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Indigenously Developed Liquid Cooled Suit and its Performance

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An indigenous liquid cooled suit with low back pressures at optimal flow rates, having heat extraction qualities meeting our requirements and capable of being integrated with the cutaway anti 'G' suits has been developed. The cooling benefit offered by LCS in the form of reduction in rise of heart rate, heat accumulation and modified Craig index is of the order of 76%, 62% and 47% respectively. Wearing of cutaway anti 'G' suit over the LCS reduces 'G' protection by 0.1G to 0.2G (mean 0.175 G), which is a considerable improvement over the earlier LCS where the loss of 'G' protection ranged from 0.4 to 0.7G (Mean 0.53G).

Introduction

The existence of excessive heat loads in most of our military aircrafts while operating at low altitudes during the summer months is well known. Ample data is available to indicate that cockpit environments under such conditions subject the pilots to physiological strain and subjective discomfort enough to lower their performance during the sorties[3,5,12,18]. A number of methods of refrigeration have been tried to minimise the thermal stress and control the physiological strain to a level compatible with functional efficiency[8,15,17]. All have met with varied success. However, the personal conditioning system in the form of microenvironmental control by liquid cooling seems to offer the best available mode for crew conditioning. From the development of the first prototype liquid cooled suit (LCS) in 1962, a large number of variants of LCS and their conditioning packs have been assessed for their efficacy in different kinds of heat stress environments[1,4,7]. The garment used for extensive laboratory trials at IAM is the LCS manufactured by Beaufort (Air Sea) Equipment Company[10] (Fig 1). This along with the inflight model refrigerant pack (Fig 2) and the miniature 24 volts DC pump developed by Sant et al[13] was found to be an effective heat exchanger even in severe thermal environments. On evaluation of the above system for possible inflight use it was found that though the refrigeration qualities were highly satisfactory, the LCS posed problems of integration with flying clothing. Trials on the human centrifuge showed that protection offered by the anti 'G' suit reduces by 0.5 to 0.6

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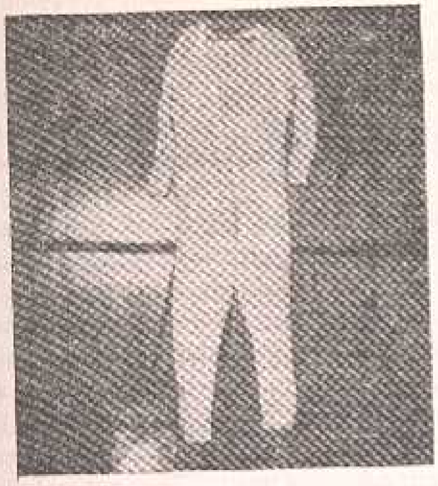


Fig. 1 *Indigenously developed Liquid Cooled*

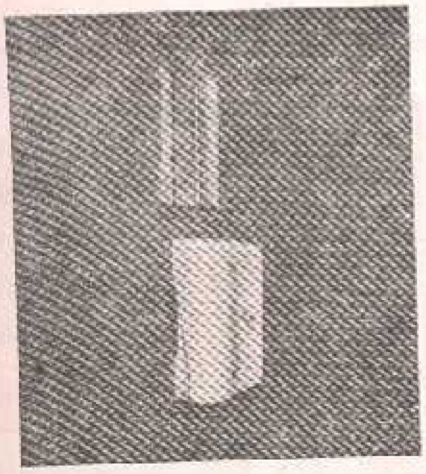


Fig. 2 *Indigenous*

'G' when worn over the LCS.[14] Conversely, the cooling efficiency is reduced by almost 20% when anti 'G' bladders are worn below the LCS.[3] In the light of these findings a project was taken up to develop a liquid cooled suit which could be integrated with normal flying clothing of the fighter aircrew and make it more practical for regular use by them.

