TECHNICAL SPECIFICATION

ISO/TS 16976-5

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2013-11-01

Respiratory protective devices — Human factors —

Part 5: Thermal effects

Dispositifs de protection respiratoire — Facteurs humains —

Partie 5: Effets thermiques

Reference number
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Foreword

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The committee responsible for this document is ISO/TC 94, *Personal safety — Protective clothing and equipment*, Subcommittee SC 15, *Respiratory protective devices*.

ISO/TS 16976 consists of the following parts, under the general title *Respiratory protective devices — Human factors*:

— *Part 1: Metabolic rates and respiratory flow rates* [Technical Specification]

— *Part 2: Anthropometrics* [Technical Specification]

— *Part 3: Physiological responses and limitations of oxygen and limitations of carbon dioxide in the breathing environment* [Technical Specification]

— *Part 4: Work of breathing and breathing resistance: Physiologically based limits* [Technical Specification]

— *Part 5: Thermal effects* [Technical Specification]

— *Part 7: Hearing and speech* [Technical Specification]

— *Part 8: Ergonomic factors* [Technical Specification]

The following parts are under preparation:

— *Part 6: Psycho-physiological effects* [Technical Specification]

Introduction

For an appropriate design, selection and use of respiratory protective devices, basic physiological demands of the user must be considered. The function of a respiratory protective device, the way it is designed and used and the properties of its material may have a thermal effect on the human body.

This part of ISO/TS 16976 belongs to a series of documents providing basic physiological and anthropometric data on humans. It contains information about thermal effects associated with wearing respiratory protective devices

Respiratory protective devices — Human factors —

Part 5: **Thermal effects**

1 Scope

This part of ISO 16976 is one of a series of Technical Specifications that provide information on factors related to human anthropometry, physiology, ergonomics and performance for the preparation of standards for design, testing and use of respiratory protective devices. It contains information related to thermal effects of respiratory protective devices on the human body, in particular:

— temperatures of surfaces associated with discomfort sensation and harmful effects on human tissues;

— thermal effects of breathing gas temperatures on lung airways and tissues;

— effects of breathing gas temperature and humidity on respiratory heat exchange;

— effects of respiratory protective devices on overall body heat exchange.

The information represents data for adult healthy men and women in the age 20–60 years.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 7730, *Ergonomics of the thermal environment — Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria*

ISO 7933, *Ergonomics of the thermal environment — Analytical determination and interpretation of heat stress using calculation of the predicted heat strain*

ISO 11079, *Ergonomics of the thermal environment — Determination and interpretation of cold stress when using required clothing insulation (IREQ) and local cooling effects*

ISO 13732-1, *Ergonomics of the thermal environment — Methods for the assessment of human responses to contact with surfaces — Part 1: Hot surfaces*

ISO 13732-3, *Ergonomics of the thermal environment — Methods for the assessment of human responses to contact with surfaces — Part 3: Cold surfaces*

ISO 16972, *Respiratory protective devices — Terms, definitions, graphical symbols and units of measurement*

ISO/TS 16976-1, *Respiratory protective devices — Human factors — Part 1: Metabolic rates and respiratory flow rates*

ISO/TS 16976-3, *Respiratory protective devices — Human factors — Part 3: Physiological responses and limitations of oxygen and limitations of carbon dioxide in the breathing environment*

3 Terms, definitions, symbols and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 16972 and the following apply.

3.1.1
clo
unit for the expression of the thermal insulation of clothing

Note 1 to entry: 1 clo is equal to 0,155 m^2 °C/W.

3.1.2
insulation required
IREQ
cold stress index as determined according to ISO 11079

3.1.3
metabolic rate
physiological energy utilization per unit of time

3.1.4
predicted heat strain
PHS
heat stress index as determined according to ISO 7933

3.2 Symbols and abbreviated terms

PPE personal protective equipment

RPD respiratory protective device

PMV predicted mean vote

PPD predicted percentage dissatisfied

T_s surface temperature: temperature of the surface contacted by skin

T_a ambient temperature: temperature of the air surrounding the body or inhaled

T_c contact temperature: temperature of the interface between skin and contacted surface

T_r rectal temperature: temperature of the core body

4 Local thermal effects

4.1 General

The effects of heat and cold described hereafter will vary according to individual sensitivity.

