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Ergonomics of the thermal environment - Determination of metabolic heat production

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Foreword

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Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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International Standard ISO 8996 was prepared by Technical Committee ISO/TC 159, *TC 5*, Subcommittee SC 1, *Ergonomics of the thermal environment*.

This third edition cancels and replaces the second edition (ISO 8996:1990).

1 Scope

The metabolic rate, as a conversion of chemical into mechanical and thermal energy, measures the energetic cost of muscular load and gives a numerical index of activity. Metabolic rate is an important determinant of the comfort or the strain resulting from exposure to a thermal environment. In particular, in hot climates, the high levels of metabolic heat production associated with muscular work aggravate heat stress, as large amounts of heat need to be dissipated mostly by sweat evaporation.

This International Standard specifies different methods for determination metabolic rate in the context of ergonomics of the climatic working environment. It can also be used for other applications - for example: the assessment of working practices, the energetic cost of specific jobs or sport activities, the total cost of activity, etc.

The estimations, tables… included in the Standard concern an "average" individual,

◊ A man 30 years old, weighting 70kg and 1.75 m tall, (body surface: 1.8 m²)

◊ A woman 30 years old, weighting 60kg and 1.70 m tall, (body surface: 1.6 m²)

The users should make appropriate corrections when they are dealing with a specal population with children, aged persons, people with physical disabilities…

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this part of ISO 8996. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this part of ISO 8996 are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies. Members of ISO and IEC maintain registers of currently valid International Standards.

IS0/CD 15265: 2001, Ergonomics of the thermal environment: risk assessment strategy for the prevention of stress or discomfort in thermal working conditions.

ISO 9886: *Ergonomics – Evaluation of thermal strain by physiological measurements.*

3 Principle and accuracy

The mechanical efficiency of muscular work – called the "useful work" (*W*) is low. In most types of industrial work, it is so small (a few percent) that it is assumed nil. This means that the total energy consumption at work is assumed equal to the heat production. For the purpose of this standard, the metabolic rate is assumed equal to the rate of heat production.

Table 1 lists the different approaches presented in this standard for determining the metabolic rate. These approaches are structured following the philosophy exposed in ISO 15265 regarding the assessment of exposure. Four levels are here considered:

Level 1, SCREENING: Two methods simple and easy to use are presented to quickly characterize the mean workload for a given occupation or for a given activity.

- Method A is a classification according to occupation
- Method B is a classification according to the kind of activity.

Both methods provide a rough estimate and there is considerable scope for error. This limits their accuracy considerably. At this level, an inspection of the work place is not necessary.

LEVEL 2 – OBSERVATION: Two methods are presented for people with full knowledge of the working conditions but without necessarily a training in ergonomics, to characterise in average a working situation at a specific time.

- In method A, the metabolic rate is determined by adding to the basal metabolic rate the metabolic rate for body posture, the metabolic rate for type of work and the metabolic rate for body motion related to work speed (tables of group assessment).
- Using method B, the metabolic rate is determined by means of the tabulated values for various activities.

A procedure is described to record the activities with time and compute the time weighted average metabolic rate, using the data from the two methods above.
The possibility for errors is high. A time study is necessary to determine the metabolic rate in work situations that involve a cycle of different activities.

LEVEL 3 – ANALYSIS: One method is addressed to people trained in occupational health and ergonomics of the thermal environment. The metabolic rate is determined from heart rate recordings over a representative period. This method for indirect determination of metabolic rate is based on the relationship between oxygen uptake and heart rate under defined conditions.
LEVEL 4 – EXPERTISE: Three methods are presented. They require very specific measurements made by experts

- In method A, the oxygen consumption is measured over short periods (10 to 20 min). A detailed time study is necessary for showing the representativity of the measuring period
- Method B is the doubly-labelled water method aiming at characterising the average metabolic rate over much larger periods (1 to 2 weeks).
- Method C is the direct calorimetry method

