

Heat Stress of Helicopter Aircrew Wearing Immersion Suit

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Abstract: The objectives of the present study were to define the lowest ambient air and cabin temperatures at which aircrews wearing immersion protection are starting to experience thermal discomfort and heat stress during flight operations, and to characterize during a flight simulation in laboratory, the severity of the heat stress during exposure to a typical northern summer ambient condition (25°C, 40% RH). Twenty male helicopter aircrews wearing immersion suits (insulation of 2.2 Clo in air) performed 26 flights within an 8-month period at ambient temperatures ranging between -15 and 25°C, and cabin temperatures ranging between 3 and 28°C. It was observed based on thermal comfort ratings that the aircrews were starting to experience thermal discomfort and heat stress at ambient and cabin air conditions above 18°C and at a WBGT index of 16°C. In a subsequent study, seven aircrews dressed with the same clothing were exposed for 140 min to 25°C and 40% RH in a climatic chamber. During the exposure, the aircrews simulated pilot flight maneuvers for 80 min followed with backender/flight engineer activities for 60 min. By the end of the 140 min exposure, the skin temperature, rectal temperature and heart rate had increased significantly to $35.7 \pm 0.2^\circ\text{C}$, $38.4 \pm 0.2^\circ\text{C}$ and between 110 and 160 beats/min depending on the level of physical activity. The body sweat rate averaged 0.58 kg/h and the relative humidity inside the clothing was at saturation by the end of the exposure. It was concluded that aircrews wearing immersion suits during the summer months in northern climates might experience thermal discomfort and heat stress at ambient or cabin air temperature as low as 18°C.

Key words: Skin temperature, Core temperature, Sweat rate, Thermal comfort

Introduction

It is well documented that helicopter aircrews exposed to warm weather are subjected to heat stress, particularly in the absence of cockpit air conditioning or personal cooling systems¹⁻³). Such heat stress can lead to an increased in body temperature, dehydration and an impairment of the aircrew performance⁴). A number of investigators demonstrated that personal air or water cooling systems could effectively alleviate the heat stress of aircrew in those conditions⁵⁻⁷). However, many helicopter aircrafts do not have air conditioning system on board and the aircrews do not have access to personal cooling systems, which remains a problem.

Because of Canada's 243,000 km of shoreline, considered

the largest in the world, many commercial and military helicopter aircrafts are required to operate over large bodies of water. This is the case for transport aircraft carrying crew to their working oil platform at sea, and Search & Rescue aircrafts performing a rescue or during training missions over water. During such flight operations, aircrews are required to wear immersion suits during the flights to protect themselves in the event of an accidental cold water immersion. Since the water temperature at sea remains below 10°C yearlong, aircrew will be required to wear the immersion suit even during summer time when the air temperature can reach 20–25°C and above, with similar cabin temperatures.

The Canadian General Standards Board recommends that immersion suits should protect aircrew for a minimum of 6

h against hypothermia during immersion in icy water. To achieve this level of protection, the immersion suit requires an insulation of 0.75 Clo when immersed⁸). This level of protection corresponds to about 2.0 to 2.3 Clo of insulation in air, the equivalent of wearing a two-layer Arctic suit. In the absence of air-conditioning or personal cooling system, aircrew wearing such insulative protection and exposed to summer conditions will likely experience heat stress and dehydration from heavy sweating, even during the mild summer conditions of a northern country. This is supported by a study conducted on Norwegian military Sea King helicopter pilots showing that during flights, the pilots are experiencing significant heat stress while wearing protective clothing even during the winter⁹).

The objectives of the present studies were to define the lowest ambient air and cabin temperatures at which the aircrew wearing immersion protection is starting to experience thermal discomfort and heat stress during flight operations, and to characterize during a flight simulation in laboratory, the severity of the heat stress during exposure to a typical northern country's summer ambient conditions (25°C, 40 RH) in the absence of air-conditioning or personal cooling system.

