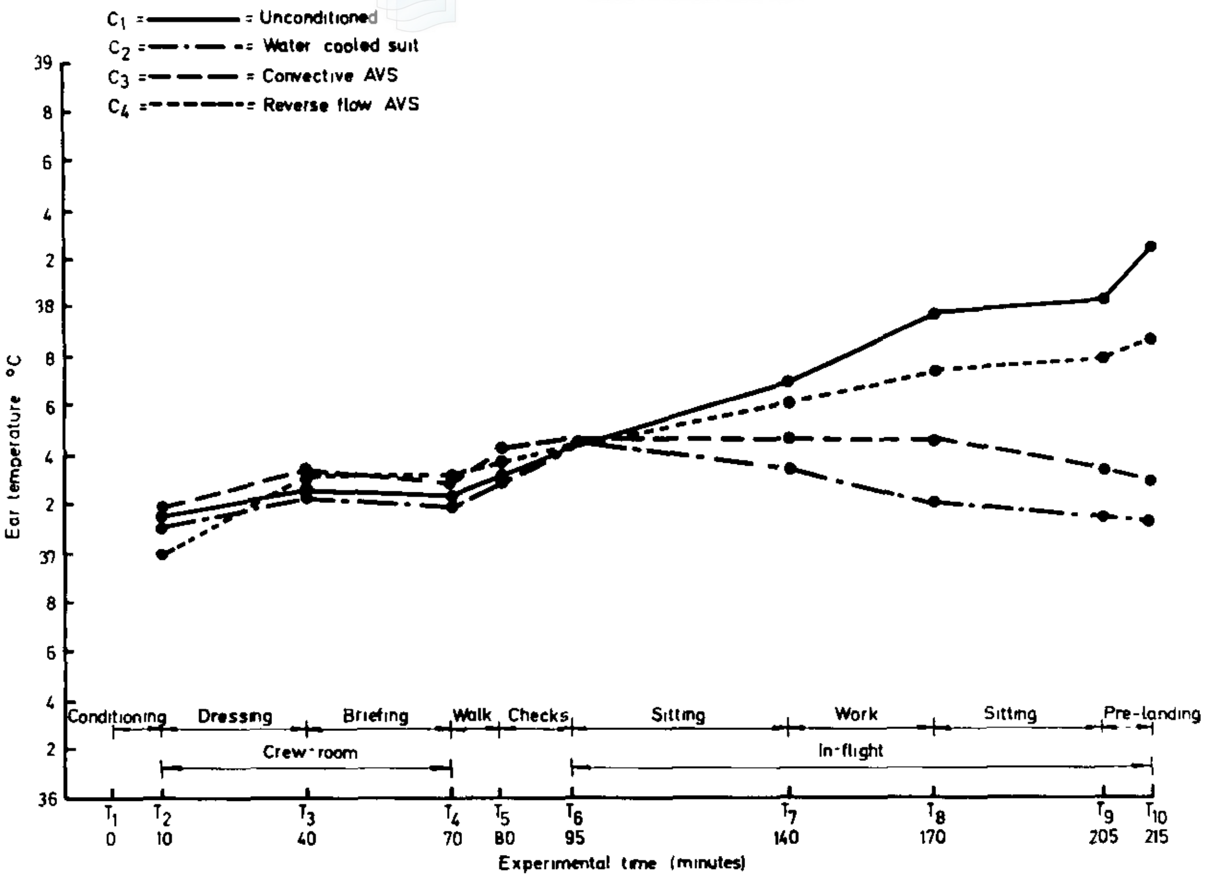

Fig. 4 Mean ear temperatures for four conditioning systems (low level clothing)

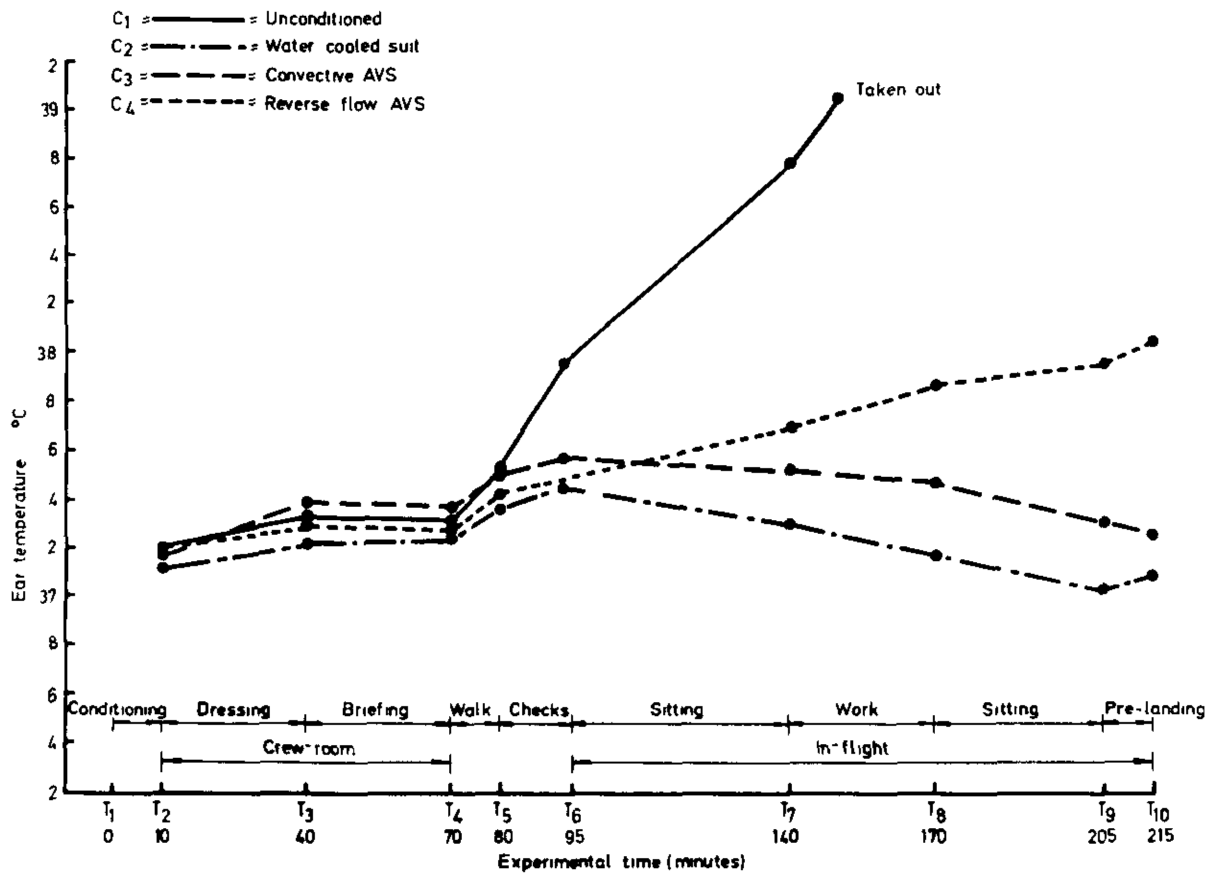

Fig. 5 Mean ear temperatures for four conditioning systems (high level clothing)