Table 1 - Levels for the determination of the metabolic rate

Level	Method	Accuracy	Inspection of the work place
I Screening	A. Classification according to occupation	Rough information Very great risk of error	Not necessary, but information needed on technical equipment, work organization
	B. Use of tables for different activities		
II Observation	A. Use of tables of group assessment	High error risk Accuracy: ±20%	Time study necessary
	B. Use of tables for specific activities		
III Analysis	Use of heart rate under defined conditions	Medium error risk Accuracy: ±10%	Not necessary
IV Expertise	A. Measurement of oxygen consumption	Errors within the limits of the accuracy of the measurement or of the time study Accuracy: ± 5%	Time study necessary
	B. Doubly-labelled water method		Not necessary but leisure activities must be evaluated. The method takes a minimum of 7 days to complete
	C. Direct calorimetry		Not necessary

The main factors affecting the accuracy of the estimations are the followings:

- Individual variability
- Differences in work equipment
- Differences in work speed
- Differences in work technique and skill
- Gender differences and anthropometric characteristics
- Cultural differences.
- When using the tables, differences between observers and their level of training.
- When using level III, the accuracy of the relationship between heart rate and oxygen uptake, as other stress factors are influencing heart rate.
- At level IV, the measurement accuracy (determination of gas volume and oxygen fraction).

The accuracy of the results, but also the costs of the study, increase from level I to level IV. Measurement according to level IV gives the most accurate values. As far as possible, the most accurate method should be used.

4 Level 1, Screening

4.1 Table for the estimation of metabolic rate by occupations

Annex A, table A.1. shows the metabolic rate for different occupations. The values are mean values for the whole working time, but without considering longer rest pauses, for example, lunchtime. Significant variation may arise due to differences in technology, work elements, work organization, etc.

4.2 Classification of metabolic rate by categories

The metabolic rate can be estimated approximately using the classification given in annex A. Table A.2. defines 5 classes of metabolic rates: resting, low, moderate, high, very high. For each class, an average and a range of metabolic rate values are given as well as a number of examples. These activities are supposed to include short rest pauses. The examples given in table A.2. illustrate the classification.

5 Level 2, Observation

5.1 Estimation of metabolic rate by task- requirements

The metabolic rate is here estimated from the following observations:

- The body segment involved in the work: both hands, one arm, two arms, the entire body
- The workload for that body segment: light, medium, heavy, as judged subjectively by the observer;
- The body posture: sitting, kneeling, crouching, standing, standing stooped
- The work speed.

Table B.1.a. in annex B gives the mean value and the range of metabolic rates for a standard person, seated, as a function of the body segment involved and the workload. Table B.2.b. gives the corrections to be added when the posture is different than seated. Table B.2. gives the metabolic rate for a moving person as a function of the displacement speed.

5.2 Metabolic rate for typical activities

Table B.3 in annex B provides values of metabolic rate for typical activities. These values are based on measurements performed in the past in many different laboratories.

5.3 Metabolic rate of a work cycle

To determine the overall metabolic rate of a work cycle, it is necessary to carry out a time and motion study that includes a detailed description of the work. This involves classifying each activity and taking account of factors such as the duration of each activity, the distances walked, heights climbed, weights manipulated, the number of actions carried out, etc.

The time-weighted average metabolic rate of a work cycle can be determined from the metabolic rate of the respective activity and the respective duration from the equation

$$M = \frac{1}{T}\sum_{i=1}^{n} M_i t_i \qquad (1)$$

where

M is the average metabolic rate of the work cycle, in watts per square metre;

M_i is the metabolic rate of the activity i, in watts per square metre;

t_i is the duration of the activity i, in seconds.

T is the duration, in seconds, of the considered work cycle and equal to the sum of the partial durations t_i.

The recording of occupational activities and the duration of the activities for a working day or for a particular period may be simplified by using the diary described in table B.4. Activities are recorded when they are changed, using a code for classification, derived from the tables for the estimation of metabolic rate by task components. The number of component to consider will vary depending upon the complexity of the activity.