Notice should be taken of the assessment scales given in ISO 8996.[1]

4.2 Effects on skin contact by the RPD

Heat transfer by conduction takes place via the hands when handling the equipment and via face, head and torso during the actual use of the equipment.

Parts of RPD are, by their very nature, in more or less direct contact with naked human skin for example in the face. In contact areas heat exchange will be affected. The magnitude of this effect is dependent on contact pressure, structure of surfaces, size of contact area, mass of material in contact, thermal conditions and thermal properties of materials in contact.

Materials used in RPD are mostly made of materials with low conductive heat transfer properties. Exceptions are metal parts, in particular, if they are not insulated.

In extreme hot or cold environments the ambient conditions may heat or cool the RPD or parts of it, thereby increasing the risk of a thermal effect on the skin.

A risk assessment of contact cooling or heating of the bare skin shall be based on

ISO 13732-1, for hot surfaces, and

ISO 13732-3, for cold surfaces.

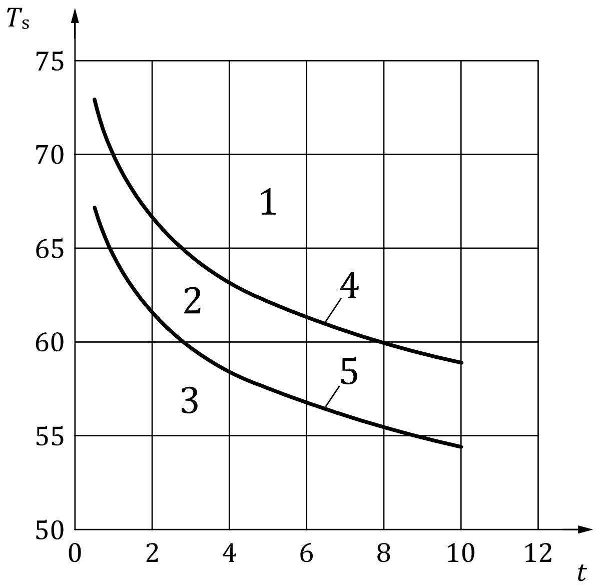
Exposure values and criteria used in the figures below are based on hand or body skin surface contacts. Face skin is likely to be more sensitive in particular to discomfort and more conservative values should be used.

4.3 Hot surfaces

ISO 13732-1 provides comprehensive information about the risk of bare skin contacting different types of materials at different temperatures. Figure 1 shows surface temperatures of polished metal that may cause skin burns. This condition appears to be the most severe case, but other metals such as steel and copper maybe as harmful at similar or slightly higher temperatures. Other materials like plastic, glass and ceramics require considerably higher temperature to cause harm to bare skin.

For long contact duration (10 min and longer) the burn threshold doesn’t depend on the type of material.

For these materials the zone 3 “safe surface” in Figure 1 moves up to the line 4, i.e. upper limit



Key

t contact duration, in s

T_s surface temperature, in °C

1 Zone 1 indicates a high risk of skin burn

2 Zone 2 indicates a possible risk of skin burn

3 Zone 3 indicates safe surface temperatures

4 upper limit

5 lower limit

Figure 1 — Surface temperature of uncoated, polished metallic surfaces with similar heat conductivity properties that may cause skin burns within 10 s

RPD is likely to be used for short duration timed in minutes and longer duration timed in hours. Table 1 indicates burn thresholds for contact periods of 1 min and longer for different materials (modified from ISO 13732-1). Values apply for contact areas that are less than 10 % of the body surface, so they should apply for most RPD.

Table 1 — Burn threshold for contact periods of 1 min and longer

Material	1 min °C	10 min °C	8 h and longer °C
Uncoated metal	51	48	43
Coated metal	51	48	43
Ceramics, glass and stone materials	56	48	43
Plastics	60	48	43
Wood	60	48	43

4.4 Cold surfaces

ISO 13732-3 provides detailed information about the assessment of cooling effects on skin in contact with various types of cold surfaces. Information is given about five types of materials: aluminium, steel, stone, plastic and wood. For each of the materials three criteria for cooling are applied.