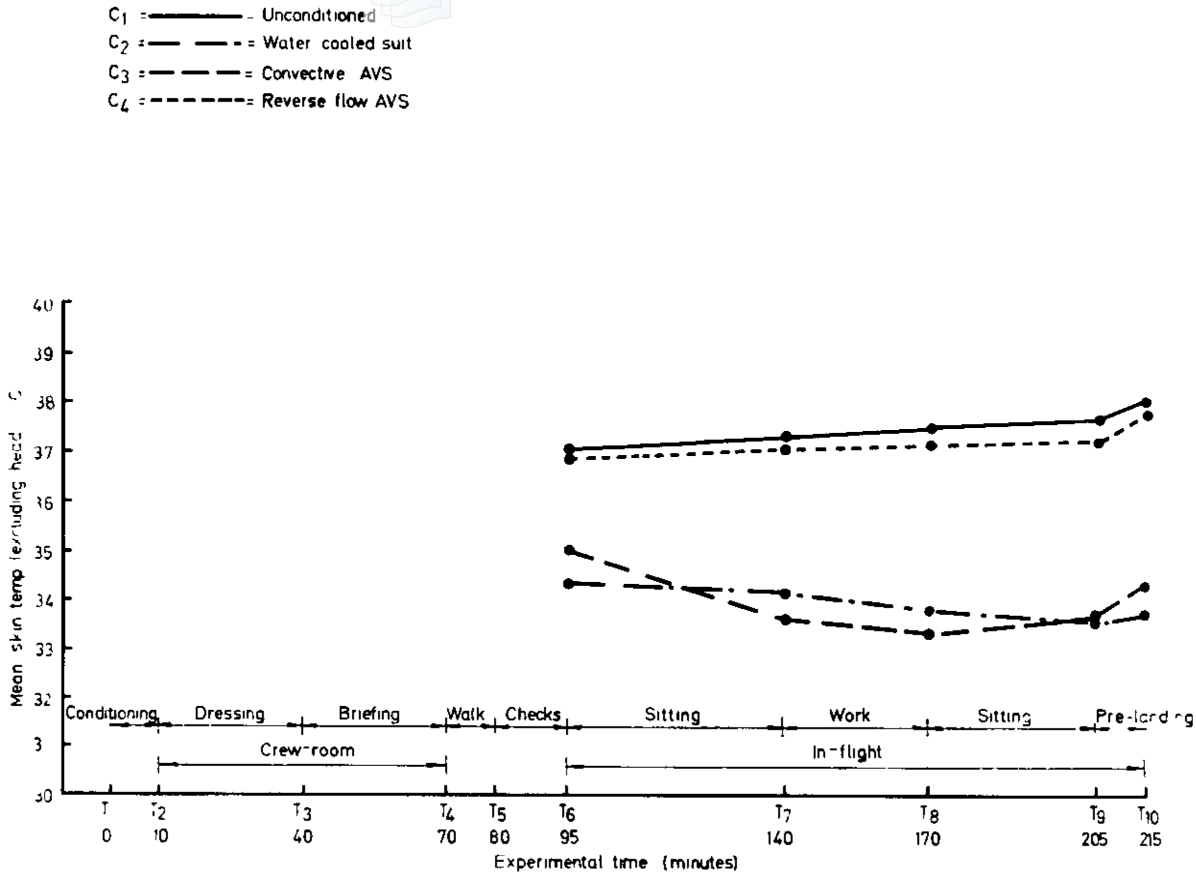

Fig.6 Mean skin temperatures (excluding head) for four conditioning systems (low level clothing)

