Isidoro Martínez

HUMAN THERMAL COMFORT

HUMAN THERMAL COMFORT

Human thermal comfort is a combination of a subjective sensation (how we feel) and several objective interaction with the environment (heat and mass transfer rates) regulated by the brain. Comfort depends on several physical magnitudes that we may group as:

- Person-related. Deep body temperature in humans is always close to 37 ºC independent of environmental temperature, as first measured in the 1660s by Boyle. It may depart a few degrees under unhealthy circumstances, particularly above that value, as with fever, or during heavy prolonged physical exercise. We must continuously evacuate heat through our skin to the ambient to compensate our metabolic dissipation, with a baseline rate of about 1 W/kg, increasing with physical activity up to 5 W/kg; e.g. it is around 100 W for an adult in office-work. Skin temperature is usually below 33 ºC, allowing the heat outflow, but it depends a lot on external conditions, clothing, and actual and previous activity levels. Besides, age and risk groups (babies, elders, ill persons), previous accommodation (e.g. changing from indoors to outdoors), habits (e.g. clothing difference among seasons and sex), personal preferences (some people feel comfortable cold or hot), and actual mood (the state of mind, feeling happy or nervous) may have an influence (comfort is not just a physiological problem but psychological too).
- Environment-related. Air temperature (or water temperature if diving), background radiant temperature (of walls, sky, and Sun, if any), air relative humidity, and wind speed. And not only average values matter, but their gradients and transients too. Non-thermal environmental variables like ambient light and noise may affect the thermal sensation too. The most difficult to measure of the parameters governing thermal comfort is the background radiant temperature, which depends on direct solar irradiance, wall solar reflectance (albedo), sky temperature, wall temperature, and all the geometric view factors involved.

There has been a tendency to combine all environmental variables in an effective or apparent temperature, and all personal response in a few degrees of comfort (or discomfort); the 7-scale thermal feeling is:

- Uncomfortable cold, when >95% of people in a significant group complain of being cold.
- Cool, or bearable cold, when some 75% of people in a significant group complain of being cold.

- Slightly cool, when only some 25% of people in a significant group complain of being cold.
- Comfortable, when <5% of people in a significant group complain of being cool or warm.
- Slightly warm, when only some 25% of people in a significant group of being hot.
- Warm, or bearable hot, when some 75% of people in a significant group complain of being hot.
- Uncomfortable hot, when >95% of people in a significant group complain of being hot.

The goal of a thermal comfort analysis may be set as finding an appropriate function of the physical parameters (background radiant temperature, air temperature, air humidity, wind speed, clothing, metabolic rate, and core temperature), which would yield the corresponding comfort/discomfort level in the seven degrees of comfort shown above. The international standard ISO 7730-2005 provides a method to evaluate this comfort function, known as predicted mean vote (PMV), and quantified as PMV=−3 for too cold, −2 for cold, −1 for mildly cold, 0 for comfortable, 1 for mildly warm, 2 for warm, and 3 for too warm. From this coarse prediction, a finer function known as predicted percentage of dissatisfied people (PPD) is defined as $\mathrm{PDD}=100-95\cdot\exp(-0.03353\cdot\mathrm{PMV}^4-0.2179\cdot\mathrm{PMV}^2)$, with PMV in the numeric scale above-mentioned, and PDD in % (e.g. if the environmental conditions yield a mean vote of PMV=0, statistically may be a PDD=5% of thermally dissatisfied persons). Mind that large spatial gradients in the variables, transient conditions (e.g. it takes a while to start sweating), crowds... may have an impact on thermal sensation, and that standard predictions apply to 'standard people'.

Thermal comfort for a person at rest or under light activity (e.g. office work) is best at air temperature of T=22±2 ºC, relative humidity of ϕ=50±20%, air speed <0.2 m/s, and mild radiation exchange, but depends on clothing habits (we prefer 2 or 3 degrees higher in summer than in winter), being indoors or outdoors, etc. Hot thermal discomfort is usually associated to global thermal stress, although local burns from high solar irradiances, irradiating stoves, or direct contact with hot objects, may be important. On the contrary, cold thermal discomfort is usually associated to local thermal stress at human extremities (toes, fingers) or exposed surfaces (ears, nose). Toes and fingers feel neutrally comfortable from 34 ºC down to 27 ºC, feel discomfort bellow 20 ºC, hurt below 15 ºC, and get injured if below 5 ºC (after a few hours).