Materials and Methods

Field trial on the Canadian east coast

1) Subjects

A field trial was conducted with a Search & Rescue organization located on the Canadian east coast of Newfoundland during a period of 8 months from January to August, covering the winter, spring and summer periods. Twenty male aircrews aged between 21 and 36 yr of age participated in the study. Twelve of the subjects were helicopter pilots and eight were flight engineers. All subjects were healthy and fit to fly, and had a medical screening before signing for their volunteer consent form. The protocol was approved by the Defence Research & Development Canada Human Research Ethics Committee (HREC at DRDC Toronto).

2) Procedures

A total of 26 flights were performed during the 8 months of the trial using Cormoran helicopter aircrafts not equipped with air conditioning systems. Each flight crew consists of 4 aircrews: 2 pilots and 2 flight engineers or backenders. The flight duration ranged between 2 and 7 h with an average duration of 3.5 h. For each flight, the following parameters were recorded: initial ambient air temperature on the runway,

dry bulb temperature, relative humidity and the wet bulb globe temperature (WBGT) index inside the aircraft during each hour of the flight, and the corresponding thermal comfort rating of 2 aircrews. The WBGT index was measured using a WBGT recorder with a 1.5 inch black globe (model RSS-214 WiBGeT; Imaging & Sensing Technology, NY). The thermal Comfort rating scale used during the trial was the Gagge Thermal Comfort Scale¹⁰).

3) Clothing

During all the flights, the subjects were dressed with the following standard items in addition to their immersion suit: top and bottom long cotton underwear, wool socks, flying leather summer boots, flying gloves, helmet, and uninflated lifevest. The cold water immersion protection was a dry immersion suit incorporating rubber neck and wrist seals, a Nomex[®] and Gore-Tex[®] waterproof and flame resistant shell, and a perforated foam insulation liner (Mustang Survival Inc., BC, Canada). The thermal insulation value of the immersion suit as measured on a thermal manikin (Thermal Instrumented Manikin, TIM; the CORD Group, NS) was 0.8 immersed Clo or 2.2 Clo in air¹¹).

Simulation study in the climatic chamber

1) Subjects

Seven helicopter aircrews (6 males, 1 female) were selected to participate in this trial. The subjects were (mean \pm SD) 36.0 \pm 9.2 yr old, 1.78 \pm 0.11 m tall, weighted 84.1 \pm 20.1 kg and had a body fat of 19.7 \pm 5.9%. All subjects were healthy and had a medical screening before signing for their volunteer consent form. The protocol was approved by the DRDC Human Research Ethics Committee (HREC).

2) Ambient conditions

The tests were conducted inside a DRDC Toronto climatic chamber maintained at 25°C, and 40% RH (wind speed of 0 to 0.2 m/s). During the simulated flight maneuvers, a 250 W infrared lamp was aimed at each subject to simulate solar load inside the cockpit of the aircraft. This condition was selected to represent a typical clear and warm summer day on the Canadian east coast of Newfoundland.

3) Procedures

Each test lasted 2.3 h and consisted of two phases: a simulated flight maneuver lasting 1.3 h followed by simulated backender activities lasting 1 h. The simulated flight maneuvers consisted of having the subjects sitting on a helicopter seat in front of infrared lamps while maintaining a metabolic rate of 1.5 MET. A metabolic rate of 1.5 MET

(1.5 times the resting metabolic rate) was defined by Faerevik and Reinertsen⁹) to represent the energy expenditure typically experienced by helicopter pilots during flight operations. The metabolic rate was maintained at 1.5 MET by asking the subjects to operate mockup helicopter foot pedals and stick at a pre-defined rate. The metabolic rate of the subjects was previously verified using a gas analyzer to calibrate the mockup simulation rate.