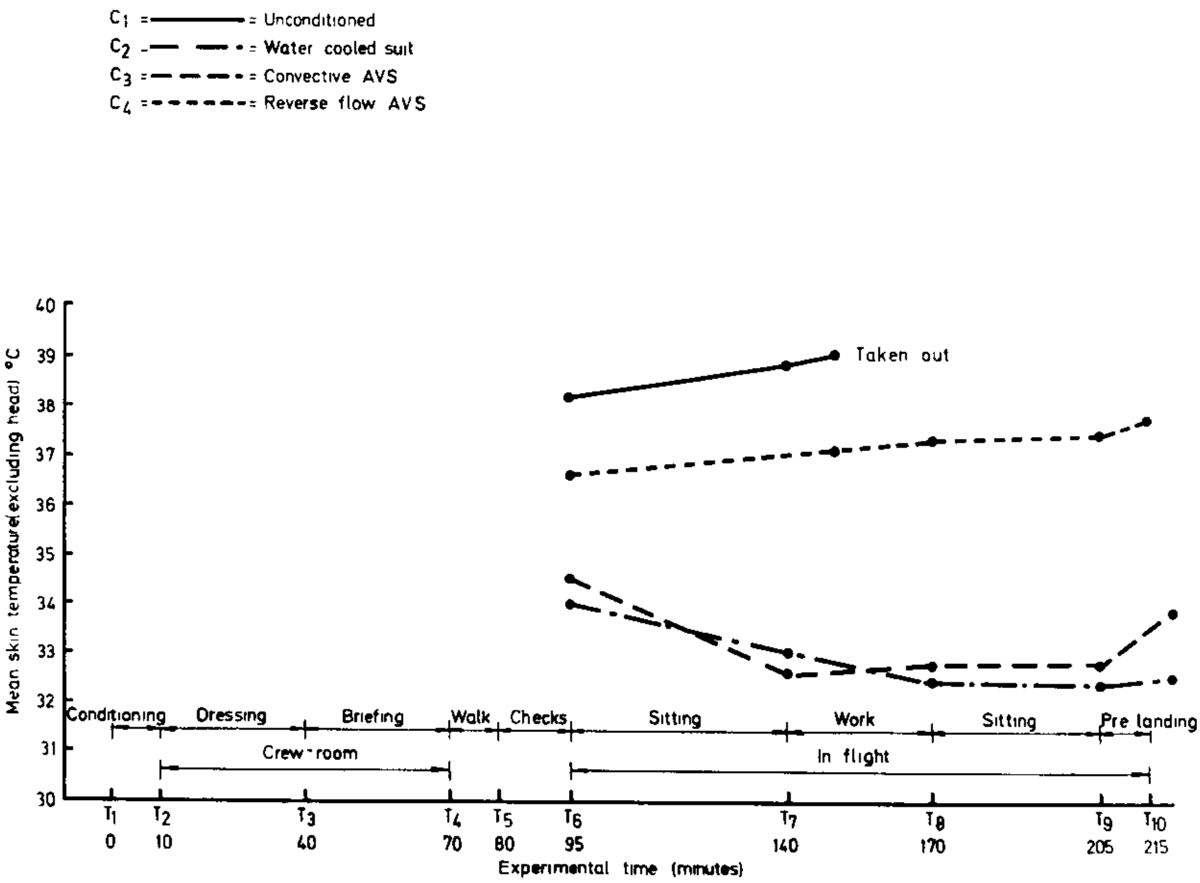

Fig.7 Mean skin temperatures (excluding head) for four conditioning systems (high level clothing)

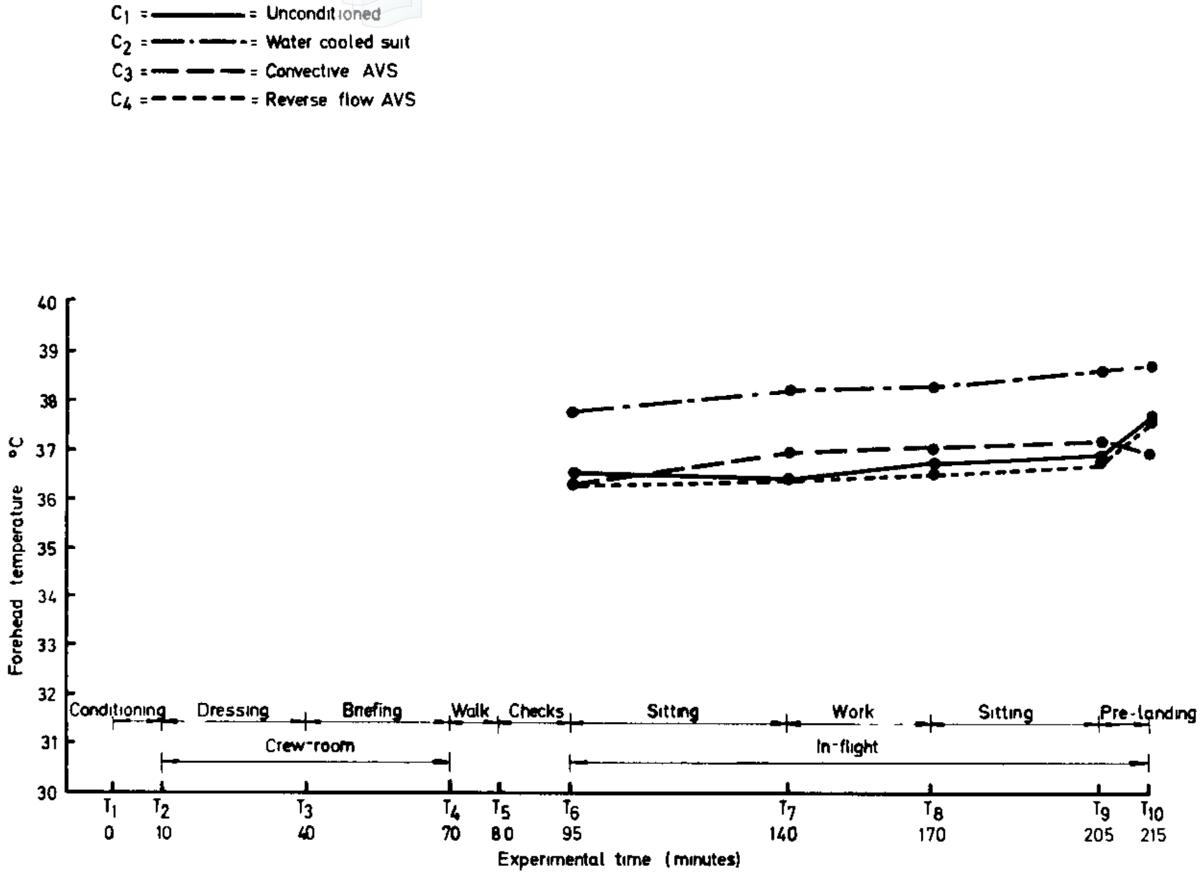

Fig. 8 Mean forehead temperature for four conditioning systems (low level clothing)