The procedure is as followed:

1. Fill the name of an occupant and other details
2. Observe the work of an occupant (at least 2 to 3 hours).
3. Determine individual task component and the corresponding metabolic rate estimated on the bases of tables B.1.a. and b. or B.2.
4. Fill the diary always when the task component is changed
5. Calculate the minutes spent in each task component.
6. Multiply the minutes on each task component by the corresponding metabolic rate.
7. Add the values.
8. Divide the sum by total number of observation minutes.

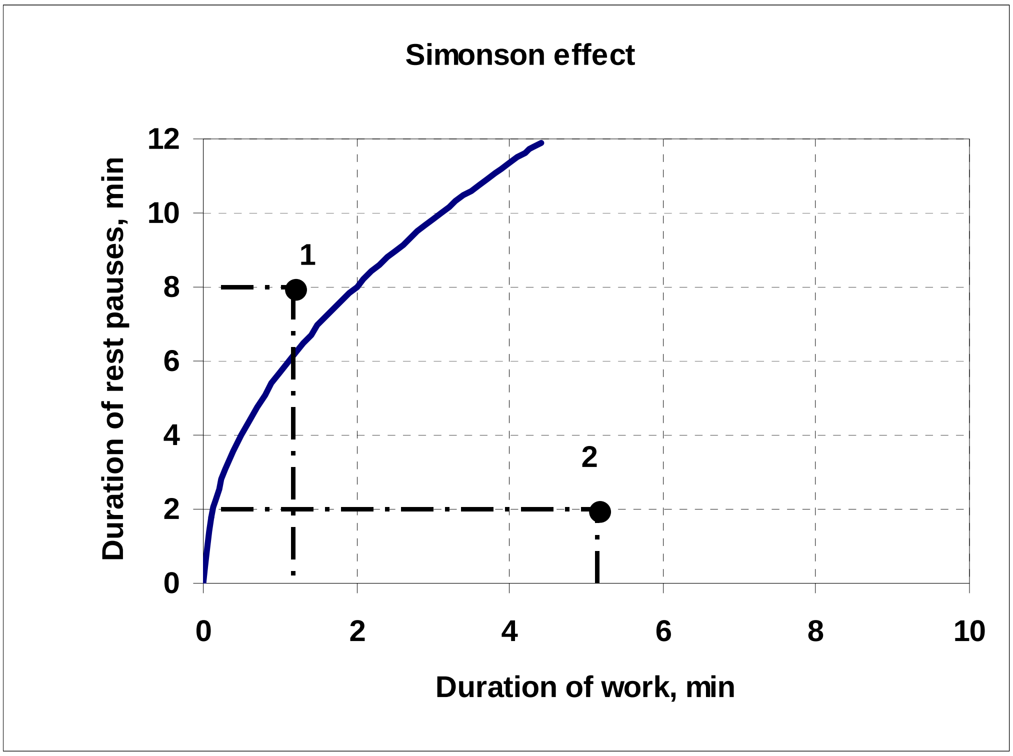
A form for the evaluation is also given in table B.5.

5.4 Influences of the length of rest periods and work

Tables in annex B cannot be used for the evaluation of the average metabolic rate for working conditions with an intermittent sequence of short periods of activity and long rest periods. In this case, the technique exposed in article 5.3. would lead to underestimations of the metabolic rate known as

the Simonson effect. The limit of validity of the combinations of work – rest periods is shown in figure 1. Example 1 concerns a cycle of 8 min. of rest and 1 min. of work. In this case the technique exposed in article 5.3 would lead to an underestimation and the tables in annex B cannot be used. For work-rest cycles such as in example 2, the tables can be used with the indicated accuracy.
Figure 1 only applies when the muscles are completely relaxed during a rest period.
An increase in the metabolic rate due to this effect depends on the type of work and the muscle groups used. Further information on this problem is not given here, because of its complexity and of its low relevancy at this level of evaluation.

Figure 1 – Domain of the increase in metabolic rate



5.5 Interpolation of the values

Interpolation of metabolic rate values is possible. When working speeds differ from those given in the tables of Annex B., conversion is only possible within a range of ± 25 % of the indicated speed.