The simulated backenders activities consisted of a series of 3 different exercises. Each exercise represented a specific task typically performed by the backenders or flight engineers of a Search and Rescue crew. Each series of activities was repeated 3 times and separated by a 5 min rest period. This cycle was repeated until the 60 min was elapsed. Activity 1 consisted of carrying equipment inside the aircraft. Each subject carried a 7 kg weight over a distance of 5 m while stepping over a two-step stairs. This activity was performed until a 1 min elapsed time was over. Activity 2 consisted of pulling a rope with a 7 kg weight equivalent tension from a face down position (duration of the activity: 30 s). This pulling activity was followed by a cranking activity with both arms using an arm ergometer (Monark 881E Upper Body Ergometer) with a torque of 1.5 N·m from a standing position (duration of the activity: 30 s). Activity 3 consisted of moving ten 7 kg sand bags into a stoke litter, pulling the stoke litter over a distance of 3 m, and unloading the stoke litter until an elapsed time of 1 min was over. This last activity simulated the manipulation of a victim inside the helicopter.

4) Termination criteria

An experimental session was terminated if one of the following criteria was achieved: 1) elapsed time of 2.3 h; 2) a core temperature of 39.3°C; or 3) 95% of the maximum estimated heart rate for three minutes.

5) Measured parameters

The following parameters were continuously measured on the subjects during the sessions: rectal temperature at a depth of 15 cm inside the rectum (as an index of core temperature; 400 series thermistor, Mallinckrodt Medicon Inc, St Louis, USA), skin temperature (YSI 44004 thermistor, Yellow Springs Instruments, Yellow Springs, OH) at 7 locations according to the Hardy and Dubois weighing system (forehead, abdomen, forearm, hand, thigh, shin, foot)¹²), heart rate (heart rate monitor Polar Vantage, Finland), and water vapor pressure (relative humidity capacitance sensors, Vaisala Sensor Systems, Woburn, MA; and YSI 44004 thermistors, Yellow Springs Instruments, Yellow Springs, OH) at 3

locations inside the clothing between the liner and the shell of the suit (the 3 locations were the chest, upper back and front thigh). The following parameters were measured periodically during the sessions: thermal comfort using the Gagge Thermal Comfort Scale¹⁰), and perceived exertion using the Borg Scale¹³). In addition, sweat rate was also measured at the end of each session by comparing the nude body weight before and after the sessions.

6) Clothing

During the tests in the climatic chamber, the subjects were dressed with the same clothing as during the first study conducted in the field (see text above under *Field trial on the Canadian east coast*).

7) Statistical analysis

The data were analyzed by repeated measures ANOVA to test for differences over time in the measured variables. Significant differences were tested using a Neuman-Keuls post-hoc procedure. Significance was accepted at the $p < 0.05$ level. Values are presented as mean \pm SE.

Results

Field trial on the Canadian east coast

A total of 26 flights were performed during the 8-month study with an average duration of 3.5 h. The ambient temperatures as measured on the runway before the flights were ranging between -15 and 25°C . Only 20% of the flights were performed during sunny days. Figure 1 shows the average thermal rating of the aircrew during the flights as a function of the ambient temperature during the 8-month study. It is observed that from an ambient temperature of -15 to about 18°C , the thermal comfort rating is at 7 or 8, which represents a state of thermal comfort. Above an ambient temperature of 18°C , the thermal rating increases rapidly to a value of 12 and stays at that rating for up to an ambient temperature of 25°C . This indicates the presence of thermal discomfort and heat stress since a rating of 12 is considered as being hot. Few thermal comfort ratings around 10 were observed at ambient temperatures between -5 to -7°C . These observations can be explained by elevated cabin temperatures during those flights ranging between 21.0 and 23.5°C .