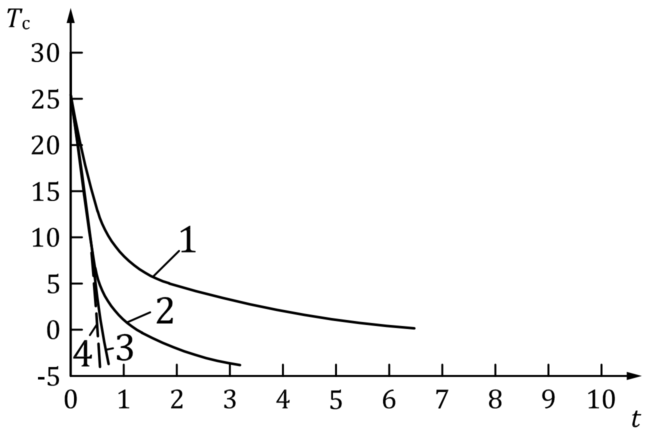
As with a hot surface, contact with a small skin surface area with cold, metallic goods may rapidly cool the skin and eventually result in local frostbite. Figure 2 shows cooling curves obtained with the finger tip touching surfaces of steel and aluminium at temperature of −20°C, −30°C, −40 °C and −50 °C. The contact temperature (T_c), which is likely to be very close to the skin surface temperature drops to below 0°C within few seconds when touching the metal surfaces.[3] The risk of developing local frostbite is highly probable.

Studies[3] have shown that

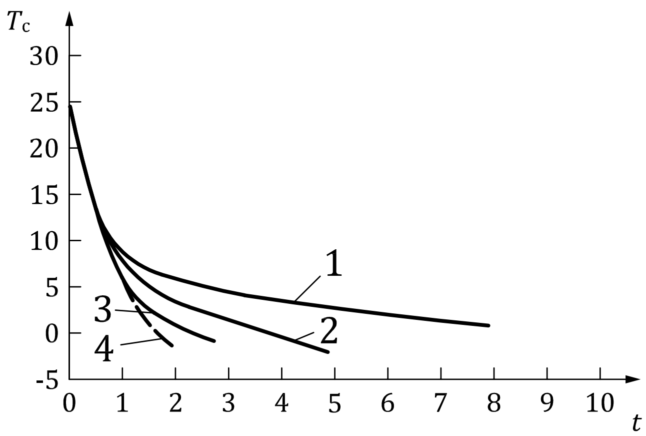
— cooling to a skin temperature of 0 °C is associated with an imminent risk of tissue freezing "frostbite"

— Cooling to a skin temperature of −7 °C is associated with the gradual development of numbness

— Cooling to a skin temperature of −15 °C is associated with the experience of pain



a) Steel



b) Aluminium

Key

t contact duration, in s

T_c contact temperature, in °C

1 − 20 °C

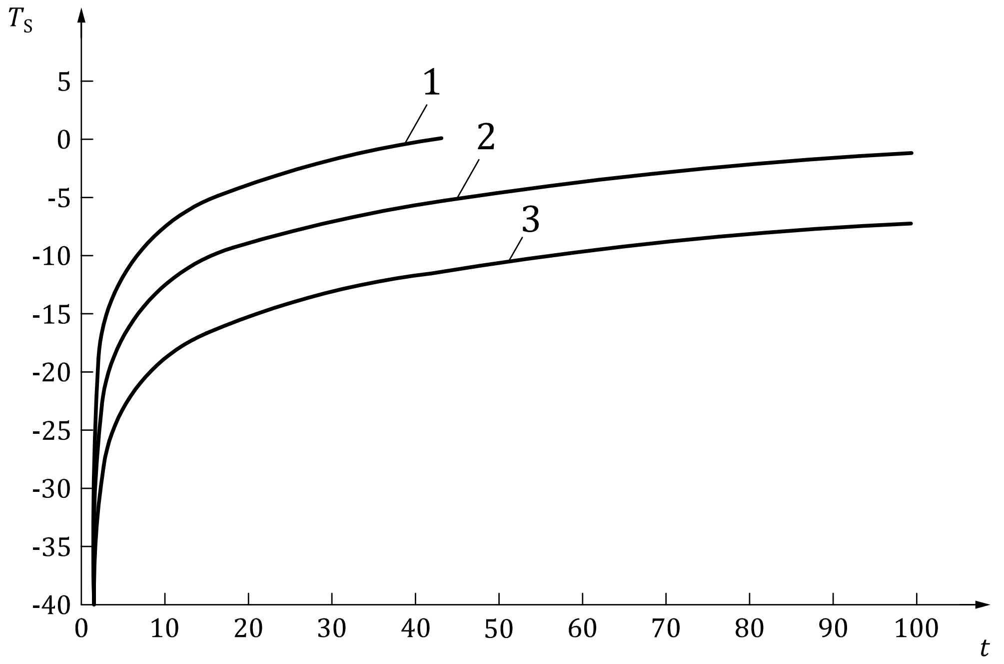
2 − 30 °C

3 − 40 °C

4 − 50 °C (estimated value shown, no published data available)