5.6 Requirements for the application of metabolic rate tables

To allow a comparison of values from different sources, values reported in the tables in Annexes A and B have been standardized with respect to the standard person working in a comfortable thermal environment.
The metabolic rate for a given person performing a given task may vary within certain limits around the mean values given in the tables, due to the influence of the factors mentioned in section 3.
However it can be estimated that:

- For the same work and under the same working conditions, the metabolic rate can vary from person to person by about ±5 %.
- For a person trained to the activity, the variation is about 5 % under laboratory conditions.
- Under field conditions, i.e. when the activity to be measured is not exactly the same from test to test, a variation up to 20 % or more can be expected.

Considering this risk of error, it is normally not justified, at this level of the evaluation, to take into consideration differences in height, gender.
The consideration of the weight of the subject might be warranted only for activities involving movements of the whole body, such as walking, climbing, lifting weight…
In hot conditions, a maximum increase of 5 to 10 Wm^{-2} may be expected due to increased heart rate and sweating. Such a correction is not justified.
On the other hand, in cold conditions, an increase of up to 200 Wm^{-2} may be observed when shivering occurs. The wearing of heavy clothing will also increase metabolic rate, by increasing the weight of the subject and decreasing the ease of movements.

6 Level 3, Analysis

6.1 Estimation of metabolic rate using heart rate

The heart rate at a given time may be regarded as a sum of several components.

$$HR = HR_0 + \Delta HR_M + \Delta HR_S + \Delta HR_T + \Delta HR_N + \Delta HR_E$$

where

- HR_0 is the heart rate, in beats per minute, at rest, in a prone position, under neutral thermal conditions;
- ΔHR_M is the increase in heart rate, in beats per minute, due to dynamic muscular load, under neutral thermal conditions;
- ΔHR_S is the increase in heart rate, in beats per minute, due to static muscular work. This component depends on the relationship between the force used and the maximal voluntary force of the working muscle group;
- ΔHR_T is the increase in heart rate, in beats per minute, due to heat stress. The thermal component is discussed in ISO 9886;
- ΔHR_N is the increase in heart rate, in beats per minute, due to mental load;
- ΔHR_E is the residual component of heart rate, in beats per minute, due, for example, to respiratory effects, circadian rhythms, dehydration.

In the case of dynamic work using major muscle groups, with only a small amount of static muscular load and in the absence of thermal strain and mental loads, the metabolic rate may be estimated by measuring the heart rate during work. A linear relationship exists then between the metabolic rate and heart rate. If the above-mentioned restrictions are taken into account, this method can be more accurate than the level I and level II methods of estimation (see table 1) and is less complex than the measurement of oxygen consumption, which provides the most accurate results.

The heart rate may be registered continuously, for example by the use of telemetric equipment, or, with a further reduction of accuracy, measured manually by counting the arterial pulse (see ISO 9886). The mean heart rate HR may be computed over fixed time intervals, for example 1 min, over different working cycles or over the whole shift time.

In the presence of considerable thermal load, static muscular work, dynamic work with small muscle groups and/or mental loads, the slope and form of the heart rate to metabolic rate relationship can change drastically. The procedure to correct the heart rate measurements for thermal effect is described in ISO 9886.

6.2 Relationship between heart rate and metabolic rate

The relationship between heart rate and metabolic rate can be measured by recording the heart rate at different stages of defined muscular load during an experiment in a neutral climatic environment. Heart rate and corresponding oxygen consumption or physical work performed is measured during dynamic muscular work at different load stages. As the type of work (cycle-ergometer, step test, treadmill) and the sequence and duration of load stages have an influence on both parameters, it is necessary to use a standardized procedure.

In general, linearity holds true for the range

◊ Above 120 beats per minute (bpm), because the mental component can then be neglected;

◊ Up to 20 beats below the maximum heart rate of the subject, because the heart rate tends to level off above this value. The individual maximum heart rate may be estimated by the following formulas

$$HR_{max} = 205 - 0.62\ Age \quad \text{or} \quad HR_{max} = 220 - Age.$$

By regression of the data within this range, the coefficients HR_0 and RM of the following expression can be determined.

$$HR = HR_0 + RM \times (M – BM)$$

Where

- M is the metabolic rate, in watts per square metre;
- BM is the metabolic rate at rest, in watts per square metre;
- RM is the increase in heart rate per unit of metabolic rate.
- HR_0 is the heart rate at rest, in a prone position, under neutral thermal conditions.

