Development of flame-retardant overalls for aircrew and their physiological evaluation

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Specialized clothing is an integral part of an aviator's protective outfit and the flame-retardant (FR) overall is one such item which provides protection against unforeseen fire hazards. The finish to impart the FR property may alter the heat exchange mechanism and may further add to the heat stress on the aircrew. Efforts were made to develop a FR fabric in the weight range of 160–190 g/m^2 using a blend of 70% FR viscose and 30% polyimide fibres. The performance of the FR overall vis-à-vis the currently used non-FR overalls flying MK II was evaluated by exposing eight healthy male subjects to simulated high-temperature environments (48°C, 50–55% RH) for one hour. Physiological responses of the subjects in terms of heart rate and temperature rise were monitored continuously during the exposure. Mean values of heart rate and heat accumulation values at the end of one-hour simulated exposure were found to be 123 bpm, 68 kcal/m^2/h and 119 bpm and 69 kcal/m^2/h, respectively for the FR overall and overalls flying MK II. The results indicate that the use of the FR overall does not add to the heat stress of the aviator. The flight trials of FR overalls corroborated the experimental findings.

Keywords: Flame-retardant overalls; Fire hazard; Protective clothing.

Specialized clothing forms an integral part of aircrew protective outfit. The minimum protective outfit worn by the aircrew includes an overall, anti-*G* suit, helmet, mask, gloves and boots. The protective outfit may vary depending on the mission requirements. The protective outfit adds onto the already existing environmental stress. Measurements of the environmental conditions in the cockpit have shown that temperatures as high as Tdb = 40–50°C and Tg – 50–60°C can occur [1–5]. The conditions become worse in aircrafts that have been heat-soaked with a closed canopy, during taxi and standby, during early flight before onboard air-conditioning becomes effective, and during low-level flight due to friction heating of the air frame.

The protective outfit worn by the aircrew complicates the process of heat exchange between the wearer and the environment. The properties of clothing, e.g. porosity, flexibility, elasticity, design and fit, thickness, number of layers, colour, texture, weight, and behaviour towards water, influence the radiative, convective and evaporative heat exchanges [6]. Because of this complexity, it is necessary to perform controlled testing with human subjects to understand the final impact of protective clothing on the wearer.

With the increasing usage of flame-retardant (FR) clothing the world over, both in commercial and military sectors, it becomes necessary to provide the aircrew with FR clothing which can protect the aircrew from unforeseen fire hazards. Two blends of FR viscose P-84 fibres have been developed for fabricating the overalls. The present paper discusses the development of FR clothing, the physiological evaluation under simulated conditions and the field trials.

Material and methods

Material. At present the aircrew use a polyester/cotton-blended overall, hereafter referred to as the 'control overall', for routine flying. The essential details of the various fabrics are given

Table 1. Physical properties of the various overall fabrics

Parameter	60/40 Polyester/cotton	50/50 FR viscose/P-84	70/30 FR viscose/P-84
Weight (g/m^2)	165	185	185
Weave	Mockleno	3/1 Twill	3/1 Twill
Warp (Tex)	12 × 2	15 × 2	15 × 2
Weft (Tex)	12 × 2	15 × 2	15 × 2
Warp threads/cm	34	36	40
Weft threads/cm	24	21	17
Air permeability (ft/s) at 10" water gauge	19.1	17.5	17.2
Flame-retardancy	–	Meets BS 3119	Meets BS 3119

in Table 1. The control overall does not possess any FR properties and, therefore, does not offer any protection to the aircrew. Also, a polyester/cotton-blended fabric is highly hazardous compared to either polyester or cotton alone as the cotton component provides a platform for the polyester to burn completely [7]. In order to provide protection to the aircrew, prototypes of FR overalls were fabricated using the developed 50/50 and 70/30 blend of FR viscose/P-84 fabric. A schematic diagram of the design of the overalls used in the study is shown in Figure 1. The FR viscose fibre was selected to develop the FR fabric owing to its positive properties, e.g. higher moisture regain, sweat absorption, soft feel on the body, formation of char on ignition and problem-free processing [8].