Figures 2 and 3 represent the thermal comfort rating of the aircrew as a function of the thermal conditions inside the aircraft. Figure 2 shows the average thermal rating of the aircrew during the flights as a function of the temperature measured inside the cabin. The average cabin temperature

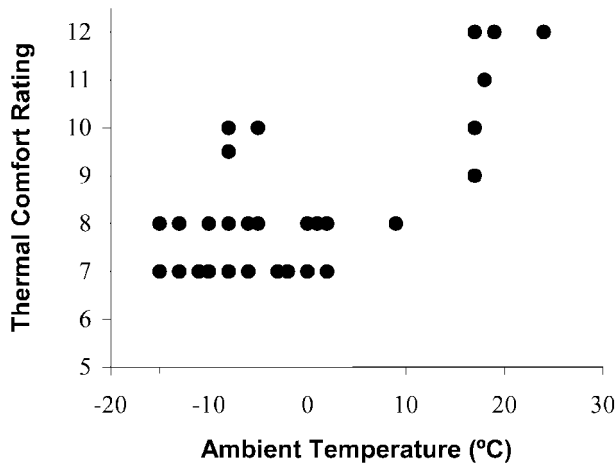


Fig. 1. Average thermal comfort rating of the helicopter aircrews during the 26 flight operations conducted at different ambient air temperatures during the 8-month testing period.

A rating of 7-8 indicates thermal comfort; above 7-8 is an indication of heat stress.

during the 26 flights ranged between 3 and 28°C. The data in Fig. 2 show a very similar trend as in Fig. 1: for cabin temperatures below about 18°C, the thermal comfort rating is 7 and 8 representing a state of thermal neutrality. When the cabin temperature increases above 18°C, the thermal comfort rating of the aircrew increases gradually to a value of 12 by 25°C and plateau to that value, representing a condition of thermal discomfort and heat stress. Figure 3 shows that for WBGT index below about 16°C, the thermal comfort rating is at 7 and 8, representing a condition of thermal comfort for the aircrew. Above a WBGT index of 16°C, the thermal comfort rating increases gradually to a value of 12 by about 23°C, indicating a level of thermal discomfort and heat stress.

A significant direct and linear relationship was observed ($r=0.35$, $p<0.02$) between the ambient air temperatures and the cabin temperatures, with similar values observed at about 18°C. Because of the way the data were collected during the flights, no direct comparison could be made between the thermal comfort ratings of the pilots and the flight engineers.

Simulation study in the climatic chamber

During the first portion of the simulation, all seven subjects lasted the full 80 min, while only 4 of the 7 subjects lasted the full 60 min of the backender activity simulation. The reason for not lasting the full 60 min was attributed to high heart rate values (see termination criteria above).

Figure 4 presents the mean weighed skin temperature of

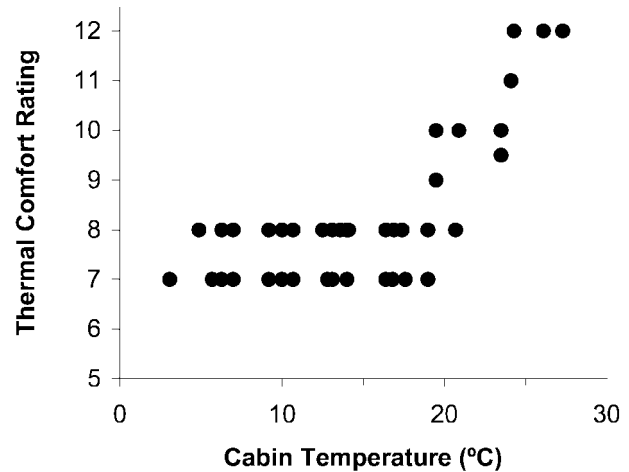


Fig. 2. Average thermal comfort rating of the helicopter aircrews during the 26 flight operations as a function of the temperature inside the aircraft cabin during the 8-month testing period.

A rating of 7-8 indicates thermal comfort; above 7-8 is an indication of heat stress.