Thermal discomfort decreases productivity and may be unhealthy, but climatization is costly, and may become very expensive and unhealthy when overdone (forcing people to wear winter cloths in summer, or being shirt-sleeves in winter). People should be knowledgeable enough about typical weather as to wear appropriate clothing, and carry with them additional garments for the early-morning to afternoon temperature oscillations that may be up to 20 ºC in places like Madrid.

Body thermal control is mainly based on peripheral blood-flow control by vasoconstriction or vasodilatation, which modifies skin temperature and perspiration, and thus regulates heat transfer flows. A full thermal model should include all heat sources and heat paths inside the human body, the thermoregulatory system that governs the skin temperature (including perspiration and shivering), and all the heat and mass transfer mechanisms from the surface to the environment. Thermal neural sensors are widespread in the skin (0.15..0.20 mm under the surface), but with wide differences in concentration, sensitivity, and response time. In general touching a surface at <15 ºC or >45 ºC produces pain.

The simplest thermal model of the human body includes three nodes: the body core (assumed to be at 37 ºC, or up to 39 ºC during heavy physical exercise), the body envelop (skin and clothing), and the environment; the body cooling (some 100 W for a standing adult) is provided by suitable interface regulations (skin temperature, clothing) depending on environmental conditions. The predominant heat path is through blood perfusion from core to skin, and through convection from skin to the environment.

There are short-time and long-time processes in acclimatization (i.e. the response of the thermoregulatory system in the human body to changes in environmental thermal conditions). It may take one week to accommodate. That is why after a sudden drop in day-mean temperature, say from 15 ºC to 10 ºC, we may feel colder that after a long period at say 5 ºC.

Apparent environmental temperature

Apparent temperature is a general term for the perceived outdoor temperature, caused by the combined effects of air temperature, radiative temperature, relative humidity and wind speed. Several definitions have been proposed:

- The wind chill index, WCI, measures the effect of wind speed on the perception of temperature. In windy conditions, if the air is cool (T_a<25 ºC) it feels cooler than it actually is (because of increased perspiration), but if the air is hot, the hot wind feels even hotter. A simple proposal may be $T_{\mathrm{WCI}} = T_{\mathrm{a}} - \sqrt{v}\left(25 - T_{\mathrm{a}}\right)/15$, with T_{WCI} and T_a in [ºC] and v in [m/s], up to v=10 m/s (e.g. for T_a=0 ºC and v=5 m/s (18 km/h) the apparent temperature is T_{WCI}=–3.7 ºC).
- The heat index measures the effect of humidity on the perception of temperature. In humid conditions, the air feels hotter than it actually is, because of the reduction of perspiration. A simple proposal may be $T_{\mathrm{HI}} = T_{\mathrm{a}} + \left(\mathrm{RH} - 50\right)\left(T_{\mathrm{a}} - 10\right)/100$, with relative humidity RH in [%], and T_{HI} and T_a in [ºC] (e.g. for T_a=30 ºC and RH=80% the apparent temperature is T_{HI}=36 ºC).
- The combined effect of radiation, humidity, temperature, and wind speed on the perception of temperature may be approximated by $T_{\mathrm{app}} = T_{\mathrm{a}} + \dot{q}_{rad}/50 + \left(\mathrm{RH} - 50\right)\left(T_{\mathrm{a}} - 10\right)/100_{\mathrm{a}} - \sqrt{v}\left(25 - T_{\mathrm{a}}\right)/15$, with the apparent and air temperatures, T_{app} and T_a, in [ºC] , the net radiation heat received per unit area, $\dot{q}_{rad}$, in [W/m^2], RH in [%], and wind speed, v, in [m/s]; e.g. for a solar irradiance of 500 W/m^2, an air temperature T_a=15 ºC, RH=30%, and wind speed v=2 m/s (7.2 km/h), the apparent temperature is T_{app}=15+10–1–1=23 ºC.
- The wet-bulb globe temperature, T_{WBGT}, is another combination to take all environmental factors into account. In its simplest form, $T_{\mathrm{WBGT}}=0.7\cdot T_{\mathrm{wet,nat}}+0.3\cdot T_{\mathrm{globe}}$, where $T_{\mathrm{wet,nat}}$ is the output of a wet-bulb thermometer but left to natural convection (not blown with ambient air at >2 m/s as in hygrometry), and T_{globe} is the output of a thermometer in the centre of a black-painted 150 mm in diameter thin sphere. This is often applied to set limits of comfort in hot environments (e.g. T_{WBGT}<33 ºC for office work, T_{WBGT}<29 ºC for mild factory work, or for level walking at 4 km/h).