Material and Methods

Development of the Liquid Cooled Suit

(a) *The Garment.* A design with re-distribution of capillary tubing was conceived with the intention of avoiding the body surface area covered by the 'G' bladders and the deficiencies of the indigenous prototype LCS Model-1 developed by Bhatia.[2] A garment capable of forming a snug fit on torso and limbs of medium statured individuals was tailored from a knitted stretch nylon fabric. Tunnels made of a thin synthetic cloth were stitched on to the internal surface of the garment. The routing of these tunnels conformed to the desired capillary tube distribution over the body. Surgical PVC capillary tubes with an internal diameter (ID) of 1.8mm and outer diameter (OD) of 2.8mm were threaded through the tunnels and cut to size at each end after catering for the maximum stretch of the garment.

(b) *Manifolds.* The manifolds had to be designed afresh in view of the back pressure and bonding problem encountered by Bhatia.[8] Perspex with its good insulation quality was used for machining an entirely new design of manifolds. The size was maintained as small as possible to minimise the pressure of rigid material within the garment. A longitudinal central core of 0.5 cm diameter with the required number of sideward channels of 0.28 mm diameter (equal to the OD of the PVC tubes) were drilled into perspex pieces of 6 × 2 × 0.6 cms. Nipples for connecting the feed and return pipes were machined at either end (Fig 3). Eight such

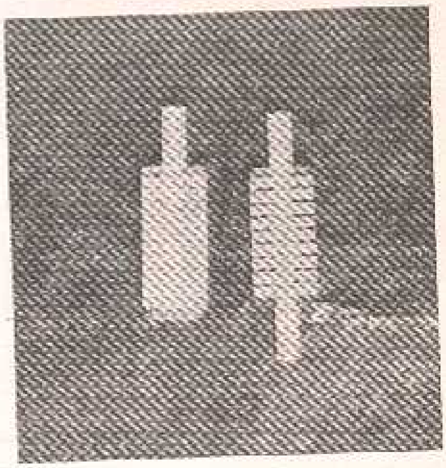


Fig. 3 *Indigenous*

manifolds have been used. Two each on the chest, back (one on either side of midline) and one at each ankle and wrist. A diagramatic representation of the distribution of PVC capillaries and the manifolds is shown in Fig 4.

(c) *Connection of PVC tubes to manifolds.* A large number of adhesives were tried to obtain a reliable and leak free bonding of PVC tubes to the

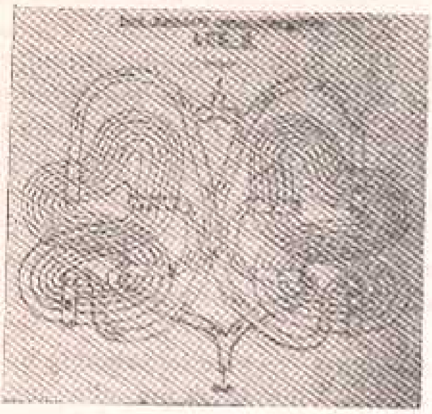


Fig. 4

manifolds. Finally, suitable bonding was achieved by an imported LG-68 compound obtained from NAL. Additional sealing was provided by applying Dunlop S-758 Sealant at the junction of each capillary with the manifolds. The interconnecting of the manifolds was achieved with measured lengths of flexible PVC tubing (0.5 cm diameter). These tubes were finally connected to the main inlet and outlet pipes through 'Y' connectors fixed onto the external surface of the garment on its back. The completed LCS with its external connections is shown in Fig 5, in its front and back views. The tubing is so routed that the abdomen upto the costal margin is totally devoid of the tubes and minimal tubing is present on the front and lateral aspect of thighs and back of the calves i.e. areas which come in contact with anti 'G' bladders. The suit was checked for its back pressures by using a five litre constant pressure head device. Flow rates measured at different pressure heads. The optimal flow rate of 1 litre/min was achieved with a pressure head of 1 psi. The characteristics of the Beaufort LCS, Bhatia's prototype LCS and the modified LCS are compared in Table I.

