Aircrew Physiological Response to Cold Environments

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1.0 INTRODUCTION

Cold stress can overwhelm physiological response to very cold exposures. Temperature is regulated by changes in cutaneous vascular network. Other factors to be considered are: shivering thermogenesis, carbohydrate oxidation, body composition, age, gender, exercise, endurance and tolerance. Aircrew can be exposed to such environment in various critique periods, mostly during the ground preflight operations. While the cockpit is protected from wind and not as cold as the outside, pilots engage in very limited physical activity and cannot wear high-bulk clothing. Time is critical until engine start is performed. The problem is not only to prevent frostbite or hypothermia, but also to ensure optimal handling of the aircraft and adequate capacity to cope with emergencies.

The Eurofighter Instrumented Production Aircraft (IPA) 4, operated by EADS CASA at Getafe near Madrid, was deployed to Vidsel in the very north of Sweden, near the Artic Polar Circle, to start with the implementation of special "Extreme Cold Weather Trials". There, the aircraft and the test team faced temperatures between –25 and –31º Celsius in that time of the season.

The deployment that tested the aircraft, its systems and performance in such environment, consisted of more than 60 people, including pilots, mechanics, technicians, engineers, doctors and other supporting personnel. All staff members participating in this exercise received a specific arctic training and were provided with special protective garment.

The test team came from EADS Military Aircraft Spain or the Eurofighter Consortium (EADS CASA, EADS Germany, BAEs Systems and Alenia), from the Spanish engine manufacturer ITP, partner of the Eurojet consortium, from INTA, the Institute for Aeronautical Research, from CIMA the Aeromedical Center in Madrid and from the Spanish Air Force, everything ran under the supervision of the Defence Ministry in Madrid. To monitor and store the test data acquired, among other equipment a mobile MIDS (Multifunction Information Distribution System) station was deployed to Vidsel.

The presence of CIMA was due to the neccesity of ensuring the security of pilots operating in such hostile environment, taking into account that there were critical periods of cold exposure that may lead to hypothermia, mainly time outside the aircraft plus time in the cockpit until engine or APU –Auxiliary Power Unit- start (that provides heating to the cockpit).

This paper is a description of a series of testing procedures, performed in extreme cold environment in order to check operational, technical and physiological responses of the EF-2000 Typhoon (Eurofighter) and the corresponding air and ground crews.

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2.0 OBJECTIVE

The purpose of these trials was to verify the operational behaviour of the European fighter aircraft and its systems under inhospitable arctic conditions at temperatures between -25 and -31 °C, evaluating the impact of temperature penetration in the aircraft and the pilot.

The aim of the exercise was to define the best and safest operational procedures of the aircraft in such an environment and establish a time frame for operations under extreme cold conditions.

Secondary objectives were to establish the needs for future prolonged operations in similar weather conditions.

3.0 SUBJECTS & METHODS

Design: Descriptive. Case series.

Sample size and selection - Eligibility criteria: Four pilots, all of them crewmembers of the newest EF-2000 Typhoon, fit to flight, non-smokers. All of them underwent a complete physical and anthropologycal examination, EKG and blood tests (including thyroid hormones) that were performed before trial, with normal results in all cases. And all of them using standard EF winter aircrew personal garment and life support equipment during the trials: Winter SEA AEA (Aircrew Equipment Assembly) or Winter Land Coverall, UK T-shirt, Longie (Thermal Protection Garmet), double socks (thin silk below thick wool), EF boots, Full Cover Anti-G Trousers, Flight Jacket, helmet, thin polyester cap below helmet, EF gloves (grey leather UK), with silk thin gloves below.

Settings and location: After some research, Vidsel Air Base (North Sweden) was chosen for being the airfield where all the necessary ‘inclement’ conditions, such as consistent low temperatures and varying rates of humidity, could most probably be met. This Swedish Air Base is part of the “Missile Test Range North” and is also used to carry out specific trials with new Unmanned Air Vehicles. Ironically, the temperatures at Sweden's Vidsel Air Base, which are normally guaranteed to provide deep-freezer climate, were initially too "mild" for the conditions required in the “Cold Environmental Trials”. The Eurofighter team therefore used these circumstances to carry out some unscheduled trials, such as taxiing on entirely icy and snow-packed runways, extending the campaign.