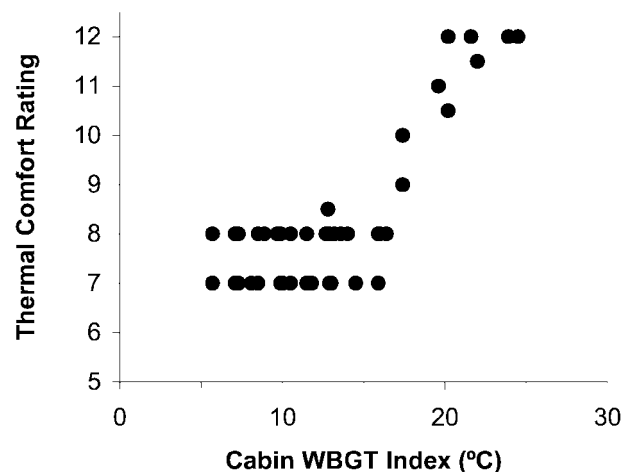


Fig. 3. Average thermal comfort rating of the helicopter aircrews during the 26 flight operations as a function of the WBGT Index measured inside the aircraft cabin during the 8-month testing period.

A rating of 7-8 indicates thermal comfort; above 7-8 is an indication of heat stress.

the subjects during the simulated 80 min flight maneuvers and the 60 min simulated backenders activities. During the flight maneuvers, the mean skin temperature (mean \pm SE) steadily increased from a thermoneutral $34.0 \pm 0.4^\circ\text{C}$ to $35.7 \pm 0.2^\circ\text{C}$. During the 60 min simulated backenders activities, the mean skin temperature further increased to $37.2 \pm 0.3^\circ\text{C}$.

Figure 5 presents the mean rectal temperature of the subjects during the two phases of the study. During the

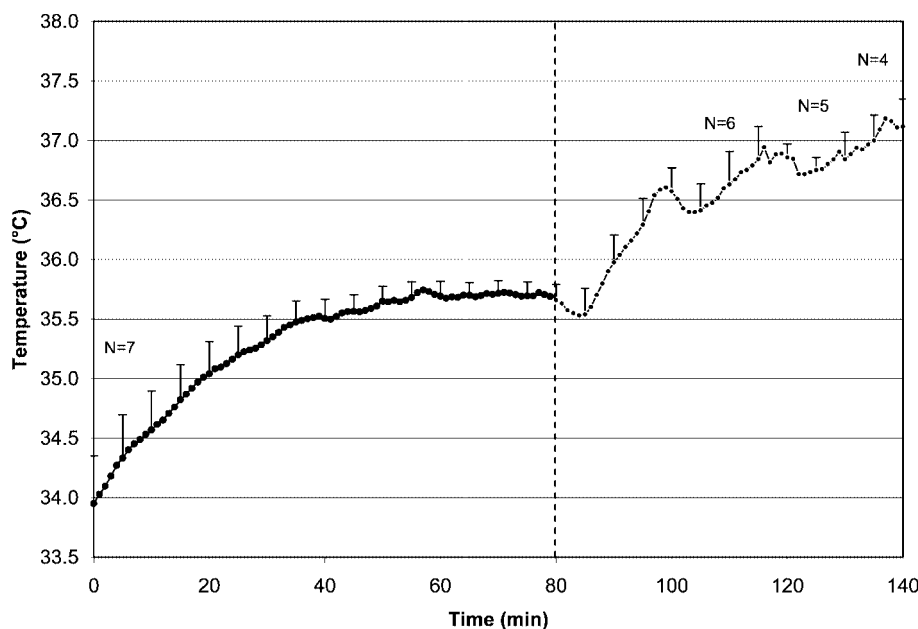


Fig. 4. Weighed mean skin temperatures of the 7 subjects during the first 80 min simulated flight maneuvers, and during the following 60 min simulated backender activities.

flight maneuvers, the mean rectal temperature (mean \pm SE) remains essentially constant at thermoneutrality (between $37.3 \pm 0.1^\circ\text{C}$ and $37.2 \pm 0.0^\circ\text{C}$) with no significant change observed. During the 60 min simulated backenders activities, the mean rectal temperature significantly increased to $38.6 \pm 0.2^\circ\text{C}$, a condition considered hyperthermic.