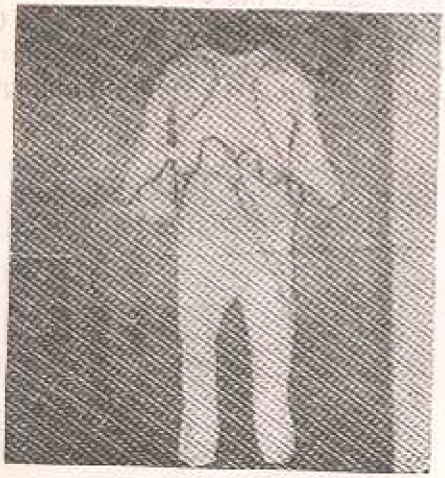
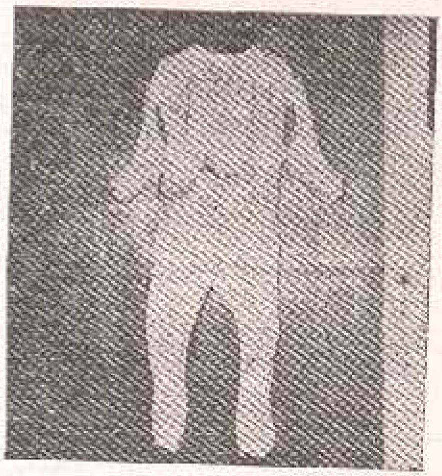


Fig. 5 *Front View*



Back View

Table I

	Beaufort LCS	Prototype LCS	Modified LCS
Total No of capillaries	88	88	56
Total length of capillaries	120 mtrs	110 mtrs	70 mtrs
ID of capillaries	1.5 mm	1.1 mm	1.8 mm
ID of manifolds	—	2.5 ..	5.0 ..
Back pressures at 1000 ml/ min flow rate	1.5 psi	Not achieved	1.0 psi
Weight of garment (empty)	1.5 Kg	—	1.2 Kg
Weight of garment (full)	1.8 Kg	—	1.7 Kg

Physiological Assessment

(a) Thermal stress studies: A total of 6 healthy male volunteers participated in the experiment. Their age and physical characteristics are given in Table II. The hot environment simulation chamber (Hot Cockpit) of IAM was used for the study. Two different thermal conditions were simulated for the experiment—thermal condition—(1)—a moderately severe heat stress environment with 50°C DB and 32.5°C WB temperatures and thermal condition-(2) simulating a more severe thermal stress environment of 57°C and 37.5°C dry and wet bulb temperatures respectively. Four subjects participated in trials in thermal environment (1) and two in environment (2).

In the experimental protocol each subject acted as his own control i.e. he was exposed to the same environment twice—once with the LCS and once without, giving a gap of at least 3 days between the two runs. The clothing used was as follows :-

(i) Cotton brief

(ii) Modified LCS

(iii) Flying overall

(iv) Nylon socks

(v) Shoes

(vi) Type 'g' inner helmet

After weighing the subject nude, he was instrumented for measuremnt of skin temperatures (four thermister probes) oral temperature (thermo-couple oral probe) and heart rate and dressed in the clothing mentioned above. After resting at room temperature for about 20 minutes the pre-exposure measurements were recorded. The subject was then made to sit in the environment chamber. Each subject was exposed for a period of 1 hour with monitoring of physiological parameters every 10 minutes. Post exposure nude weight was recorded to calculate the total sweat loss. During exposures with LCS on, the fluid (50% glycol + 50% water) was circulated through the 200 K cal inflight model refrigerant pack with a 220 volts AC pump capable of maintaining a flow rate of 1000ml/min through the LCS. The consolidated results are shown in Tables III, IV and V.