This winter campaign took place during a 3 month period (9/december/2004 to 9/march/2005) in the best weather conditions to carry on the study including very low temperature and the absence of high humidity or wind.

Outcome measures:

First, anthropometric characteristics of every pilot involved in the trial were measured. Including body weight, body height and body mass index (computed as weight divided by height squared). Skinfold thicknesses (triceps, supra-iliac) were measured in triplicate at the left side of the body using a skinfold caliper, and mean values were used for the calculation of body fat percent (BF%) and body density, using the prediction equations from the literature from skinfolds: Equation for body density (Sloan[1]):

- Body density (BD) = 1.0764 – (0,00081 x S1) – (0,00088 x S2)
- S1 = Suprailiac skinfold (mm)
- S2 = Tricipital skinfold (mm)

And Brozek´s equation to determine body fat percent and body fat mass[2] (BFM):

- BF% = (4,57 / BD – 4,142) x 100
- BFM = Weight x BF%

Waist circumference and hips size were also measured and waist-to-hip ratio (WHR) calculated. Waist-to-hip ratio (WHR) is a simple but useful measure of fat distribution obtained by measuring the circumferences of the waist at its narrowest point and the hips at their widest and simply dividing the values, and interpreted according to standards[3]. Finally, body surface area (BSA) was also calculated using Mosteller Equation:

- BSA = [√ Height (cm) * Weight (Kg)] / 60

Once in Sweden, a room in the hangar was provided for all the medical material neccesary for pre and post trial determinations (a pulsioximetry to determine heart rate and oxygen saturation, a glucometer to determine capillary glucose, a thermometer to determine skin temperature, a sphygmomanometer and a phonendoscope to measure blood pressure) and the devices needed for monitoring of pilots (rectal temperature probes and electrodes, wires and transmitters for cardiac monitoring).

We also had at our disposal a computer and two screens for real time monitoring of vital parameters, all located in the ground station were all operations were followed.

We defined 3 possibilities of pilots´ monitoring:

- Core temperature by using a rectal temperature probe: Ground trials not requiring movement of the aircraft, compulsory if outside temperature was ≤ -25ºC. We established a drop in core temperature below 35ºC (mild hypothermia) as the critical point to quit the trial.
- Cardiac monitoring: Pulse and ECG: Always in trials not requiring movement of the aircraft. And in trials requiring movement (taxi, flight) only until movement begins (to avoid electromagnetic interference with aircraft).
- Surface temperature: Ground trials not requiring movement of the aircraft, and if it is authorized by Test Director: 9 sensors located in: external surfaces of helmet, jacket (R/L), arms (R/L), legs (R/L) and boots (R/L).

Methodology:

In preparation for each step of the test campaign, the aircraft was parked overnight in the open, exposed to wind and weather. This ensured that the cold was able to penetrate into every nook and cranny of the airframe and the systems installed, giving them what is called a “cold soak” (a period of 9 hours of environmental exposure of the aircraft in order to ensure a minimal airframe temperature of -28ºC, if possible). With the fighter aircraft "deep frozen" in this way, the campaign consists of both ground and flight tests to verify the correct performance of all aircraft systems at extreme low temperatures.

Therefore, all tests include a previous exposition (“soak”) of the aircraft to the external temperatures. The trials will include, among others:

- Alert Mode operations (Stand-by, Auxiliary Power Unit): observation of a two-hour cockpit readiness in stand-alone operation, during which the power supply for the aircraft systems only comes from the on-board APU.
- Power-up.
- Electrical System evaluation.
- Hydraulic fluid behaviour.

- Liquid Conditioning Vest and Environmental Control System operations.
- Fuel System operations.
- Landing Gear actuations.
- Loading and unloading of external stores.

After the briefing and once everything was ready and all the necessary monitoring working correctly, the pilots will head up the aircraft. Time before reaching the cockpit was reduced to less than 5 minutes, in order to minimize the exposure to outside temperature.