Figure 2 — Change in *Tc* of finger in contact with metallic surfaces at temperatures of −20 °C, −30 °C, −40 °C and −50 °(estimated)

Figures 3 to 5 show the surface temperature of a specific material that might cause the different type of cooling effects.[3]



Key

t contact duration, in s

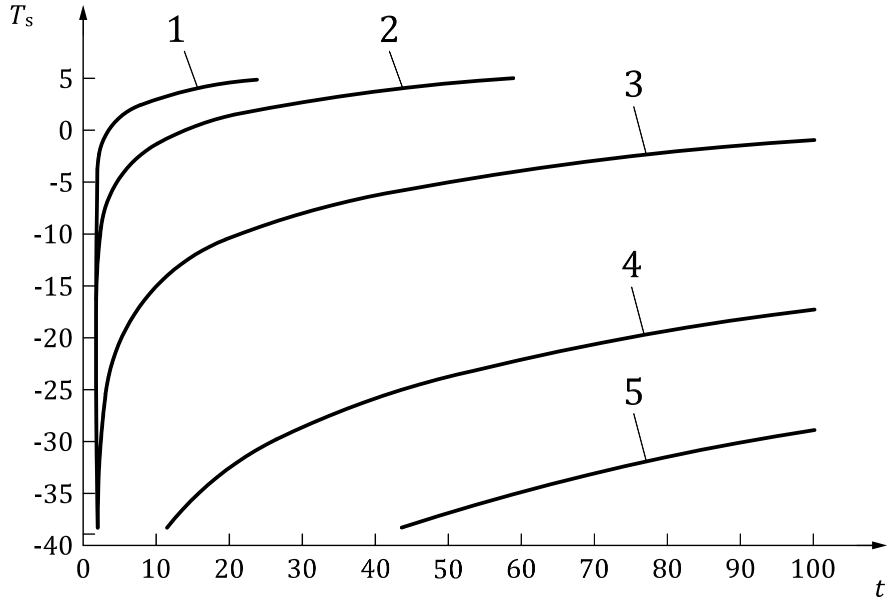
T_S surface temperature, in °C

1 aluminium

2 steel

3 stone

Figure 3 — Frostbite threshold — Acceptable surface temperature as function of time for T_c to reach 0 °C (finger touching cold surfaces between 0,5 s and 100 s)



Key

t contact duration, in s

T_s surface temperature, in °C

1 aluminium

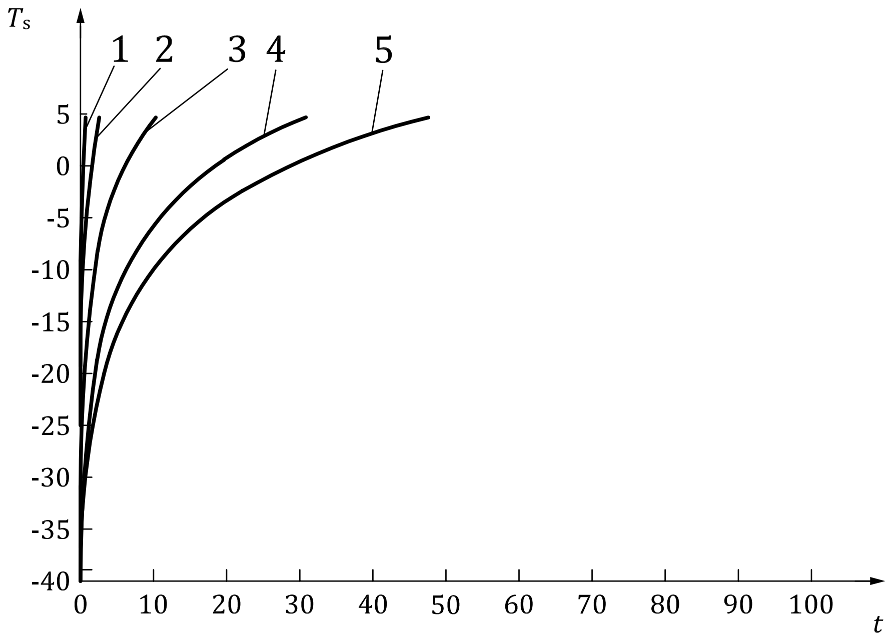
2 steel

3 stone

4 nylon

5 wood

Figure 4 — Numbness threshold — Acceptable surface temperature as function of time for T_c to reach −7 °C (finger touching cold surfaces between 0,5 s and 100 s)