(b) Assessment with anti 'g' suit: Trials were conducted on the human centrifuge available at IAM to observe the difference in protection offered by the anti 'G' suit when worn next to the skin and when worn over the modified LCS. Four subjects participated in the centrifuge trials. All were healthy and had previous experience on the centrifuge (Table VI).

Table II

Age and physical characteristics of the subjects who took part in heat stress studies

Subject	Age (yrs)	Height (cm)	Body weight (Kgs)	Body surface area (m^2)
DKB	31	166.0	61.36	1.68
DR	29	173.0	52.00	1.60
BS	35	173.0	55.20	1.64
MBD	40	172.0	62.17	1.72
EMI	40	171.5	66.00	1.76
RSY	28	162.0	62.72	1.67
Mean	33.8	169.6	59.91	1.68
SD	5.3	4.5	5.23	0.06

Table III

Thermal protection offered by LCS Model II along with inflight model of refrigerant pack for one hour exposure at 50°C DB & 32.5°C WB

Subject	Rise in Heart Rate (Beats/min)			Heat Accumulation (K Cal/M²)			Modified Craig Index		
	Control	LCS	Diff	Control	LCS	Diff	Control	LCS	Diff
DKB	40	8	-32	80.00	30.30	-49.7	3.42	1.34	-2.08
DR	53	16	-37	53.15	13.23	-39.9	2.68	1.51	-1.17
BS	20	4	-16	47.50	18.40	-29.1	2.22	1.41	-0.81
MBD	21	4	-17	47.46	24.60	-22.9	2.21	1.31	-0.90
Mean	33.5	8	-25.5	57.03	21.63	-35.4	2.63	1.39	-1.24
SD	15.9	5.7	—	15.55	7.42	—	0.57	0.09	—
Cooling benefit			76%			62%			47%

Table IV

Thermal protection offered by LCS Model II along with inflight model of refrigerant pack for 1 hour exposure at 57°C DB and 37.5°C WE

Subject	Rise in Heart Rate Beats/min			Heat Accumulation (K cal/m²)			Modified Craig Index		
	Control	LCS	Diff	Control	LCS	Diff	Control	LCS	Diff
EMI	26	10	-16	56.70	40.00	-16.7	3.0	1.72	-1.28
RSY	31	-6	-37	66.02	22.44	-43.58	3.55	1.36	-1.99
Mean	28.5	2	-26.5	61.36	31.22	-30.14	3.17	1.54	-1.63
SD	3.5	11.3		6.59	12.42		0.25	0.25	
Cooling Benefit			93%			49%			51%

Table V

Comparison of total sweat losses between control and LCS Model II runs in the Hot Environment Chamber

Subject	Total Sweat Loss					
	Control		L C S		Difference	
	Gms	% of body weight	Gms	% of Body weight	Gms	% of body weight
DKP	730	1.19	40	0.06	-690	-1.13
DR	523	1.0	270	0.52	-253	-0.48
BS	500	0.9	250	0.45	-250	-0.45
MBD	540	0.87	250	0.40	-290	-0.47
EMI	844	1.28	280	0.42	-564	-0.86
RSY	840	1.34	200	0.32	-640	-1.02
Mean	663	1.1	215	0.36	-448	-0.74
Cooling Benefit						68%

Table VI

Age and physical characteristics of the subjects who took part in centrifuge trials

Subject	Age (yrs)	Height (Cms)	Body weight (Kgs)
BS	35	173.0	55.2
JKG	35	179.0	72.0
GKS	42	174.0	66.0
DKB	31	166.0	61.4
Mean	35.8	173.0	63.7
S D	4.6	5.4	7.1

The experimental protocol consisted of three different runs on the centrifuge for each subject.

(i) *Protocol I:* The subject was seated in the Gondola wearing an overall only. His relaxed 'G' tolerance was determined using peripheral light loss (PLL) at 56° as the end point.

(ii) *Protocol II:* The subject wore a cutaway anti 'G' suit next to the skin and his PLL determined.