Nevertheless a small hut was installed a few meters away from the aircraft, next to the hangar. It was used mainly by ground crew (working on rotating shifts with an approximate duration of 30 minutes, depending on weather conditions), and also by the pilots, in the event of not being able to heat the cockpit for a long time, time to be established depending on clinical considerations.

During the trial constant communication with the pilot was available through the test director, but it was not possible to see the pilot unless he was out of the aircraft (there is a camera installed in the cockpit, but focusing outside).

4.0 RESULTS

Temperatures at Vidsel that winter were not the expected. It was the warmest winter in decades, which meant that campaign had to be extended in order to achieve the desired temperatures. Nevertheless, during the whole campaign, more than 45 operations where carried out, 17 of them flights, temperatures reaching -33ºC in some cases.

Total number of trials requiring physiological monitoring of the pilot were 8, with subjects exposed to outside temperatures between –7,5ºC and –29,7ºC, and different exposure times. Analysis of data for these trials was done, to determine physiological responses and fitness to carry on with the trial at every moment.

Table I shows anthropometric characteristics of every pilot involved in the trial, including body mass index, body density, body fat, skinfold thicknesses (triceps, supra-iliac); all resulting between normal limits for their age and gender. Pilot no 3 has a lower percent of body fat as a result of being a keen sportsman.

Tables II, III, IV and V show trials carried on by each pilot: number 1, 2, 3 and 4 respectively. In every case pre and post trial determinations were also within normal limits, as well as core temperature (when available) and cardiac monitoring.

These are the most significant findings of each trial:

Trial number 1 was considered as a confidence trial, to check the equipments and to make sure everything was working right: transmitters, distance to antennas and location, quality of reception in the ground station, etc.

Trial number 2 showed some technical difficulties monitoring core temperature that were solved the same day, in order to guarantee future reception, even in the worst conditions. Rest of parameters were within normal limits. Pilot stayed inside the cockpit for 30 minutes with a temperature -8ºC until APU started. In a comfort scale he scored this situation as 6 over 10.

Trial number 3 consisted of an “alert mode” which involves staying inside the cockpit for 2 hours (APU working) until starting of the engines. In both this trial and in the previous one, APU started working in a reasonable period of time (shorter in the second trial), which means heating in the cockpit available as soon as it starts. In this trial exposure to very cold environment was limited, regardless, pilot referred cold hands. Surface temperature sensors recorded coldest figures in upper parts of the body (helmet and arms). There were no drops in core temperature.

Trial number 4 involved running APU and engines. APU started in a few minutes, and there were no problems at all. Everything stayed within normal parameters, with a drop in core temperature of 1,2ºC along the trial: 1ºC in the first 5 minutes, once the pilot was sitting in the cockpit, but staying nearly constant for the following 30 minutes.

Trial number 5 consisted of an “alert mode”. Pilot refused to be instrumented (core temperature). During this trial highest cockpit temperature was reached (29ºC), 80 minutes after APU start.

In trial number 6 we only had available cardiac monitoring, because we expected taxiing to be performed. But it was cancelled due to technical problems.

According to schedule, trial number 7 was expected to be a flight. This was one of the coldest days during the campaign and APU could not be started easily. This meant that pilot stayed inside the cockpit with temperatures from –16,6º to –12,6º for more than half an hour. He was asked in several occasions about comfort in the cockpit, but he always answered in a positive way, saying he was feeling good (except for very cold hands) and asserting his intention of trying to start up the APU once and again. But, after the sixth attempt, test director, pilot and medical services all agree on that pilot had to leave the cockpit and take shelter from the cold in the hut and warm up for at least half an hour; before trying the APU start again. In the second round, after 27 minutes, trial had to be aborted due to technical problems.