Body core temperature

Body temperature in humans is closely regulated to keep it nearly independent of environmental temperature, and it has been used for health diagnosis since ancient times (this was one of the first applications of physical thermometry, in 17th century). It was soon discovered that the deeper inside the body, the lesser disturbances from the environment, so that the most reliable body core measurements are taken with more or less invasive means (hypodermic needle, inside the oesophagus, inside the rectus, below the tongue, under the axilla, or at the tympanum), although non-invasive measurements are taking aver, with infrared detection at the tympanum, the temporal artery, at the front, and so on. Body core temperature is around 37 ºC, but during long-distance running competitions (say >10 km), and shortly afterwards, people may reach core-temperature may rise up to 38.5 ºC or even 39.5 ºC

ENERGY BALANCE

Several models have been proposed to analyse heat transfer from human body to the environment, from simple global steady balances, to detailed unsteady 3-D finite-element simulations. The simplest model just considers the whole human body as an open system (i.e. including respiratory and perspiration mass flows), with an energy balance:

$$mc\frac{\mathrm{d}T}{\mathrm{d}t}=\dot{M}-\dot{W}-\dot{Q}_{\text{conv+rad+cond}}-\sum\dot{m}\Delta h \qquad (1)$$

where $mc\mathrm{d}T/\mathrm{d}t$ is the transient accumulation of energy within the core and the skin masses (only possible for short times, usually neglected), $\dot{M}$ is the metabolic heat rate (can be calculated from the oxygen consumption and carbon dioxide production), $\dot{W}$ the work being done (can be measured when exercising in an ergometer, and can be neglected in most circumstances, since muscular mechanical efficiency is low; a maximum for an athlete may be $\eta\equiv\dot{W}/\dot{M}=0.25$), $\dot{Q}_{\text{conv+rad+cond}}$ is the heat loss to the surrounding by air convection, radiation to cool walls or the sky (solar heating contributes positively, if any), and conduction to solid supports (foot contact, seat contact), and $\sum\dot{m}\Delta h$ is the enthalpy loss associated to the warmer and wetter exhalation and perspiration mass flows (expired air can be assumed saturated at the exit temperature, which is 37 ºC minus 0.2 ºC per ºC of ambient-air-drop; e.g. for ambient air at 10 ºC, exhalation is at 37–0.2·(37-10)=31.6 ºC). It is customary to substitute the enthalpy flows by equivalent heat flows through mouth and skin, and split them into corresponding latent-heat and sensible-heat contributions. Equation (1) is commonly found in the literature as $S=M-W-C-R-K-E_{skin}-C_{resp}-E_{resp}$, where S stands for storage, M for metabolism, W for work, C for thermal convection, R for thermal radiation, K for thermal conduction to solids (floor, chair, table...), E_{skin} for evaporation at the skin, C_{resp} for convective loss in respiration, and E_{resp} for evaporative loss in respiration. The energy balance can be used in cold cases to find the clothing insulation required (mainly affecting C) to keep steady body temperature (S=0), or in hot cases to find the expected sweating, and the duration limit exposure under more stressing thermal conditions.

Radiation heat transfer is particularly dominant outdoors, especially when exposed to solar radiation in summer. Notice that sunlit may add additional discomfort (besides thermal), as visual dazzling, or skin eczema. Black skin has a solar absorptance of α_{sun}=0,85 and white skin α_{sun}=0.60 (with ε=0.98 emissivity in both cases), what is bad for cooling, but melanin protects from UV sun-burn, what is more important when overexposed to sun rays.