(iii) *Protocol III:* The PLL was determined when the subject wore the cutway anti 'G' suit over the modified LCS.

In all experimental protocols, the rate of onset of 'G' was 0.5 'G' per second, duration at peak 'G' was 10 seconds and the decay was maintained at 0.1 'G' per second. The difference of 'G' levels observed between protocols II and III is taken as loss of 'G' protection due to the LCS (Tables VII and VIII).

Table VII

'G' Tolerance of subject—relaxed, with cut away anti 'G' Suit alone and with a combination of LCS—Model II and Anti 'G' Suit

Subject	Relaxed tolerance (g)	Tolerance with 'G' Suit (g)	Tolerance with 'G' suit over LCS (g)	Increase in tolerance with 'G' suit (g)	Increase in tole-rance with 'G' suit over LCS (g)	Diff in Tole-rance between 5 & 6 (g)
1	2	3	4	5	6	7
BS	3.8	4.8	4.6	1.0	0.8	0.2
JKG	3.7	5.0	4.8	1.3	1.1	0.2
GKS	5.4	6.6	6.4	1.2	1.0	0.2
DKB	3.5	5.1	5.0	1.6	1.5	0.1
Mean	4.1	5.37	5.2	1.275	1.1	0.175

Table VIII

'G' tolerance of subjects wearing LCS—I and the cut away anti 'G' suit over the LCS—taken from Bhatia[2]

MS	3.5	4.5	4.0	1.0	0.5	0.5
RB	2.7	4.0	3.3	1.3	0.6	0.7
ML	3.4	4.4	4.0	1.0	0.6	0.4
Mean	3.2	4.3	3.76	1.1	0.57	0.53

Inflight Trials

Laboratory trials had shown that the liquid cooling system with all its components viz. the LCS, mounted quick release connectors (earlier developed and tested for their ejection characteristics[13]), 20 volts DC miniature pump (capable of operating on aircraft power supply) and the stainless steel refrigerant pack stowed inside the fibre glass pack (Fig 2) is adequate in all respects and is capable of being interfaced with the aircraft for inflight trials. The system was installed in a jet trainer aircraft, the appropriate locations for the pump and QRCs being decided in consultation with the concerned authorities (Fig 6) for the right hand seat. After a functional check on the ground, airborne assessment was carried out in two low and medium level sorties while maintaining the mean cockpit temperature at 50°C. The system functioned satisfactorily.

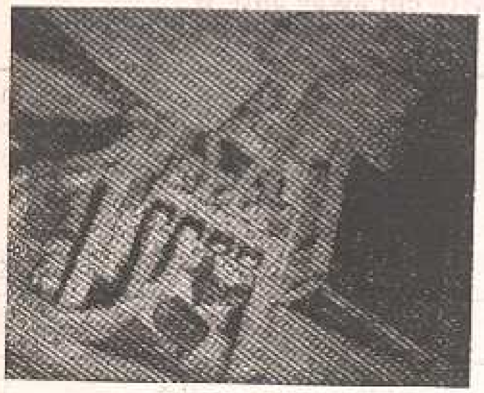


Fig. 6

Results

The physiological responses in the form of mean skin temperatures (MST) oral temperatures (OT) mean body temperatures (MBT) heart rates (HR) and total sweat losses were tabulated for each subject in the two thermal environments. The differences between the control and LCS runs indicated the cooling benefit with LCS in each of the parameters. Tables III and IV indicate the thermal protection offered by the LCS in terms of rise in HR, heat accumulation and modified Craig Index for subjects exposed to the two environments. The percentage reduction in the three parameters (cooling benefit) during the LCS runs is indicated at the bottom of the tables. Total sweat loss during control and LCS runs for all six subjects are compared in Table V. Cooling benefit is indicated at the bottom. Table VI shows the age and physical characteristics of subjects that took part in centrifuge trials. Table VII indicates the 'G' tolerance levels in terms of observed PLL under the three different situations. Table VIII has been taken from Bhatia[2] for comparison with results shown in Table VI. This table indicates the results of centrifuge trials with the indigenous prototype LCS.