Trial number 8 was planned to be same as previous. In order to avoid a situation as the one lived the day before, and taking into consideration the lack of real time information about pilot´s temperature, all personnel involved in the trial (pilots, doctors and test director) achieved a formula acceptable to all and decided to suggest stopping trial if pilot had to stay in the cockpit without heating for more than 20 minutes. In this case, trial was interrupted almost 25 minutes after pilot sat in the cockpit, not being able to get any heating. After a 30 minutes break in the hut, trial restarted, managing to start the APU in 11 minutes. 14 minutes after the start, cockpit temperature is 10ºC and 5 minutes later, 14ºC.

5.0 DISCUSSION

We tried to establish human tolerance limits according to clinical symptoms, cardiac and temperature monitoring. We have accounted several physiological factors related such as nutritional and general status of each individual, previous load of flight operations (one week), time spent outside the cockpit before the test, time inside the cockpit before APU start and time to get a comfortable temperature at the cockpit.

It is always important to ensure that pilots have eaten accordingly before the flight, and very specially in such environmental conditions. In this way, the determination of capillary glucose was useful, as a tool to show the importance of this subject.

Two of the pilots were thinner and had less body fat mass (pilots 3 and 4) than the others. None of them had problems, not even a big drop in core temperature as a result of cold exposure. Pilot no 4 had the biggest fall in temperature we could register but within normal limits. However we can deduce only from one trial (with temperature monitoring) in each case, and with different outside temperatures, which is clearly not enough to draw any conclusion.

Eventhough none of them reached core temperatures below 37ºC, most of them complained of cold hands and feet. When heating is inadequate, tolerance is usually limited by pain in hands and feet. Feeling cold hands is an important drawback to operations because pilots lose dexterity long before pain developes and manual dexterity is crucial. For this reasons we consider that maximum possible foot and hand insulation should be warn, allowing the neccesary manipulation of controls. In our case, gloves were not enough protective.

We found that, at the very beginning of the trials, cockpit temperature was not as low as outside temperature, but there are big differences among trials (from 11,3ºC to 2ºC between cockpit and outside). It is important to know cockpit temperature before establishing a safe time frame in which pilot should leave the aircraft.

One of the most important difficulties we found during these environmental trials was that we were not able to use the monitoring we arranged when planning the campaign. It should have allowed as to have real time information of heart rate and core temperature even during the flights. Not having this information when trials involved movement of the aircraft was a big disadvantage when it came to guarantee pilot´s safety. In those cases, cardiac monitoring, constant communication with the pilot (to check alert mental state) and the information about cockpit temperature were extraordinary helpful. In every case crew status must be reassessed every 20 minutes, at least.

Anyway, every test was different, they were performed in diverse conditions, and the number of trials is so small, that it is difficult if not impossible to provide strict directions. Nevertheless there are some matters we consider of great importance:

- It is essential to ensure a good nutritional and hydration status of the crewmembers.
- It is also basic a preflight establishment of a maximum time at the cockpit without heating on (20 minutes in our case, learned from trials 7 and 8). This should be based on outside and cockpit temperature, wind speed (windchill scales), humidity, previous workload or cold exposure and the degree of the "cold soak" (if any).
- It is vital to ensure a warm shelter near the aircraft.
- It maybe important to add some suplementary measures depending on the test performed.

We had some minor diseases (respiratory infections mainly) and close contact between all personnel (living in the same hotel, sharing cars, and working together in small facilities) helped to spread the disease in some cases. Not always was possible to ventilate rooms, some places we had to rely just on the air conditioning system. We also had to deal with some minor injuries (slipping due to ice or oil in the hangars) and sports injuries (skiing).

And another disturbing setback, was an "enviromental drawback": low humidity in the area added to the constant use of heating and air conditioning systems made the air so dry that it resulted in skin problems, dryness of all mucoses and the worsening of minor respiratory diseases.

6.0 CONCLUSION: LESSONS LEARNED

After three-months winter deployment near the Artic Polar Circle, we reached to this conclusions, summarize as lessons to be learned for future environmental trials:

Before deployment:

- Medical examination: essential for all personnel involved in the trial.
- Plan with as much detail as possible the monitoring and ensure to get all devices on time (before departure) in order to check them all and in order to know exactly what can you count on with.