Figure 6 presents the mean heart rate of the subjects during the simulated 80 min flight maneuvers and the 60 min simulated backenders activities. During the flight maneuvers, the mean heart rate (mean \pm SE) remains essentially constant at just above resting level (78 ± 2 beats/min). During the 60 min simulated backenders activities, the mean heart rate significantly increased to a maximum of 160 ± 11 beats/min during the active phases of the simulation and decreased significantly to between 110 ± 5 and 120 ± 10 beats/min during the resting phases of the simulation.

On average over the duration of the trial, the sweat rate from the whole body was 0.58 kg/h for an average sweat loss of $1,353$ ml. At the end of the 80 min flight maneuvers, the Rate of Perceived Exertion (RPE) and the Thermal Comfort Rating (TC) were 11.0 ± 0.3 (fairly high) and 8.2 ± 0.2 (warm but fairly comfortable) respectively. At the end of the 60 min simulated backenders activities, the RPE and the TC increased significantly to 13.7 ± 0.6 (between somewhat hard and hard) and 10.0 ± 0.3 (hot).

The water vapor pressure inside the clothing was similar for the three measured body sites. For this reason, we decided

to pool the data from the three sites. On average the water vapor pressure inside the immersion suit increased significantly during the 80 min flight maneuvers from a baseline value of 21 ± 4 to 33 ± 3 mmHg by the end of the maneuvers (corresponding to 59 ± 8 and $82 \pm 4\%$ relative humidity, respectively). At the end of the 60 min simulated backenders activities, the water vapor pressure was further increased to an average of 40 ± 3 mmHg (corresponding to $98 \pm 9\%$ relative humidity).

Discussion

Field trial on the Canadian east coast

The main purpose of this trial was to define the lowest ambient condition at which helicopter aircrew wearing immersion suit will start experiencing thermal discomfort and heat stress during flight operations in the field. We defined the ambient condition in terms of three easily measured parameters in the field: ambient air temperature outside the aircraft, cabin temperature and cabin WBGT index. To minimize interference with normal flight operation and to optimize the participation of the aircrew subjects to the study, we selected the thermal comfort rating as an indicator for the presence and the extent of the thermal discomfort and heat stress experienced by the aircrew. It is well established that thermal comfort reflects an integration of various thermal drives¹⁴⁻¹⁷, and is influenced by both the

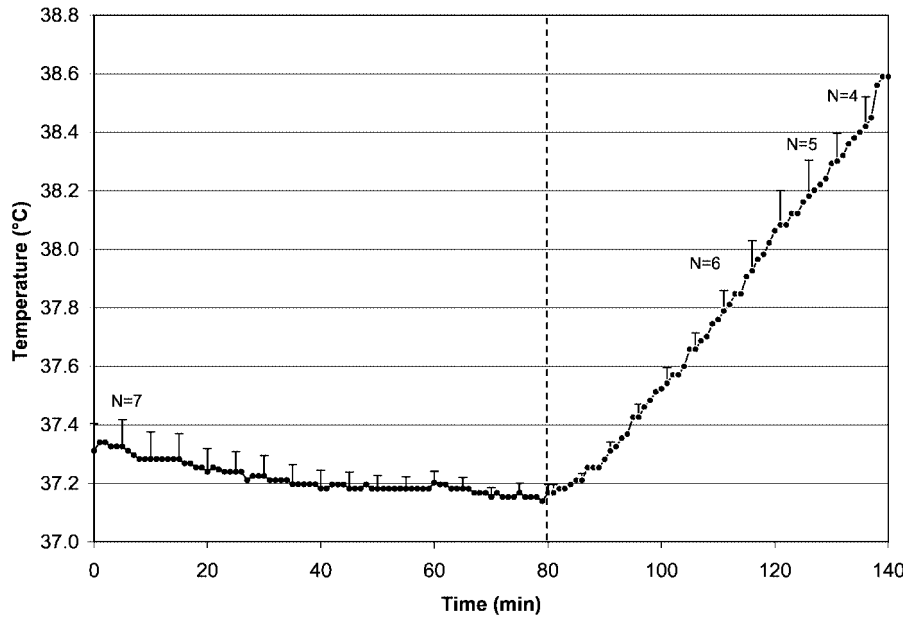


Fig. 5. Mean rectal temperatures of the 7 subjects during the first 80 min simulated flight maneuvers, and during the following 60 min simulated backender activities.