Discussion

The garment forms a snug fit on different statured individuals. The heights of subjects used for experiments varied from 162.0—179.9 cms. In all cases the LCS formed a close and comfortable fit. It compares well with the comfort and fit of Beaufort LCS[10]. Having to necessarily leave bare areas on the abdomen, thighs and calves for the anti 'G' bladders, a larger distribution of the capillary tubing has been given over other areas. The loss of cooling benefit over bare areas has been gained by higher heat extraction from trunk and upper limbs. These are areas with higher skin temperatures than the periphery and hence areas of greater heat dissipation[9,11].

The back pressures in the suit are low and are easily provided by the pumping unit envisaged for inflight use. They are lesser than the Beaufort model LCS[10] which has a pressure drop of 1.5 psi as compared to 1.0 psi in the modified LCS at an optimum flow rate of 1000 ml/min. This has been achieved by the use of larger diameter capillary tubing, improved design of the manifolds and partly due to the decreased total length of the tubing (70 mtrs as compared to 120 mtrs).

In selecting the experimental conditions for heat stress studies, an attempt has been made to simulate in the laboratory, the environment and the system as it will be used in fighter aircraft so that the assessment made is as realistic as possible. In the one hour exposure to the moderately severe thermal environment of 50°C DB and 32.5°C WB there was a significant reduction in all the physiological parameters during LCS runs. The cooling benefit offered by the LCS (Table III) in the form of reduction in rise of HR, heat accumulation and modified Craig Index is of the order of 76%, 62% and 47% respecti vely. It compares well with earlier series of experiments reported by Banerjee et al[1] in identical trials with the Beaufort LCS. A similar trend is observed in the more severe environment of 57°C DB and 37.5°C WB. The cooling benefit being almost 90% in rise of HR and 50% each in heat accumulation and modified Craig Index (Table IV). Comparison of sweat losses between control and LCS values shows an average cooling benefit of about 70%. The average loss of body weight due to sweat loss is only 0.36% when cooled as compared to 1.1% in controls. This significant reduction in sweat loss due to cooling, apart from being an indicator of reduced physiological strain assumes importance as body dehydration reduces tolerance to acceleration[16].

All subjects (in both environments) felt comfortable throughout the 1 hour runs with LCS on. The cooling effect was felt upto the end of the exposure without excessive cooling on any part of the body. The fact that a certain amount of formed ice remained in the refrigerant pack at the end of each LCS run proves the point that 200 K cal refrigeration is more than adequate for our requirement[13,17].

The heat extraction capacity of the modified LCS is satisfactory as evidenced by the results which are comparable with those of the Beaufort LCS[1,17]. The redistribution of the PVC capillary tubing with their larger bore allowing a better mass flow of the circulating fluid over higher heat dissipation areas along with reduced insulation between the capillaries and the skin are the responsible factors even though the total length of the tubing is considerably reduced. To some extent the direction of liquid flow from the centre to the periphery over a larger temperatue gradient has helped.

The protection by the anti 'G' suit is best afforded when the bladders impart even pressure over the areas when worn next to the skin[6]. However, the LCS is also required to be worn next to the skin for maximum benefit[2]. The results of centrifuge trials are shown in Table VII. It is seen that wearing of cutaway anti 'G' suit over the LCS reduces 'G' protection by 0.1 to 0.2 'G' (mean 0.175 'G'). This shows a considerable improvement over the trials conducted on the prototype LCS (Table VIII) where the loss of 'G' protection ranges from 0.4 to 0.7 'G' mean 0.53 'G'). It is less than the values reported in an earlier study by Gupta et al[6] who found that the average reduction of tolerance was 0.25 'G' when the anti 'G' suit was worn over the flying overall. It is possible that the snug fitting garment without any folds under the bladders accord this improvement. Though, even this small reduction in 'G' protection is not desirable, it is felt that this reduction would be largely offset by the cooling benefit in reduced sweat loss. Tailaferro et al[16] have reported that a sweat loss of 1% or more of body weight reduces tolerance to acceleration and 2-3% dehydration reduces 'G' tolerance by 15-18%.