Key

t contact duration, in s

T_S surface temperature, in °C

1 aluminium

2 steel

3 stone

4 nylon

5 wood

Figure 5 — Pain threshold — Acceptable surface temperature as function of time for T_C to reach –15 °C (finger touching cold surfaces between 0,5 s and 100 s)

4.5 Effects of inhaled breathable gas to airways and lung tissues

4.5.1 General RPD function

During respiration there is a heat exchange function also for the RPD. There is at least initially a cooling effect on hot air and a warming effect of cold air. This effect is not well known and depends on type of RPD- material, activity level and environmental conditions. For example, the use of high pressure compressed air should present no problem in hot air as air is cooled during the expansion from the tube. In contrast RPD whose function is based on chemical reaction may present a problem as the breathable gas is heated by the chemical process.

Inhaled breathable gas has low density (even at cold temperature) and low heat capacity. The anatomical and physiological construction of the airways, in particular the upper respiratory tract, provides significant features for preservation of body heat and moisture and mitigation of environmental cooling or heating.

4.5.2 Effects caused by hot breathable gas

At very high temperatures, inhaled breathable gas may result in pain sensation and eventually in tissue burn. During short exposures, nasal breathing may become difficult at approximately 125 °C ambient, dry inhaled breathable gas temperature. Mouth breathing may become difficult at approximately 150 °C ambient, dry inhaled breathable gas temperature. Moist inhaled breathable gas will increase heat exchange and significantly shorten tolerance time at high temperatures. Water saturated inhaled breathable gas at 60 °C to 70 °C increases discomfort at rest (steam sauna) and will be intolerable for longer times during activity.

With RPD, tolerable temperatures are likely to be much lower due to longer exposure times and higher ventilation rates. Warm or hot inhaled breathable gas will also heat the respiratory interface, contributing to a local conductive heat gain in the face/head area.

It is known that at high inhalation temperatures and relative humidity irritation of the lung tissues and air ways may occur. For example at temperature levels of 90 °C at less than 20 % RH at “light work” or 70°C at less than 70 % RH at “moderate work” or even 45 °C with up to 100 % RH at “very, very heavy work” might cause irritation.

Temperatures given in Table 2 should be regarded as maximal temperatures and only applicable to short exposures. The burden on respiratory and whole body heat exchange is significant also at lower temperatures with longer work times, see also Clause 5.

Table 2 — Maximal temperatures for warm or hot inhaled breathable gas

Class	Work	Average metabolic rate W/m^2	Temperature of inhaled breathable gas at RH ≤ 20 % °C	Temperature of inhaled breathable gas at 20 % < RH ≤ 70 % °C	Temperature of inhaled breathable gas at RH > 70 % °C
1	Resting	65	90	70	50
2	Light work	100	90	70	50
3	Moderate work	165	90	70	50
4	Heavy work	230	80	65	45
5	Very heavy work	290	80	65	45
6	Very, very heavy work	400	80	65	45
7	Extremely heavy work	475	80	65	45
8	Maximal work	600	80	65	45
These values have been derived from ISO 11079.					

4.5.3 Effect caused by cold breathable gas

At very low temperatures inhaled breathable gas cools the airways, eventually resulting in broncho-constriction and epithelial irritation. Symptoms may be coughing and asthmatic-like reactions.

ISO 11079 suggests the following temperature limit values for cold inhaled breathable gas. The low strain values refer to effects of more sensorial type, such as discomfort. The high strain level indicates values that may cause irritation, coughing and eventually long term health effects such as asthmatic symptoms.

See Table 3.

Breathable gas through a RPD at such low temperatures is not very likely to cause harm as the respiratory interface itself will act as a kind of heat exchanger and provide some re-warming of inhaled breathable gas.