- Medical intelligence (vaccines if neccesary, outbreaks, common diseases, hospitals, emergencies services, etc). Take with you a medical record of everyone involved in the campaign (at least essential information such as diseases, medication, glasses prescription, etc).
- Breafing pre-deployment: Essential for all personnel involved. It should include, at least, the following topics:
  - Explanation of the purpose of the trials and deployment (accomodation, food, communications available, medical assistance). Work shifts.
  - Climate: local weather (average and worst conditions), windchill concept.
  - Extreme cold human physiology. Cold effects. Countermeasures.
  - Clothing: Winter protective garnment: description, design, proper wear and maintenance, etc. With as much detail as possible, describing advantages and disadvantages of the different textiles (synthetic and natural).
  - Safety recommendations when working outside.
  - Hygiene, nutrition, hydration (fluid intake but also the use of artificial tears and moisturizing of skin and mucoses).
  - Health. Minor diseases. Most common problems expected.
  - Sports. Cold protection. Injuries.
  - Other practical aspects such as driving on ice, car maintenance and daily inspections, batteries function in cold conditions, etc.

During deployment:

- Monitoring problems (logistic problems, spare batteries, technical problems, refusing,) force to establish clinical margins to go/no go with a specific trial.
- Nutrition: make sure all the team hot foods, beverages.
- Watch working shifts and rest periods (specially ground crew, because they will be more time exposed to cold temperatures, although probably best protected than the rest).
- Ensure a warm shelter near outside operations area.
- Cold exposure: check duration, get frequent feedback from air and ground crew members.
- Diseases: Continue warning about the risk of close contact or overcrowding related to infection dissemination and remember how to counteract air dryness.
- Leisure time: sports, winter sports, tourism, safe driving.

During trial:

- Ensure the pilot is wearing all protective garment and that it is in good condition.
- Check the monitoring (batteries included) is in good working order.
- Minimize the exposure to outside temperature before reaching the cockpit.
- Guarantee a warm shelter near the aircraft.
- Before starting the trial, establish pilot a safe time frame to leave the cockpit to warm up in case no heating is available.
- Manual dexterity and alert mental state are of great importance. Hands should have layered protection, permitting the manipulation of controls. Foot insulation is also essential.

- And always watch carefully groundcrew during operations: body insulation, work shifts, etc; as they are always more exposed to cold temperatures than any other during the trial.

Table I: Pilots´ Anthropometric Characteristics

	PILOT 1	PILOT 2	PILOT 3	PILOT 4
Age (years)	54	47	39	38
Body height (cm)	178	177	182	175
Body weight (Kg)	76	83	75	70
Body Surface (m^2)	1,93	2,02	1,95	1,84
Body Mass Index (Kg / m^2)	24	26,4	22,6	23
Tricipital skinfold (mm)	13	14	12	11
Supra-iliac skinfold (mm)	25	26,5	21	21
Waist circumference	88	89	83	81
Hips size	90	90	85	85
Waist-to-hip Ratio	0,98	0,99	0,97	0,95
Body fat %	14,28	14,03	12,92	13,27
Body density (g / cc)	1,06655	1,067174	1,06995	1,06907
Body fat mass (Kg)	10,85	14,03	9,69	13,27

Table II: Trials Performed by Pilot Number 1

PILOT 1	TRIAL NO 7	TRIAL NO 8
Description	Flight (soak -25ºC)	Flight (soak -30ºC)
Monitoring	EKG	EKG
Outside Temperature (initial/final)	-25,3ºC to -17ºC	-29,7ºC to -12,3ºC
Total duration (minutes) [time until APU start]	105 [42 + 27]	255 [25 + 11]
Vital Signs (pre / post trial)		
Axillary temperature (ºC)	36 / 36,2	35,6 / 36,4
Capillary glucose (mg/dl)	94 / 126	105 / 104
O_2 Saturation (%)	98 / 99	98 / 98
Heart Rate (bpm)	88 / 71	81 / 72
Blood pressure (mmHg)	110/70 - 110/70	110/75 - 115/70
Vital Signs during trial		
Heart Rate (bpm) Mean (min-max)	88 (70-120)	87 (63-128)
Core Temperature (initial/final)	No registration	No registration
Cockpit temperature (initial/final)	–16,6º to –12,6º (leaves cockpit for 30 min); -12,6ºC to –5,02ºC	–22,6º to –18,5º (leaves cockpit for 30 min); –18,6º to 21ºC