In the 2-nodes model (core 'c', and skin 's'), the energy balance for each part may be written as:

$$m_\mathrm{c} c_\mathrm{c} \frac{\mathrm{d}T_\mathrm{c}}{\mathrm{d}t} = \dot{M}_c - \dot{W} - \dot{Q}_\mathrm{bp} - \dot{Q}_\mathrm{cond,c} \tag{2}$$

$$m_\mathrm{s} c_\mathrm{s} \frac{\mathrm{d}T_\mathrm{s}}{\mathrm{d}t} = \dot{M}_\mathrm{s} + \dot{Q}_\mathrm{bp} + \dot{Q}_\mathrm{cond,c} - \dot{Q}_\mathrm{conv} - \dot{Q}_\mathrm{rad} - \dot{Q}_\mathrm{cond} - \dot{P} + \Phi_\mathrm{Sun} \tag{3}$$

where (2) represents the balance between net metabolic heat release in the care ($\dot{M}_c - \dot{W}$), and its transport towards the skin by blood perfusion, $\dot{Q}_\mathrm{bp}$, and conduction, $\dot{Q}_\mathrm{cond,c}$ (if $m_C c_C \mathrm{d}T_C/\mathrm{d}t$ is neglected), and (3) represents the transport of energy from inside to the outside (if skin metabolism and transients are neglected). In (3), $\dot{Q}_\mathrm{conv}$ represents the sensible heat loss to the surrounding air (including sensible heat through breathing), $\dot{Q}_\mathrm{rad}$ the heat loss by radiation to cool walls or the sky (solar heating is accounted separately), $\dot{Q}_\mathrm{cond}$ the heat loss by solid contact, $\dot{P}$ is the evaporative cooling (sum of respiratory evaporation through breathing, and perspiration evaporation through the skin), and Φ_Sun is the solar heat input, if any. In steady condition at rest, metabolic heat is transferred from core to skin by blood perfusion and tissue conduction, $0 = \dot{M}_\mathrm{c} - \dot{Q}_\mathrm{bp} - \dot{Q}_\mathrm{cond,c}$, and evacuated from skin to environment mainly by convection and perspiration, $\dot{Q}_\mathrm{bp} + \dot{Q}_\mathrm{cond,c} + \dot{M}_\mathrm{s} = \dot{M}_\mathrm{c} + \dot{M}_\mathrm{s} = \dot{Q}_\mathrm{conv} + \dot{P}$. Clothing has a direct impact on both sensible heat convection (and radiation, if important), and on perspiration heat transport, quantified by clothing thermal resistance and vapour permeability, respectively.

The above two-node thermal model of the human body can be enhanced for more detailed analysis by using more layers instead of just a core and a skin (e.g. a deep core, a muscle layer or bone layer, a fat layer, and a skin layer. Table 1 gives some representative properties for the heat balance on a human head. A fat layer is a good thermal insulator, with a thermal conductivity k=0.19 W/(m·K) much lower than normal moisten tissues (k=0.5..0.6 W/(m·K)). Hair cover has also strong insulation effect.

Table 1. Typical properties for thermal balance in an adult human head.

Property	Brain	Skull	Skin
Thickness, δ [mm]	85	4	4
Density, ρ [kg/m^3]	1050	1500	1000
Thermal capacity, c [J/(kg·K)]	3700	2300	4000
Thermal conductivity, k [W/(m·K)]	0.50	1.16	0.34
Blood perfusion rate, $\dot{w}_b$ [s^{-1}]	$10\cdot10^{-3}$	0	$0.4\cdot10^{-3}$
Metabolic rate, ϕ_m [W/m^3]	10 500	370	370

Under light metabolic release, heat is evacuated mainly by convection to surrounding air, with perspiration increasing as ambient temperature increases, sharing half and half the heat transfer around T_air=26 ºC, with latent heat transport becoming preponderant for higher temperatures. Under high metabolic rates (heavy work) perspiration dominates (sweating). Thyroid hormones regulate the level of metabolic activity, which may change rather quickly (in a minute or so) in response to alterations in the level of physical activity.

Comfort skin temperature for a person at rest is around 33 ºC, so that when the metabolic rate or the environment tries to force higher or lower skin-temperature values, we defend by altering some of the thermal couplings:

- When we feel cold, we restrict blood flow through skin capillaries. We can put on additional clothing (particularly on neck, ears, hands, feet, nose...), procure some additional heat input (rub our hands, have a hot drink, make a fire, switch on a stove, have a hot shower…), or procure a warmer environment (space heating). If cold persists, we shiver. Severe cold cause hypothermia, starting with skin sore (at skin temperature below 15 ºC there is pain and loss of sensitivity), frostbites (e.g. at −20 ºC, bare skin starts freezing after about 3 h), and following death at rectal temperatures below 32 ºC. Wet clothes should be soon removed to avoid increased thermal conductance (but wet-suits are often used underwater in mildly-cold waters). There are, however, some medical applications of hypothermia.
- When we feel hot, we promote blood flow through skin capillaries, and skin perspiration. We can put off some clothing (particularly near the neck), procure some refreshment (have a cold drink, moisten our skin, switch on a fan, have a cool shower or bath…), or procure a cooler environment (air conditioning). Sweating is the basic mean to compensate the energy balance under hot conditions (e.g. a person walking at noon on a summer day with air temperature T_{air}=40 ºC and solar irradiance 1 kW/m^2, rejects some 250 W by sweating, to compensate a metabolic release of 100 W, a solar input of some 100 W (direct plus reflected plus diffuse), an infrared input of some 25 W from the hot soil, plus some 25 W coming by convection from air (40 ºC>37 ºC), balancing the 250 W. Maximum safe dehydration should not go beyond 5% of body mass (4 kg water loss for a 80 kg person). It is important to keep in mind that if solar input contributes to hot discomfort (either by direct body exposure or by input heating through windows), the first most important remedy is shading. Severe hot may cause hyperthermia: heat stress, heat syncope (fainting), heat exhaustion (panting and fast weak pulse), and heat stroke (loss of thermal regulation, rectal temperature reaches 41 ºC, and death usually follows).

The energy balance equations (1) and (2) are often set per unit surface area. Human body surface area in adults may be assumed to be around A=1.8 m^2. Sometimes metabolic rates per unit area are stated in 'met' units (1 met=58.2 W).

To quantify the effect of clothing on thermal comfort, the unit of thermal resistance 'clo' (1 clo=0.155 m^2·K/W) is often used (one clo is the amount of thermal resistance necessary to maintain thermal comfort for a sitting-resting subject in a room at 21 ºC, 50% RH, and 0.1 m/s air speed; a naked body has 0 clo, and artic clothing may approach 4 clo).

Metabolic rate

Metabolism (Gr. μεταβολη, change) is the set of physic-chemical process taking place all the time at cellular level, resulting in cell growth, production of thermal and mechanical energy, replication, and elimination of waste material. Metabolism can be separated in two stages: anabolism (chemical synthesis, active pumping through membranes, and cell motion, all helped by energy storage in phosphate bonds in the energy carrier ATP), and catabolism (chemical break down to release energy, common to autotrophic and heterotrophic organisms).

Basal metabolism is required to maintain blood circulation, respiration, and nerve transmissions in an organism. Not every cell in an organism show similar metabolic rates; the brain in a human adult at rest, with only 2% of the whole body mass, contributes some 20% to the metabolic dissipation (the major part to keep neuron connections, and a minor part to create new connections).

According to age and activity, overall metabolic energy release-rate in humans ranges from 0.5 W/kg in elders to 2 W/kg in children, with a typical 1 W/kg in adults. For instance, for a 70 kg person, basal metabolic rate (sleeping) is around 70 W, while being standing it is around 100 W, walking or writing some 150 W, doing light work 200 W, heavier work or walking at 4 km/h 300 W, and under maximum sustained work some 500 W (from which nearly 100 W output as work and the rest as heat, losing about 0.5 kg/h of water; i.e. 10 to 15 times more than at office work).

Actual metabolic rates can be measured by gas analysis in respiration, either by oxygen consumption or by CO_2 generation (and breath rate), or estimated by heart rate.

Blood perfusion

The heat balance within the human body is a complicated process involving heat diffusion (proportional to tissue diffusivity, k), metabolic heat generation, ϕ_m, heat convection by free fluid flow (blood, urine... usually unsteady or pulsating), perfusion in soft tissue from arteries to capillaries and veins, and interaction with the environment. Heat transfer with biological tissue is mainly by blood perfusion (i.e. the flow of blood by permeation through tissues: skin, muscle, fat, bone, and organs, from arteries to capillaries and veins); the cardiovascular system is the key system by which heat is distributed throughout the body, from body core to limbs and head. The characteristic length of perfusion is 0.1 mm.