The successful inflight trials with LCS and other components of cooling system make it a feasible proposition for incorporation in military aircraft.

Conclusion

An indigenous liquid cooled suit with low back pressures at optimal flow rates, having heat extraction qualities meeting our requirements and capable of being integrated with the cutaway anti 'G' suits has been developed. With other components of the system being tailored to fit specific types of aircraft, it could be effectively used to alleviate heat stress in our aircrew.

References

1. Banarjee, PK, MK Vyawahare, CA Verghese and JS Sant ; Liquid conditioned suit and its use in alleviating heat stress in Military Flying. Av Med 23 (2) : 79-84, 1979.
2. Bhatia, SCB : Aeromedical requirements of liquid cooled suits (LCS) with cut away anti 'G' suit for optimum protection. MD Thesis (Av Med) 1981 (unpublished).
3. Dikshit, MB : Report on aircrew cooling trolley trials in S-22 aircraft 1971 (unpublished).
4. Fonesca, GF : Effectiveness of four water cooled under garments and a water cooled cap in reducing heat stress. ASEM 47 (11) : 1159-1164, 1976.
5. Gupta, VK : Field studies on thermal stress in fighter operations in Assam Valley. IAM Dept Report No 13, 1970.
6. Gupta, VK, SP Deshmukh and Kuldip Rai : Comparison of protection provided by the cutaway anti 'G' suit worn inside and outside the flying overall. IAM Dept Report No 103, 1980.
7. Harrison, MH and AJ Belyavin : Operational characteristics of liquid conditioned suits. Av Sp En Med 49 (8) : 994-1003, 1978.
8. Kaufman, WC and JC Pittman : A single liquid transport cooling system for aircrew members. Aerospace Med 37 1239-1243, 1966.

9. Kerslake, D McK, JD Nelms and J Billingham. Thermal stress in aviation, in a Text Book of Aviation Physiology (Ed by JA Gillies) 441-478, Pergamon Press, New York.

10. London RC. : A review of work in the United Kingdon on water cooled suits, in proceedings of the symposium on individual cooling. Kansas State University, pp-138-169, and Royal Aircraft Establishment, Tech Memo EP-418, 1969.

11. Ramanathan, NL : A new weighting system for mean surface temp of the human body. Appl Physiology 19 : 531-534, 1964.

12. Sant JS : Report on aircrew cooling trolley trials in MIG aircraft 1971 (unpublished).

13. Sant JS, CA Verghese, MK Vyawahare, PK Banerjee, EM Iyer and DT Shakunthala—changes in visual functions and performances efficiency under the effects of low frequency vibration and heat stress. AFMRC Project 1052/78, 1981.

14. Singh AK : Study of + Gz protection given by an anti-G' suit on top of a liquid cooled suit. Av Med 26 (2) : 96-99, 1982.

15. Sinha, KC & CA Verghese : Effects of precooling on heat tolerance and estimation of precooling requirements, J Aero Med Soc of India 12 : 25, 1969.

16. Taliaferro, EH, RR Wempen and WJ White : The effect of minimal dehydration upon human tolerance to positive acceleration. Aerospace Med., 36, 922-926, 1965.

17. Verghese, CA : Microenvironmental protection in Military flying. Av Med 25 (1) 43-45, 1961.

18. Verghese, CA and KC Sinha : Thermal evaluation trials in a hot cockpit under simulated heat load conditions in various IAF a/c in use. AFMRC Project 190/65, 1968.