Subjects. Eight healthy males, ages 21–27 years (mean age 25) volunteered to participate as subjects after being informed about the experimental details and the associated risks. Several physical characteristics of the subjects are listed in Table 2. The subjects remained unaware of the fibre composition and the details of the overalls.

Chamber conditions. The study was carried out in a climatic chamber set at Tdb = 48°C and Twb = 38°C, giving a relative humidity of 50% and air movement of 16.7 m/min.

Experimental details. Each subject was exposed for one hour to the set chamber conditions thrice while wearing different types of overalls. A gap of a minimum of two days was kept between consecutive exposures. The subjects, on arrival at the laboratory, were weighed with minimum clothing and instrumented for measurement of (a) oral temperature (Tor), (b) skin temperature from four different sites, viz. chest, upper arm, mid thigh and calf and (c) heart rate. The subject after instrumentation was dressed with the overall to be evaluated just prior to entering the chamber. The basal heart rate and temperature was recorded before the subject entered the chamber.

Experiments were terminated prematurely (i.e. before 1 h of elapsed time) by any of four criteria: (a) core temperature exceeding 39°C; (b) core temperature rise above initial temperature exceeding 2°C; (c) heart rate exceeding 140 bpm; or (d) the subject requesting to leave the chamber.

Upon exiting the chamber after exposure, the subject was undressed and his weight was recorded with minimum clothing to obtain sweat production or fluid loss.

Parameters measured. The thermal strain on the wearer as a result of the exposure for one hour was assessed in terms of heart rate, change in mean skin temperature, heat accumulation and sweat rate. Mean skin temperature (Tsk) was determined based on Ramanathan's weightage [9]. Meanbody temperature (Tb) was calculated as 0.65 Tor + 0.35 Tsk. Heat accumulation (H) has been calculated using the relation