It is known that at low inhalation temperatures and relative humidity irritation of the lung tissues and air ways may occur. For example, at a temperature level of −40 °C “light work”, at −30 °C “moderate work” and at −20 °C “very heavy work” might cause irritation.

Table 3 — Low temperatures that refer to sensorial effects

Class	Work	Average metabolic rate W/m^2	Temperature of inhaled breathable gas °C
1	Resting	65	−40
2	Light work	100	−40
3	Moderate work	165	−30
4	Heavy work	230	−20
5	Very heavy work	290	−20
6	Very, very heavy work	400	−30
7	Extremely heavy work	475	−30
8	Maximal work	600	−40

5 Effects on whole body heat balance

The body exchanges heat with the environment basically through the respiratory system and via the skin. Heat exchange by respiration comprises convective and evaporative components.

5.1 Respiratory heat exchange

Respiratory heat loss accounts for 5–15 % of the body's heat loss depending on the level of activity. Heat transfer to hot and cold air through the airways is controlled to some extent, in particular with nasal breathing. With moderate to heavy exercise mouth breathing is necessary and the heat and moisture exchange becomes less efficient. In the cold it adds to respiratory heat loss and in the heat it reduces respiratory heat loss. On the other hand, the respiratory interface, a filter and the dead space may provide some damping of the immediate effect of environmental temperatures. In high heat and high humidity situations the mask worn may exacerbate the effect. The magnitude of these effects is not known.

Respiratory heat exchange can be described as a function of the minute ventilation and the temperature difference between inhaled and exhaled air.

The following empirical equations are used:

$$E_{\text{res}} = 0{,}0173 M (p_{\text{ex}} - p_{\text{a}}) \quad (1)$$

$$C_{\text{res}} = 0{,}0014 M (t_{\text{ex}} - t_{\text{a}}) \quad (2)$$

$$t_{\text{ex}} = 29 + 0{,}2 t_{\text{a}} \quad (3)$$

where

E_{res} is the evaporative heat exchange, in W/m^2;

C_{res} is the convective respiratory heat exchange, in W/m^2;

M is metabolic rate in W/m^2;

p_{ex} is the water vapour pressure of expired air, in kPa;

p_{a} is ambient water vapour pressure, in kPa;

t_a is the ambient temperature, in °C.

It is assumed that expired air is water saturated and has a temperature (t_{ex}), that is related to inspired (ambient) temperature (t_a) by Formula (3).[4]

Convective heat exchange is normally quite small, but may reach noticeable magnitudes in certain circumstances. Evaporative respiratory heat loss is generally greater than the convective component. RPD using compressed breathable gas as a source may provide cool and dry gas. That may be beneficial in hot environments but a disadvantage in cold conditions.

Under conditions when RPD may cause increased levels of inhaled CO_2, ventilation may increase, enhancing respiratory heat loss (see ISO/TS 16976-3).

In hyperbaric environments respiratory heat exchanges increase in proportion to the increased ambient pressure. In deep sea diving heating of air may be required in order to compensate for respiratory heat losses. This is particularly true if helium is used as a breathing gas to a larger extent.

RPD using compressed air as a source provides dry air that in most cases is inhaled at a lower temperature than ambient due to decompression. This means that more evaporative heat and more water is lost for the same minute ventilation than under normal breathing conditions. This provides for some extra heat loss in warm environments but at the expense of increased water loss.

In the cold the extra heat loss may still be positive at high work rates. At lower work rates the extra heat loss may require compensation by e.g. extra clothing for the maintenance of heat balance. At high work rates in the heat associated with mouth breathing, more heat is expelled to the environment and therefore is a positive effect.

5.2 Skin surface heat exchange

Most of the body heat dissipates via the skin. The impact of a RPD is therefore, much dependent on the coverage of the skin surfaces and the properties of the material that covers the skin.

The head is important for heat exchange both from a subjective and physical point of view. The head is more sensitive to thermal stimuli than many other parts of the body. The head and neck represents approximately 10 % of the body surface area. It is a significant area for heat exchange, particularly in the cold. Blood flow to head and brain is not reduced in the same manner as to extremities during vasoconstriction. Certain types of RPD may have even large of coverage of the body. For ventilated chemical protective suits it may be 100 %.