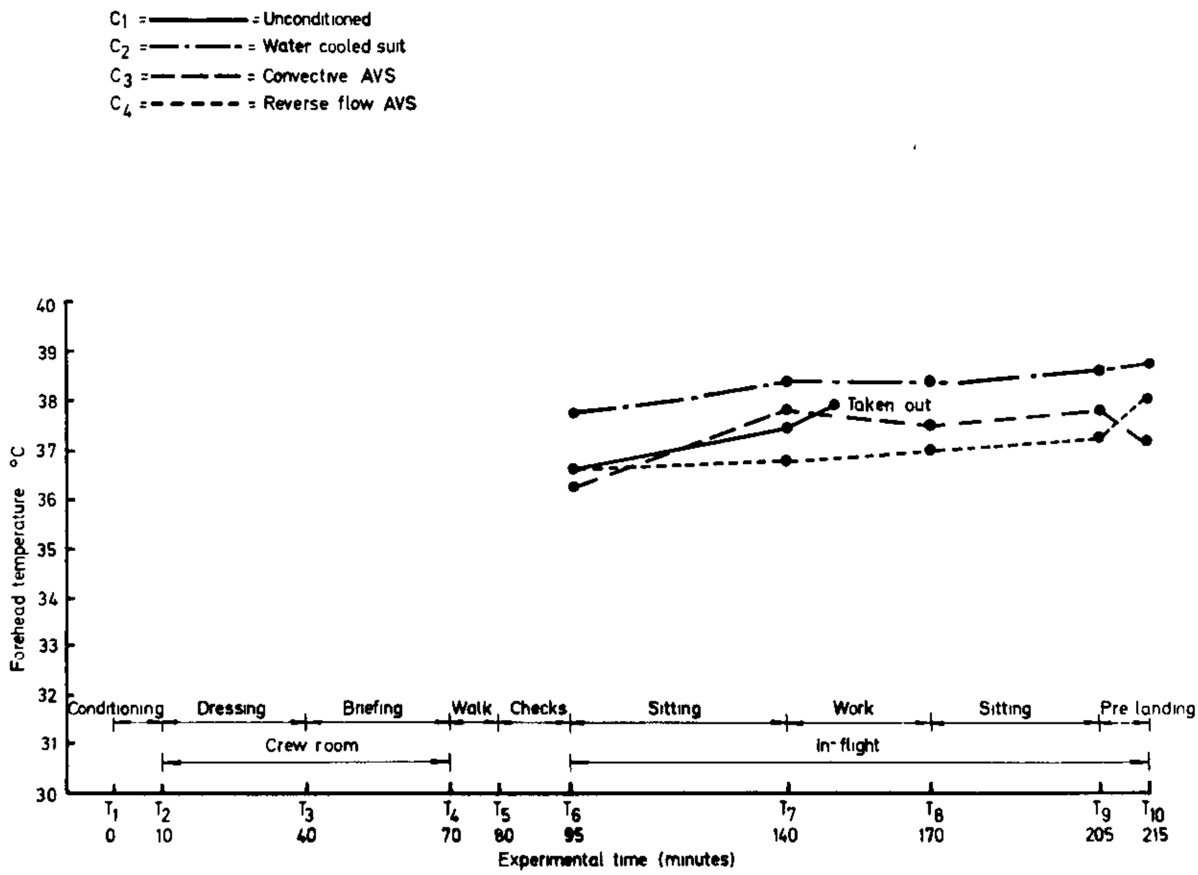

Fig. 9 Mean forehead temperature for four conditioning systems (high level clothing)

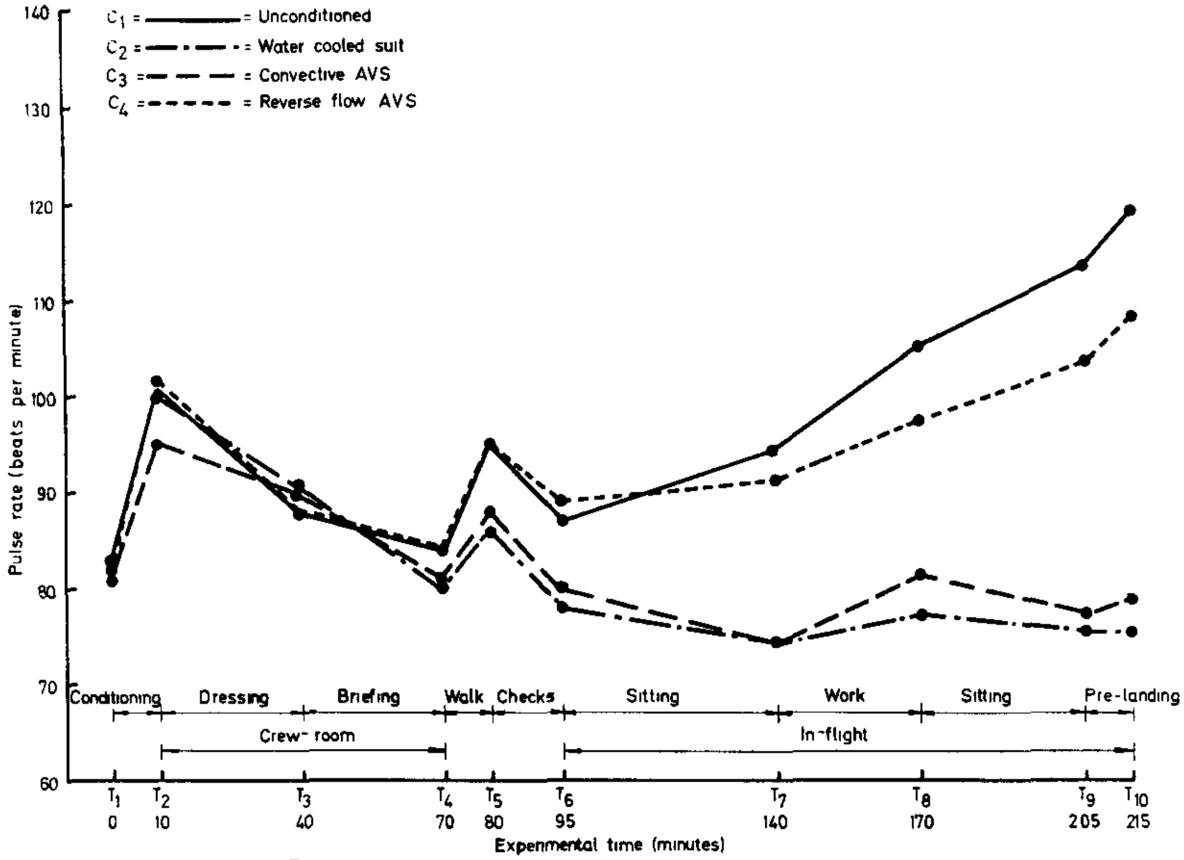

Fig.10 Mean pulse rate for four conditioning systems (low level clothing)