Table III: Trials Performed by Pilot Number 2

PILOT 2	TRIAL NO 1	TRIAL NO 9
Description	Confidence	Alert Mode (soak -30ºC)
Monitoring	EKG	Temperature and EKG
Outside Temperature (initial/final)	1,5ºC to 1,6ºC	-14,4ºC to -9,6ºC
Total duration (minutes) [time until APU start]	45 [15]	180[30]
Vital Signs (pre / post trial)		
Axillary temperature (ºC)	35,9 / 35,6	36 / 35,8
Capillary glucose (mg/dl)	85 / 98	100 / 91
O_2 Saturation (%)	99 / 98	98 / 98
Heart Rate (bpm)	70 / 62	64 / 58
Blood pressure (mmHg)	110/80 – 120/75	120/80 - 120/80
Vital Signs during trial		
Heart Rate (bpm) Mean (min-max)	77(69-103)	65 (57-86)
Core Temperature (initial/final)	No registration	37,7º to 37,3º (min 37,1ºC)
Cockpit temperature (initial/final)	4ºC to 12ºC	–10,9º to 23ºC

Table IV: Trials Performed by Pilot Number 3

PILOT 3	TRIAL NO 2	TRIAL NO 3	TRIAL NO 5	TRIAL NO 6
Description	Starting engines (soak -17ºC)	Alert Mode (soak -20,5ºC)	Alert Mode (soak -21ºC)	Taxi (soak -21ºC) Aborted
Monitoring	Temperature and EKG	Temperature and EKG	Temperature and EKG	EKG
Outside Temperature (initial/final)	-12ºC to -10,5ºC	-18,7ºC to -18,1ºC	-17ºC to -12,9ºC	-7,5ºC to -6,9ºC
Total duration (minutes) [time until APU start]	100 [30]	70 [10]	140 [45]	60 [60]
Vital Signs (pre / post trial)				
Axillary temperature (ºC)	36,5 / 36,4	35,9 / 35,6	36,2 / 35,5	36 / 35,6
Capillary glucose (mg/dl)	100 / 94	108 / 101	148 / 100	100 / 98
O_2 Saturation (%)	99 / 99	98 / 99	100 / 99	100 / 99
Heart Rate (bpm)	67 / 52	57 / 54	52 / 43	48 / 47
Blood pressure (mmHg)	130/80 - 120/80	110/80 - 115/85	130/80 – 120/80	105/75 – 100/75
Vital Signs during trial				
Heart Rate (bpm) Mean (min-max)	62 (45-103)	66 (52-103)	56 (51-147)	57 (46-84)
Core Temperature (initial/final)	Technical failure	37,4ºC to 38,1ºC	Pilot refuses temperature monitoring	No registration
Cockpit temperature (initial/final)	–10ºC to 18ºC	–15,3ºC to 17,2ºC	-11ºC to 29ºC	-6,4ºC to -4,8ºC

Table V: Trials Performed by Pilot Number 4

PILOT 4	**TRIAL NO 4**
Description	Starting engines (soak -22ºC)
Monitoring	Temperature and EKG
Outside Temperature (initial/final)	-20ºC to -12,6ºC
Total duration (minutes) **[time until APU start]**	60 [15]
Vital Signs (pre / post trial)	
Axillary temperature (ºC)	36,5 / 36
Capillary glucose (mg/dl)	138 /141
O_2 Saturation (%)	98 / 96
Heart Rate (bpm)	80 / 65
Blood pressure (mmHg)	95/75 – 90/60
Vital Signs during trial	
Heart Rate (bpm) Mean (min-max)	94 (78-115)
Core Temperature (initial/final)	39,1ºC to 37,9ºC
Cockpit temperature (initial/final)	-8,7ºC to 20ºC

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