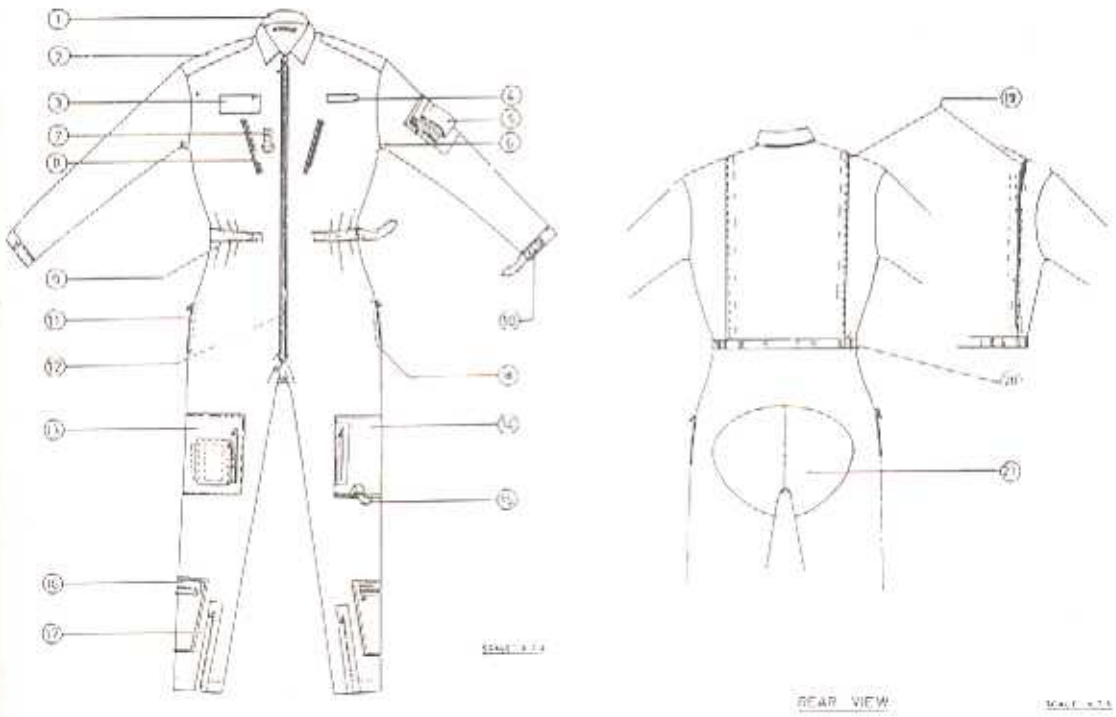

Figure 1. Design features of the FR overall: 1, collar; 2, shoulder epaulette; 3, name tab; 4, wing tab; 5, pen/pencil pocket with padding; 6, ventilation hole; 7, oxygen mask D ring; 8, breast pocket; 9, waist-adjusting tab; 10, adjusting tab at arm sleeve; 11, slit closed with zip fastener; 12, front zip fastener with two sliders; 13, right thigh pocket holding PVC sheet on the top; 14, left thigh pocket; 15, closing tab for left thigh lower pocket; 16, lower leg pocket; 17, left sleeve with gusset and zip fastener; 18, side pocket; 19, back pleat; 20, waist band; 21, reinforcement patch at the seat.

Table 2. Physical characteristics of the subjects

Name	Age (yr)	Body weight (kg)	Height (cm)	Body surface (m^2)
A	26	68.02	176	1.82
B	27	52.80	169	1.59
C	21	69.22	168	1.76
D	26	54.99	159	1.54
E	26	61.85	162	1.63
F	25	58.37	158	1.55
G	27	64.44	170	1.72
H	24	47.66	163	1.47

$$H = \frac{\text{Body weight (kg)} \times \text{Specific heat} \times \Delta Tb}{\text{Body surface area } (m^2)},$$

where ΔTb is the difference between Tb at any time point and the initial Tb.