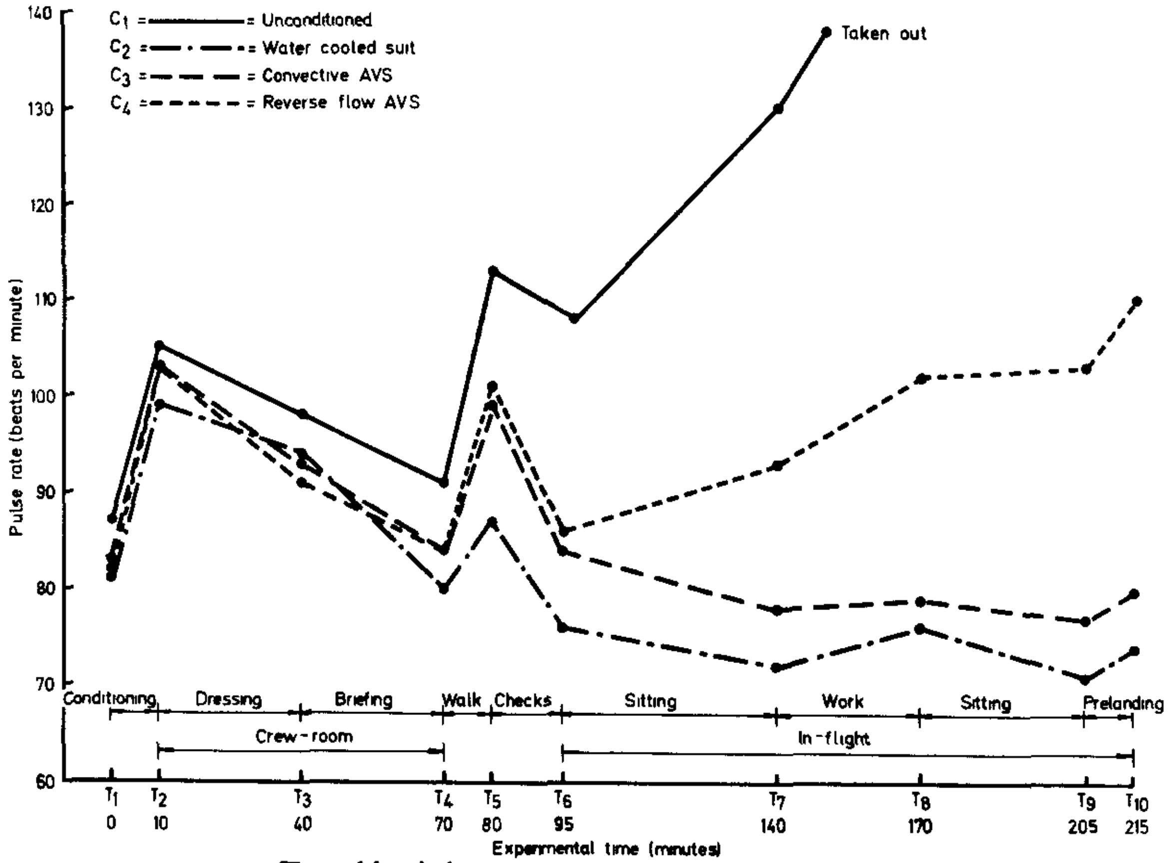

Fig.11 Mean pulse rate for four conditioning systems (high level clothing)

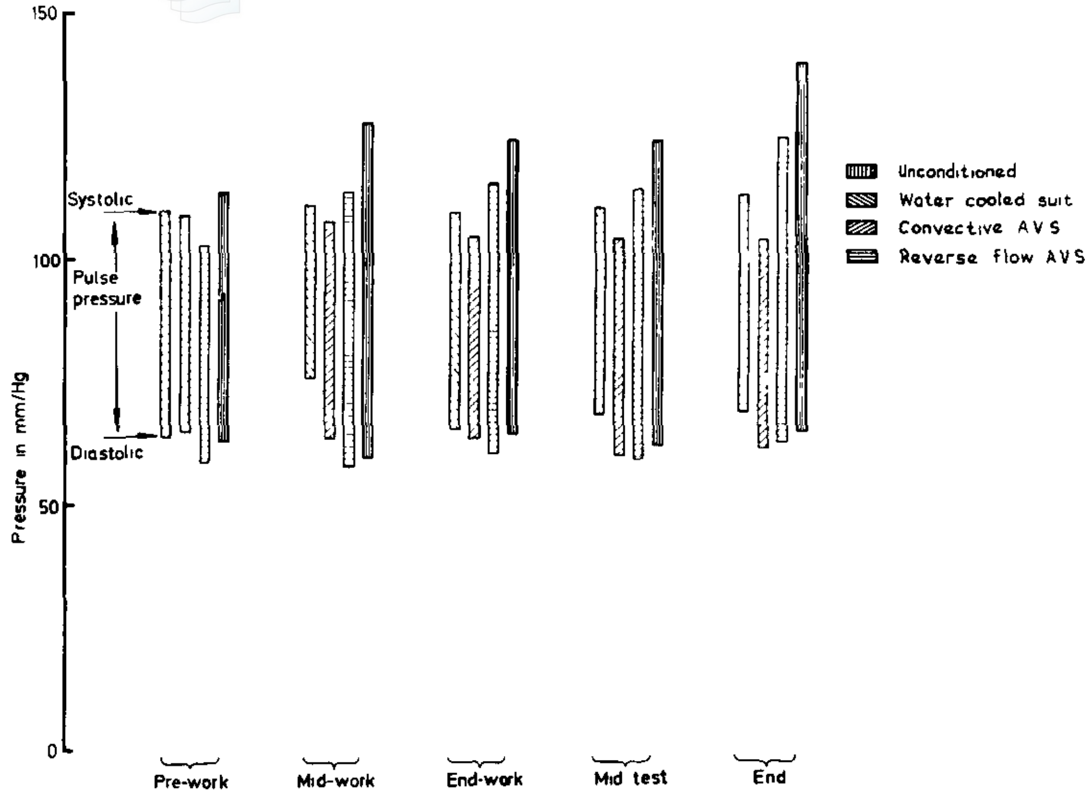

Fig. 12 Mean systolic and diastolic blood pressures in low level assemblies at times during the in-flight phase