Thermal effects of respiratory interfaces are likely to be more of a sensorial nature – comfort/discomfort. The quantitative effect of a RPD on whole body heat exchange is small. In the heat it is likely to add to thermal discomfort. In the cold the respiratory interface provides an additional protection of the face area due to its insulation and the heat exchange effect. Contact with cold metal parts must be avoided.

RPD with a hood implies coverage of the head and parts of the upper torso with material that is impermeable to water vapour. Evaporative heat exchange of covered areas is affected. On the other hand, hood systems usually have assisted ventilation. This may improve or impair the thermal conditions depending on the outside environment. In a cold environment ventilation may increase local heat losses and contribute to a larger overall body heat loss. In a warm environment, ventilation improves local evaporation and slightly reduces heat stress. Only in very hot and humid conditions is a negative effect expected.

In some user applications the RPD is combined with other types of personal protection. In these conditions the thermal effects can be large, for example with a chemical protective suit or a fire fighter turnout gear. Exposure times often become limited to 30–60 min due to the availability of breathable gas as well as due to rising levels of heat stress. Technical solutions are available that provide means of cooling the clothing microclimate, for example by supplying air for ventilation or by using phase change materials (PCM) in suits or extra vests. The heat exchange in these conditions can be analysed and the contribution of RPD and other personal protection can be calculated.

5.3 Increased metabolic rate

Through assessment of respiratory and skin heat fluxes it is possible to make an analysis of the conditions for whole body heat exchange. This is necessary for an estimation of possible risks of hyperthermia or hypothermia.

In a hot environment work with respiratory protective devices may aggravate the thermal stress by

a) increasing metabolic rate through the weight of the equipment;

b) impeding heat exchange at some parts of the body surfaces, in particular the head;

c) combined effects of a protective device and normal or other protective clothing.

The use of RPD, and any other PPE, adds to the physical work of the wearer, increasing physiological strain and respiratory minute volume. Some RPD may weigh more than 10 kg and increases the energy cost of moving, walking and climbing. ISO/TS 16976-1 includes these energy costs of work for the three highest classes.

5.4 Thermoneutral conditions

Much work with RPD, in particular, filtering devices takes place under normal indoor conditions in industries or outdoors under temperate conditions. Filtering devices may cause general ergonomic discomfort, but are not likely to interfere to a large extent with heat exchange, thus not affecting conditions for thermal comfort.

ISO 7730 provides a method for assessment of conditions for thermal comfort, mainly at low to moderate activity and during indoor conditions. RPD affects respiratory heat exchange (Formulae 1–3, 5.1). RPD serves as a heat exchanger, which affects the respiratory heat exchange.

5.5 Heat stress

ISO 7933 can be used for the assessment of whole body heat stress. This index is based on a heat balance equation and calculates the increase in rectal temperature and accumulated water loss due to sweating for a work period. Recommended exposure time is calculated when defined limit criteria are reached for these two physiological variables.

In addition to the normal input values in ISO 7933, the following modifications need to be made in order to predict the thermal influence of the RPD and any other PPE.

a) assessment of the effect of RPD weight on metabolic rate (see 5.3);

b) determination of the thermal insulation of the complete clothing ensemble including RPD and any other PPE;

c) determination of the water vapour resistance of the complete clothing ensemble including RPD and any other PPE;

d) assessment of the impact of the RPD on respiratory heat exchange;

e) assessment of the impact of the RPD on microclimate heat exchange (ventilation).

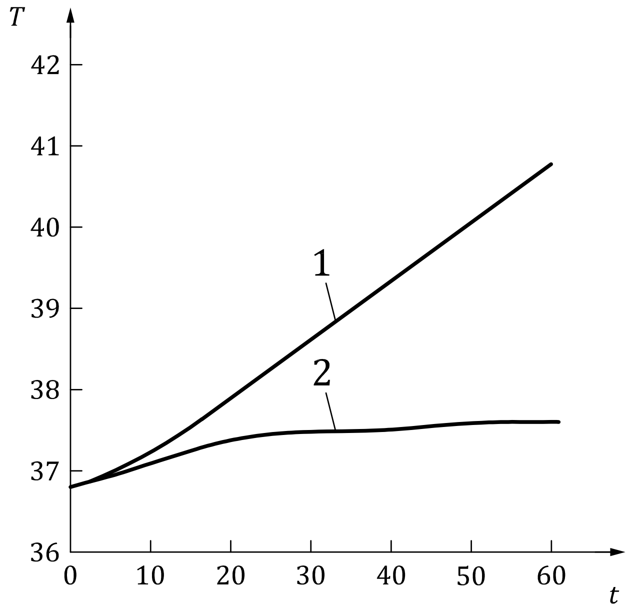
Increased energy cost of work is negative in a hot environment.[2] More body heat production is a problem when heat dissipation to the environment is hampered. If work rate is not reduced for the additional energetic burden of the RPD (and any other PPE) heat stress will increase and eventually result in earlier fatigue or heat injury (see Figure 6).