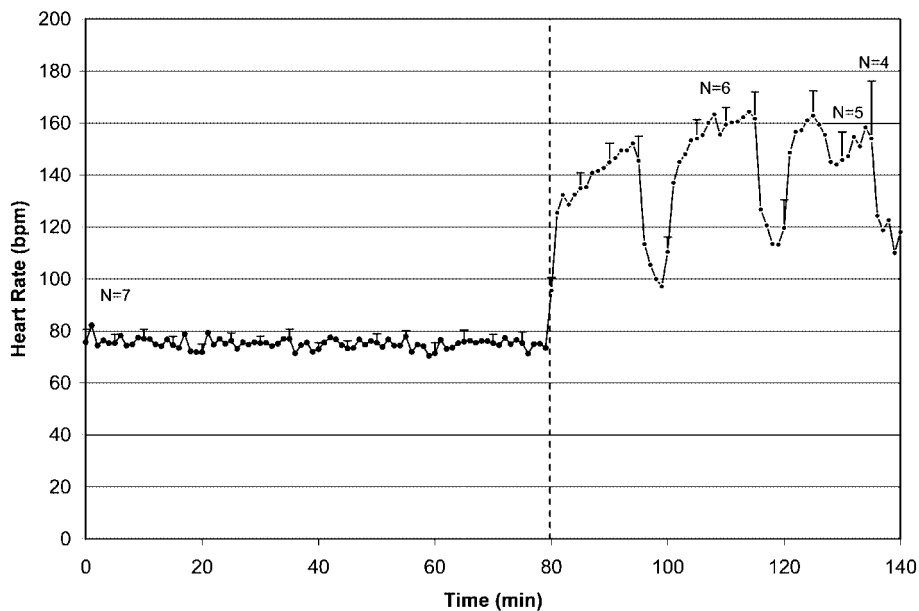


Fig. 6. Mean heart rate of the 7 subjects during the first 80 min simulated flight maneuvers, and during the following 60 min simulated backender activities.

core and skin temperatures of the body¹⁸), making it a useful integrative index of thermal stress. This approach proved to be successful and we were able to obtain data from 26 flights over a period of 8 months covering the Canadian winter, spring and summer seasons.

The results from this trial show that at an ambient air

temperature or a cabin temperature of 18°C and a cabin WBGT index of 16°C, aircrews are starting to feel uncomfortably warm in their immersion suit. This observation is supported by a recent study conducted on subjects dressed with similar clothing and exposed to various ambient conditions in a climatic chamber¹⁹). The results

from this study showed that subjects started to sweat and to feel warm and significantly uncomfortable at an ambient temperature above 18°C. The same study concluded from subjective evaluation of thermal sensation and comfort that the thermoneutral zone (TNZ) is between 10 and 18°C when subjects are wearing aircrew protective clothing. The TNZ defines a range of ambient conditions where the subjects control their thermal balance by the regulation of skin blood flow and where the metabolic rate is minimum due to the absence of shivering and sweating.

The present study shows that for ambient temperature conditions above 18°C, aircrew wearing immersion suit will likely be affected by heat stress during flight operations. Previous studies have indicated that heat stress can eventually lead to the decrement of aircrew performance⁴⁾ and operational endurance²⁰⁾, although this is still a controversial issue in practice because skill can be an important variable in performance degradation during thermal stress²¹⁾. Nevertheless, it is advisable to consider starting using a personal cooling system at ambient conditions above 18°C. Consequently, a personal cooling system will likely be required even for aircrew from Nordic regions such as Canada and Scandinavian countries when immersion protection is required yearlong during flight operation over large bodies of water.