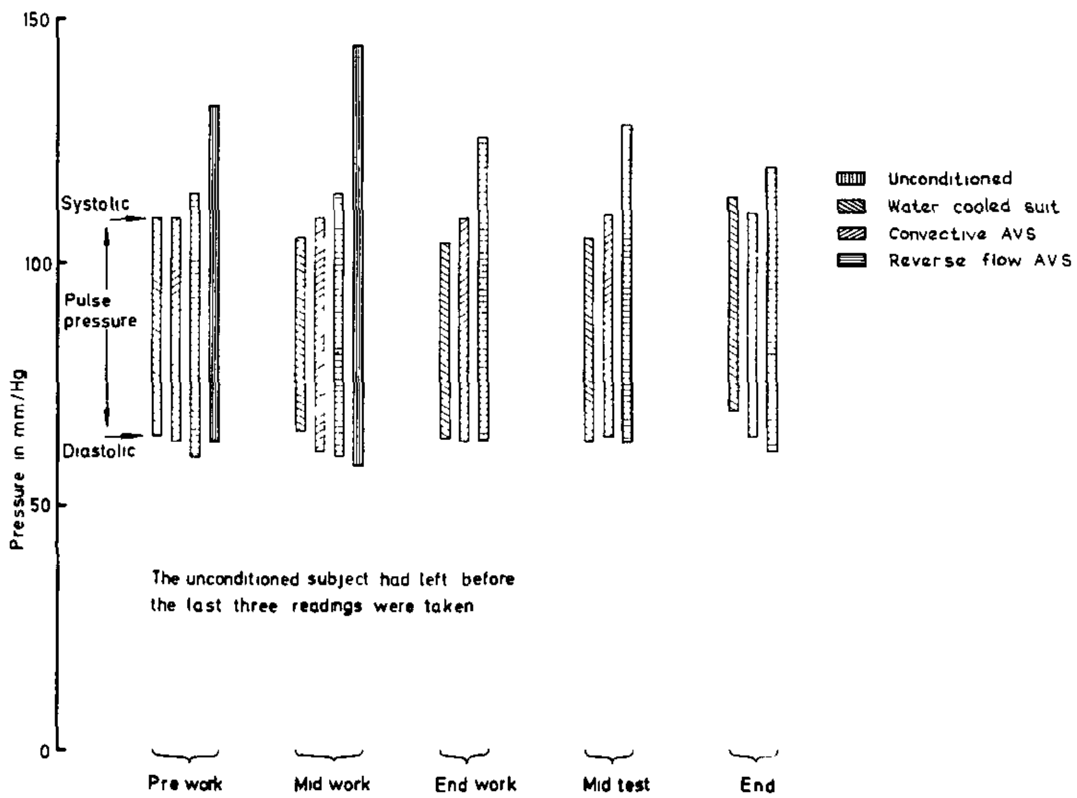

Fig. 13 Mean systolic and diastolic blood pressures in high level assemblies at times during the in-flight phase