With SCBA the additional burden and heat stress of weight is slightly counteracted by breathing cool air. The whole body heat balance can be assessed by analysing the predicted heat strain (PHS), described in ISO 7933.

With filtering devices little additional heat stress can be anticipated. However, local discomfort most likely arises from diminished heat losses from the face and head area.

Special problems arise with pure oxygen breathing apparatus that may increase inhalation temperature and aggravate heat stress. Again an assessment of heat stress may be done with ISO 7933.

SCBA provides cool air for inspiration. On the other hand, SCBA is quite heavy and adds to the physical work. The net effect is an increased heat stress that can be assessed by ISO 7933. An example is given in Figure 6. A person is working at 165 W/m^2 at 35 °C outdoors in sunshine in normal clothing. Rectal temperature increases slightly but stays below 38 °C even after 60 min of work. When the person works under the same condition with SCBA and fire fighter suit, heat balance is not achieved and rectal temperature rises sharply to well beyond 40 °C after 60 min. Work rate becomes higher and heat exchange is hampered by the equipment. When wearing the RPD in these conditions work should be terminated in less than 30 min. The major effect is ascribed to the suit. However, the RPD adds significantly to metabolic rate and aggravates conditions.



Key

t time, in minutes

T_r rectal temperature, in °C

1 SCBA and fire suit

2 normal clothing without SCBA

Figure 6 — Effects on rectal temperature of moderate exercise in normal clothing and when wearing fire suit and SCBA in hot environment (35 °C, 60 % RH)

ISO 7933 calculates the required sweat rate for given heat exposures. This provides information about adequate water intake to avoid dehydration. Uncompensated sweat losses cause dehydration of the body with detrimental effects on cardio-vascular function and work capacity. With longer exposures to heat, a rehydration scheme should be applied so that the worker gets access to sufficient amounts of water. For the cases described in the text above (and Figure 6) the sweat loss after 60 min is 0,76 l and 1,0 l, respectively.

5.6 Cold stress

The thermal stress during work in a cold environment with RPD can be assessed by ISO 11079.

In addition to the normal input values in ISO 11079, the following modifications need to be made in order to predict the thermal influence of the RPD/PPD.

a) assessment of the effect of RPD weight on metabolic rate (See 5.3);

b) determination of the thermal insulation of the complete clothing ensemble including RPD/PPE;

c) assessment of the impact of the RPD on respiratory heat exchange;

d) assessment of the impact of the RPD on microclimate heat exchange (ventilation).

The addition of RPD and any other PPE to normal work clothing for cold conditions most likely increases local insulation and whole body insulation. This is beneficial to the maintenance of heat balance in the cold. When SCBA is used the increased metabolic rate generates more body heat and may require adjustment of clothing or a general adjustment of work pace. On the other hand, respiratory cooling may offset a part of this effect. ISO 11079 provides a computer program that allows the simulation of various scenarios and the subsequent analysis of conditions for heat balance.

A person is performing moderate work (165 W/m^2) at −15 °C in a wind of 1 m/s. He is walking at about 4,2 km/h The required clothing insulation for good heat balance is 2,4 clo according to ISO 11079 (IREQ is 2,4 clo). If the same work requires SCBA the metabolic rate will increase to about 250 W/m^2. With the same analysis using ISO 11079 the IREQ is now reduced to 1,1 clo or 1,5 clo if the extra respiratory cooling is included. If clothing is not adjusted to lower insulation value the excess heat production needs to be dissipated by sweat evaporation. This is complicated in the cold as most of the evaporated sweat will condense in clothing. This reduces its cooling power and the insulation properties of textiles. An alternative is to reduce work pace with SCBA so that the final metabolic rate with SCBA becomes again 165 W/m^2, which allows a good heat balance with the worn clothing.

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