Simulation study in the climatic chamber

The objective of the flight simulation was to characterize in laboratory, the severity of the heat stress during exposure to a typical Canadian summer ambient condition (25°C, 40 RH) in the absence of air-conditioning or personal cooling system. The simulation was divided in two parts: a simulated flight maneuver lasting 80 min followed by simulated backender activities lasting 60 min. During the flight maneuver, the metabolic rate was low and close to the resting level with a heart rate of 78 ± 2 beats/min. At the end of the 80 min simulation, the subjects were not experiencing a significant level of heat stress as shown by a thermal comfort rating of 8.2 (warm but fairly comfortable), the absence of an increase in core temperature and only a slight increase of the skin temperature to about 35.7°C. The relative humidity inside the clothing was elevated to 82% but was likely not an important limiting factor to the evaporative heat transfer. The results from the present study are similar to the data reported by Faerevik and Reinertsen during a simulation in laboratory using a similar protocol, protective clothing and ambient conditions²²⁾. They reported no significant decrement in cognitive performance during the exposure to those conditions. Our study would support the

conclusions of Faerevik and Reinertsen, that an ambient condition around 23 to 25°C does not cause any significant detrimental change in the physiology of the aircrew when the work load is low and close to the resting level such as for pilots.

At first sight, this conclusion seems to contradict the observation from the first trial where aircrew reported to be heat stressed in an environment above 18°C. This last observation, however, was an average for pilots and backenders having a higher metabolic rate than the subjects involved in the 80 min flight simulation. As it will be discussed below, the metabolic rate can have a significant impact on the level of heat stress while wearing an immersion suit.

During the 60 min simulated backender activities, the subjects experienced a significant level of heat stress as showed by the elevated thermal comfort rating (rating of 10 or hot), the elevated skin temperature (37.2°C) and core temperature (38.4°C), and the amount of sweat produced (1.35 L or 1.6% dehydration) by the end of the simulation. The heat stress was likely attributed to the combined effect of an elevated metabolic rate above resting, and the impairment of the evaporative heat loss as reflected by the saturated microenvironment inside the immersion suit (98% RH). Consequently, the majority of the sweat loss by the subjects was accumulated inside the clothing instead of being evaporated into the environment. This observation is supporting the conclusion of previous studies that wearing immersion suit impacts on evaporative cooling resulting in an increase in heat storage in the body^{23, 24)}. The level of physiological strain and microenvironment observed in the present study by the end of the 60 min simulation of backender activities is equivalent to exposing the subjects to an environment of 40°C at rest. Indeed, the skin and core temperatures (37.2 and 38.4°C, respectively) from the present study were similar to the values of skin and core temperatures reported by Faerevik and Reinertsen for subjects dressed with a similar immersion suit and following an exposure to 40°C at rest (37.8 and 38.4°C, respectively)²²⁾. The level of dehydration was also similar between the two studies (1.6% for the present study compared to 1.2% in Faerevik and Reinertsen's study). Furthermore, the water vapor pressure observed inside the clothing in the present study (40 mmHg) was very close to the water vapor pressure reported by Sullivan and Mekjavic during exposure of their subjects wearing a similar immersion suit (Gore-Tex®) to an environment of 40°C (39 mmHg)²⁴⁾. This level of physiological strain was reported to cause a significant decrease of the cognitive performance²²⁾.

In is concluded from the present studies that during flight operations, aircrews wearing immersion suit can be affected by heat stress at an ambient and cabin temperature above 18°C. For pilots with a low metabolic rate, the thermal strain and consequently the performance decrement is likely not significant for up to an ambient temperature of 25°C. For backenders with an elevated metabolic rate, exposure to an ambient temperature of 25°C will result in a significant dehydration and heat strain equivalent to an exposure to an environment of 40°C at rest. This situation will cause an increase in the core temperature with a possible decrement of the performance.

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