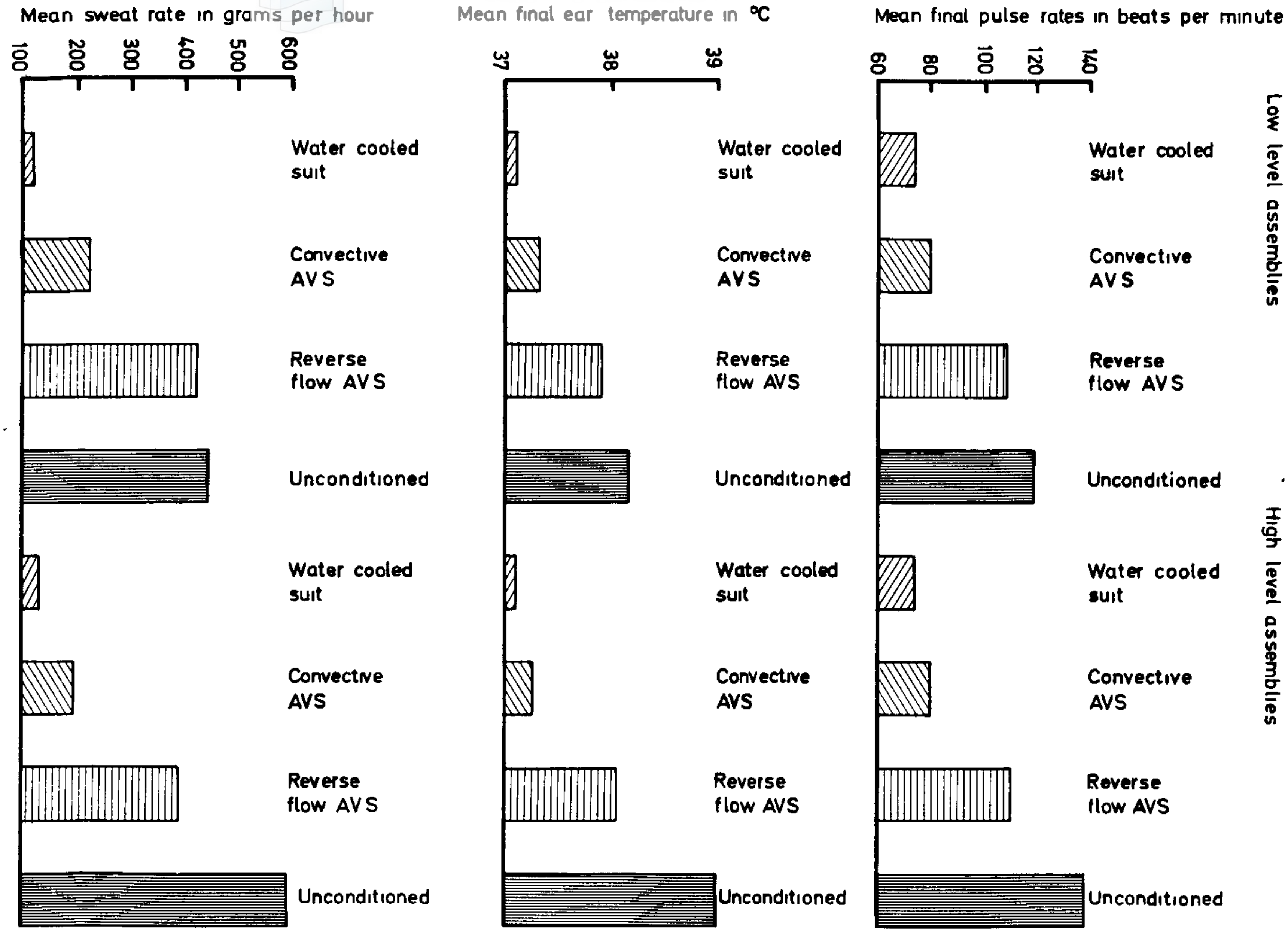

Fig.14 Mean final temperatures, pulse and sweat rates

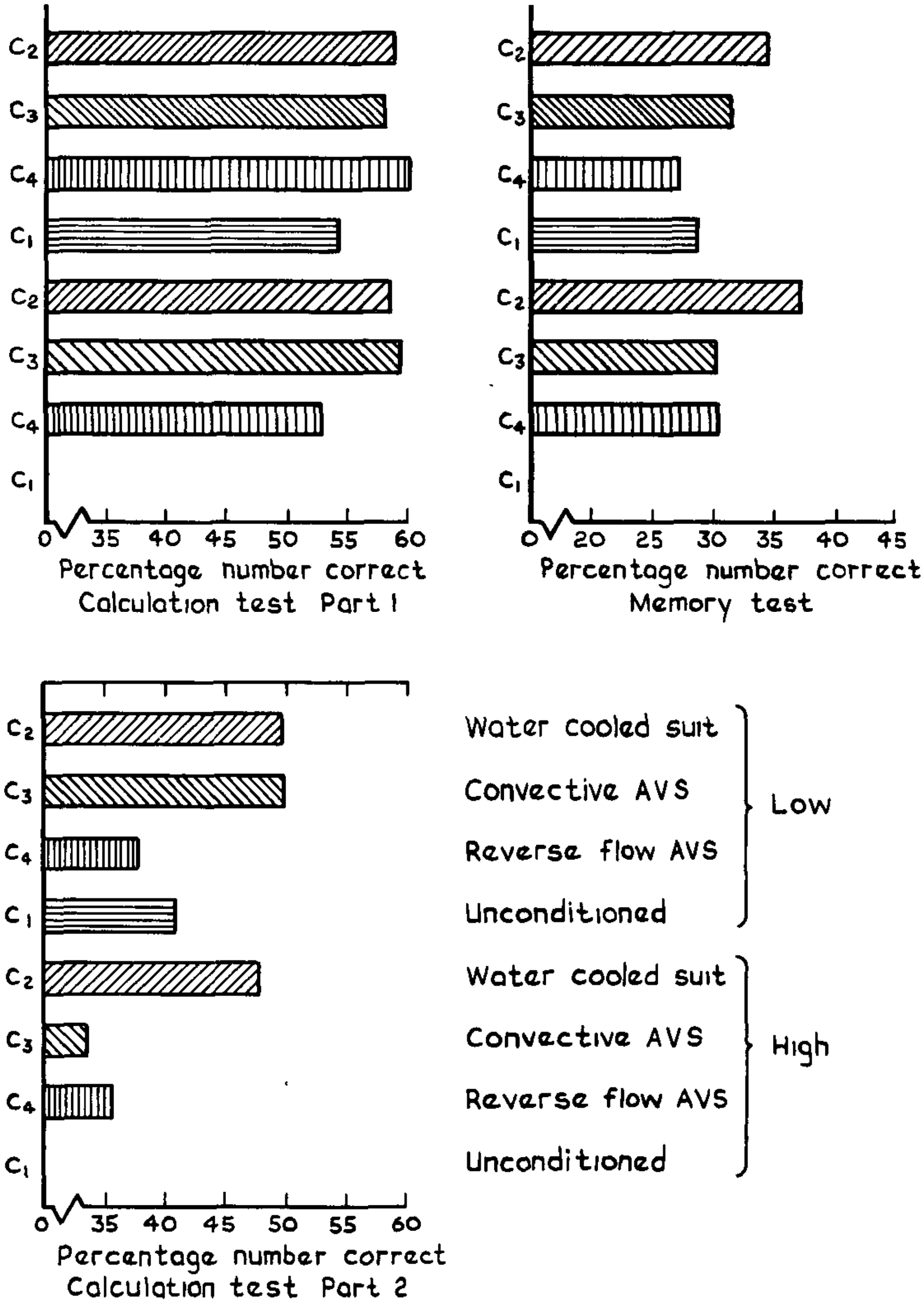

Fig. 15 Behavioural tests

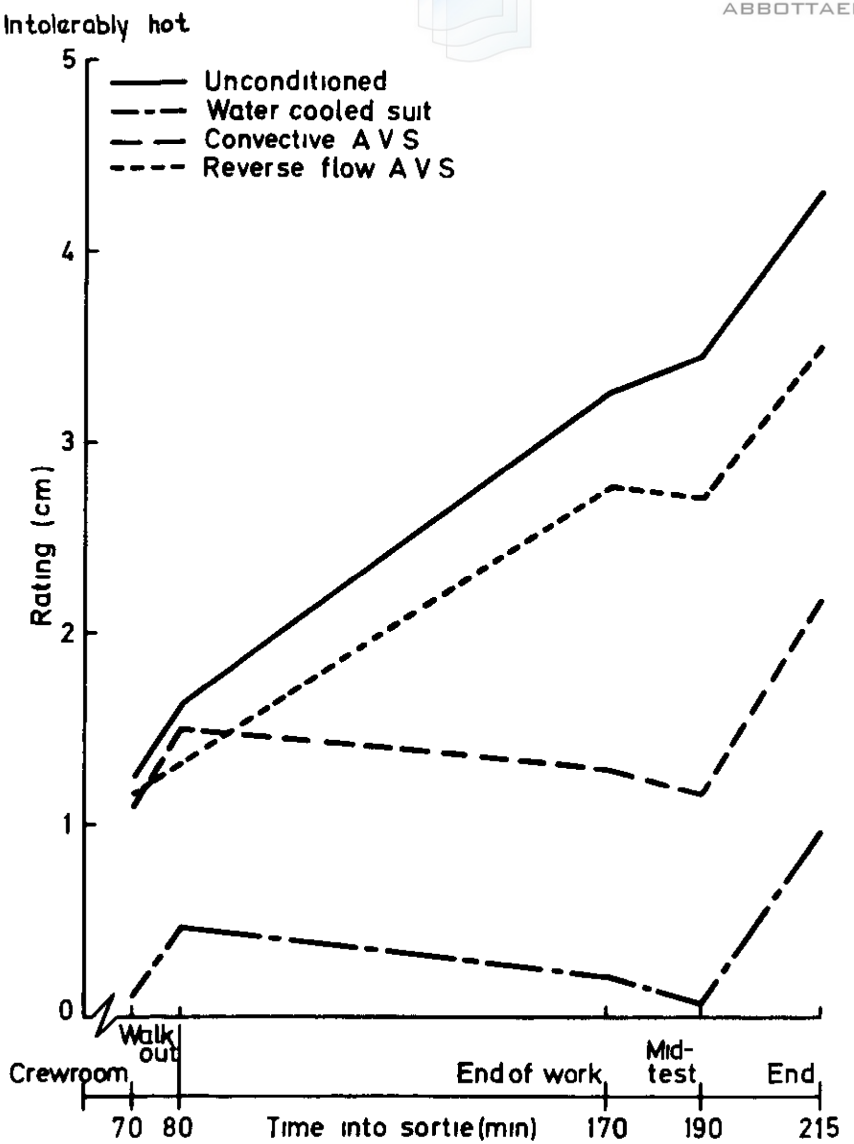

Fig. 16 In sortie-subjective ratings low level assembly