Let $\dot{w}_b$ be the volumetric flow rate per volume of tissue (blood perfusion rate, a scalar magnitude typically in the range $20\cdot10^{-3}$ s^{-1} at 30 ºC, to $100\cdot10^{-3}$ s^{-1}, at 37 ºC; it is temperature-dependent); the energy balance per unit volume can be set as:

$$\rho c\frac{\partial T}{\partial t}=k\nabla^2 T+\phi_m+\dot{w}_b\rho_b c_b\left(T_b-T\right)+\phi$$

kown as the bioheat equation, where c_b and ρ_b are blood thermal capacity and density, T_b is arterial blood temperature, and ϕ is any externally-applied heat source or sink per unit volume, if any, e.g. for radiotherapy. The perfusion term was first formulated by Harry H. Penne in 1948, when he proposed that the rate of heat transfer between blood and tissue is proportional to the product of a volumetric perfusion rate and the difference between the arterial blood temperature and the local tissue temperature, based on measurements from radial temperature distribution in the forearm of lying persons (he introduced fine thermocouples through the arms). To measure tissue perfusion in vivo, magnetic resonance imaging (MRI) techniques are used.

Heat transfer in biological systems is relevant in many diagnostic and therapeutic applications that involve changes in temperature. For example, some skin cancers are treated with hyperthermia with short-duration high-intensity heating; the tissue temperature is elevated to 42..43 °C using microwave, ultrasound, or laser light.

It has also been shown that an elevated skin temperature (45 ºC, maintained for a long while in a skin patch) caused an outward diffusive flux of oxygen by perfusion of oxygen from the swallowed outermost blood capillaries in the dermis, so that oxygen content could be measured at the surface of the skin.

Metabolism and cell temperature

Life processes are temperature-dependent chemical reactions, taking place in the cells constituting the organism, and resulting in heat and work production, cell growth and replication, and material waste. Heat is mainly released at mitochondria, where sugars and oxygen brought by blood combine to yield energy and waste.

Body temperature in homoeothermic animals (mammals and birds), is closely controlled to keep it nearly independent of environmental temperature. That regulation has been used for advantage in life evolution, since constant temperature allows enzymes to control metabolic processes in the most efficient way to procure sustained cellular activity (at the expense of 5 to 10 times higher specific metabolic rate); poikilothermic animals may develop similar activity levels but only for short times.

At cellular level, most living matter must operate in the range 0..70 ºC, because above 70 ºC protein denaturalise (they unfold and clung together irreversible, and DNA double-helix separate in two single helices), whereas below 0 ºC water freeze and life is suspended (but not irreversibly at cellular level).

Many single-celled organisms can be frozen (in vitro and with chemical additives) indefinitely to cryogenic temperatures (depending on the cooling rates), and then be thawed with no decrease in activity. It can be useful for conservation of genetic material (human reproductive cells and embryos, embryos of endangered species and economically important breeds of wild and domesticated animals and plants…).

There are also some thermophiles micro-organisms (most of them from the archaea kingdom), which can live permanently above 70 ºC. The first one studied was a bacteria found in Yellowstone Park in 1969, living at 80 ºC, “thermos aquaticus”; in the 1990s, some other micro-organisms were found in the oceans living at 110 ºC, and recently some others at 131 ºC.

Flushing

Physiological flushing is the abrupt redness in the face of a person (and some other skin parts), due to an excess of heart pumping beyond needs, caused by a sudden stop in muscle work, or by a strong emotion, or by drugs reaction, or by some illness.

Special thermal suits

Special thermal suits are used to protect people working on very hot (e.g. at a furnace), very cold (e.g. refrigerated stores, underwater), or very constrained environments (e.g. space suits).

- Cold water suits are protective garments worn by people exposed to cold waters (water sports, divers, sailors) to keep warm and protect skin from cuts, scrapes and stings. Two types exists:
    - Wet suits, so called because they allow water to come in contact with the skin (the skin warms the water, and the tight-fitting wet suit prevents the warmed water from seeping out and colder water seeping in). They range from very thin material (lycra) usually worn in warm waters, to thick (3..6 mm) foamed-neoprene garments (containing small bubbles of nitrogen gas) worn in colder waters (<20 ºC).
    - Dry suits, so called because they prevent water contact with the skin (other than the head and hands). They are used in colder waters (<15 ºC), and consist of a water-proof membrane of neoprene (artificial rubber) or latex (natural rubber) with appropriate seals, and usually worn with undergarment cloth to allow for some perspiration. For extremely cold waters (0 ºC) a wet suit is worn below the dry suit.
- Fire resistant and thermal protection suits (with helmet and gloves), made of metallized cloth, to allow working near fires or inside furnaces and boilers, may allow short operations up to 1200 K, and prolonged operation at 600 K. They usually incorporate self-contained breathing means.
- Liquid cooling garment for space suits (aside).

Back to Index