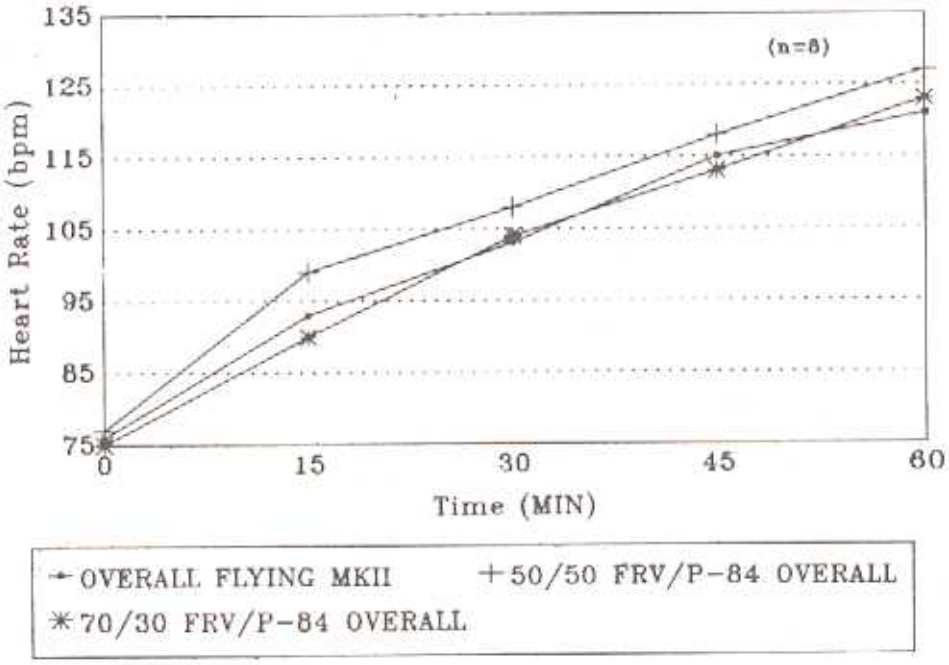

Figure 2. Heart response of a subject on exposure to heat stress for one hour

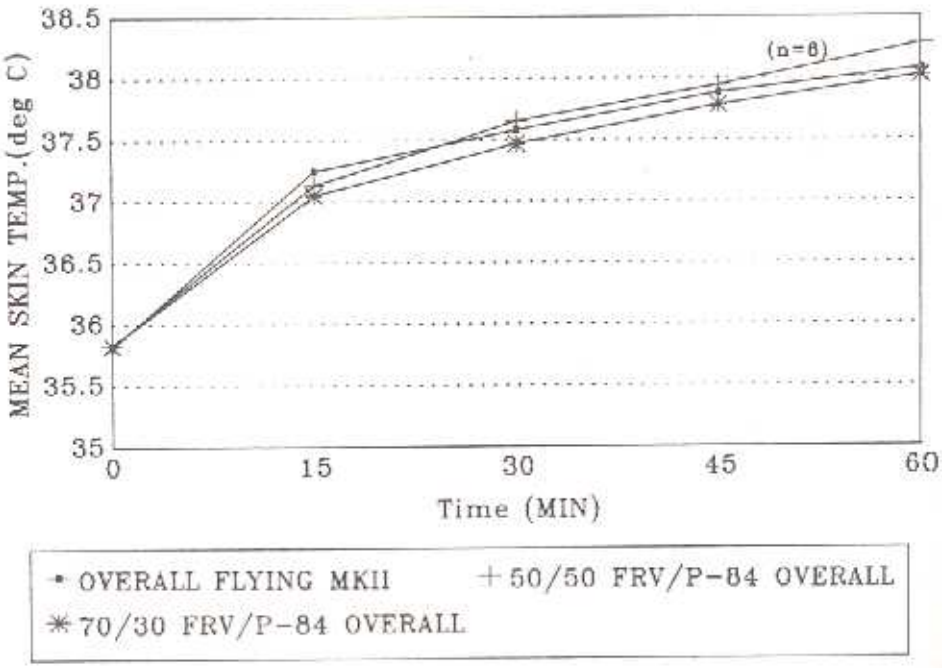

Figure 3. Changes in mean skin temperature on exposure to heat stress for one hour

Results and discussion

Figures 2 and 3 present the physiological responses obtained with the three overalls. Student's paired *t*-test was used to know whether there exists any significant difference between the control overall and the FR overalls under study.

As shown in Figures 2 and 3, the heart rate and the mean skin temperature showed an increase for all the overalls under study. The control overall and the 70/30 FR viscose/P-84 overall show the same kind of response and this clearly indicates that the FR overall does not offer any extra thermal stress to the wearer *vis-à-vis* the control overall. Heart rate and heat accumulation for the overalls flying MK II and for the FR overall were found to be 123 bpm, 68 kcal/m^2/h and 119 bpm and 69 kcal/m^2/h, respectively. Even the sweat rate, as shown in Figure 3, was found to be almost the same for control and for 70/30 FR viscose/P-84 overall.

The 50/50 FR viscose/P-84 overall was found to result in slightly higher heart rate (127 bpm) and heat accumulation (73.0 kcal/m^2/h) compared to either 70/30 FR viscose/P-84 overall or the control overall. This may be attributed to the lower percentage of FR viscose, i.e. 50 *vis-à-vis* 70 of 70/30 FR viscose/P-84 overall. The sweat rate was slightly lower than the other two overalls. However, the differences were not statistically significant.

Based on the chamber trials, 70/30 FR viscose/P-84 overall was selected for further flight trials.

Flight trials were conducted in as many as 26 squadrons of Indian Air Force, and in all 65 pilots participated in the trials. These trials were conducted at temperatures varying from +3°C to as high as +48°C. The pilots were given individual questionnaire to obtain the feedback for further improvement of the overall. The questionnaire given contained questions on the design aspect and the subjective feeling of comfort. After the flight trials, the questionnaires received from the users were analysed and the analysis revealed that the developed FR overall is as comfortable as the currently used overall flying MK II. The subjective assessment of comfort thus corroborates the objective evaluation, i.e. physiological evaluation under simulated conditions.

Conclusions

The thermal response offered by the developed 70/30 FR overall was found to be similar to that of the currently used overalls flying MK II. This clearly indicates that the property of flame-retardancy does not impair adversely the thermal response. Thus, the FR overall can be used advantageously to provide additional protection against fire hazards, without sacrificing the thermal comfort. The flight trials conducted corroborated the laboratory findings that the two types of overalls, viz. the overalls flying MK II and the 70/30 FR viscose/P-84 overall, offer the same thermal response. The flight trials also indicated the suitability of the design of the FR overall.

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