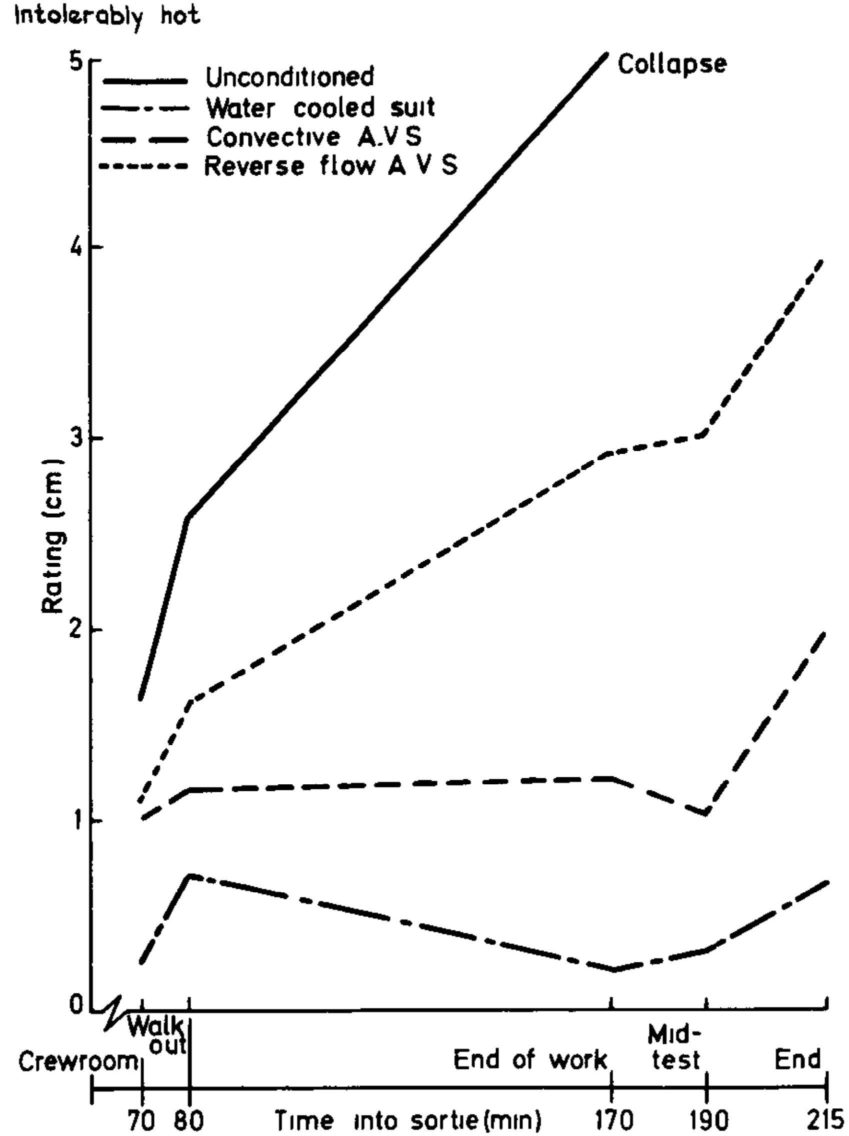

Fig. 17 In sortie-subjective ratings high level assembly

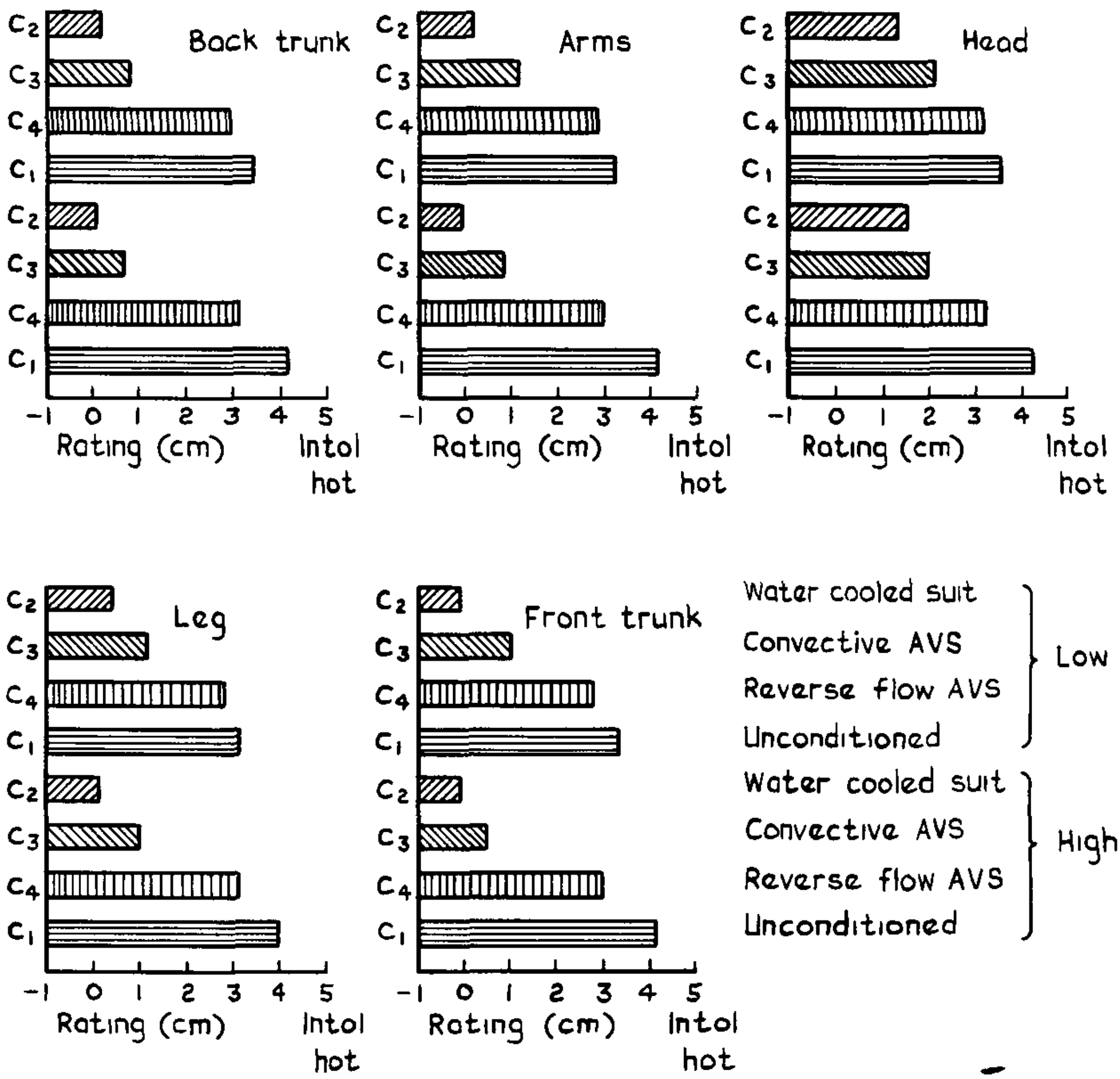

Fig 18 Subjective ratings by body areas

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