This expression can also be written:

$$M = BM + (HR - HR_0) / RM$$

The relation is used to derive the metabolic rate from the measured heart rate.

With a further loss of accuracy, the maximum working capacity can be estimated using the following formulas as a function of age and weight:

- Men: $CMT = (41.7 - 0{,}22 . A) .p^{0{,}666}\ Wm^{-2}$
- Women: $CMT = (35.0 - 0{,}22 . A) .p^{0{,}666}\ Wm^{-2}$

Table C.1. in Annex C provides directly estimations of the HR-M relation for ages ranging from 20 to 60 years and weights ranging from 50 to 90 kg.

7 Level 4, Expertise

7.1 Determination of metabolic rate by measurement of oxygen consumption

7.1.1 Partial and integral method

The metabolic rate can be determined by two main methods:

- partial method, to be used for light and moderately heavy work
- integral method, to be used for heavy work of short duration

The use of these two methods is justified as follows.

- In the case of light and moderately heavy work, the oxygen uptake reaches a steady state equal to the oxygen requirement after a short period of work.
- In the case of heavy work, oxygen requirement is above the long-term limit of aerobic power and, in the case of very heavy work, above the maximal aerobic power. During heavy work, oxygen uptake cannot reach oxygen requirement. The oxygen deficit is balanced after work has ceased. Thus, the measurement includes the working and the subsequent resting period. The integral method should be used for an oxygen consumption of more than 60 litres of oxygen per hour (60 l 0_2 / h), equivalent to 1 litre of oxygen per minute.

Figure 2 shows the procedure followed using the partial method.

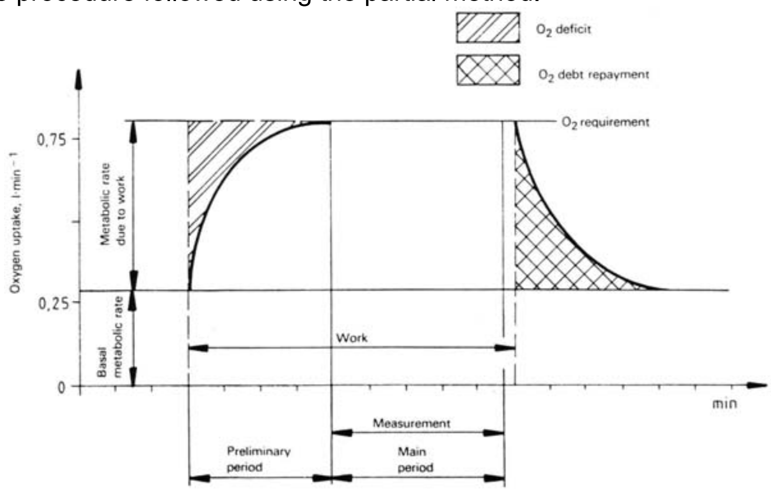


Figure 2 – Measurement of metabolic rate using the partial method

Since the steady state is reached after 3 min to 5 min, the collection of expired air starts only after about 5 min (preliminary period), without interrupting the work,. The work continues for 5 min to 10 min (main period). Gas collection can be either complete - for example with a Douglas bag - or regularly sampled - for example with a gas meter. It stops when work ceases.
With the integral method (figure 3), expired gas collection is started immediately at the beginning of the work and the work is continued for a certain time, usually for not more than 2 min to 3 min (main period). At the end of the work, the subject is asked to sit down and the air collection is continued until the resting value is reached. During this recovery period, the oxygen debt incurred during the work is repaid. Since the measurement includes the working (main period) and sitting (recovery period) activity, the metabolic rate needed for sitting has to be subtracted from the measured value in order to get the metabolic rate related to the work alone.

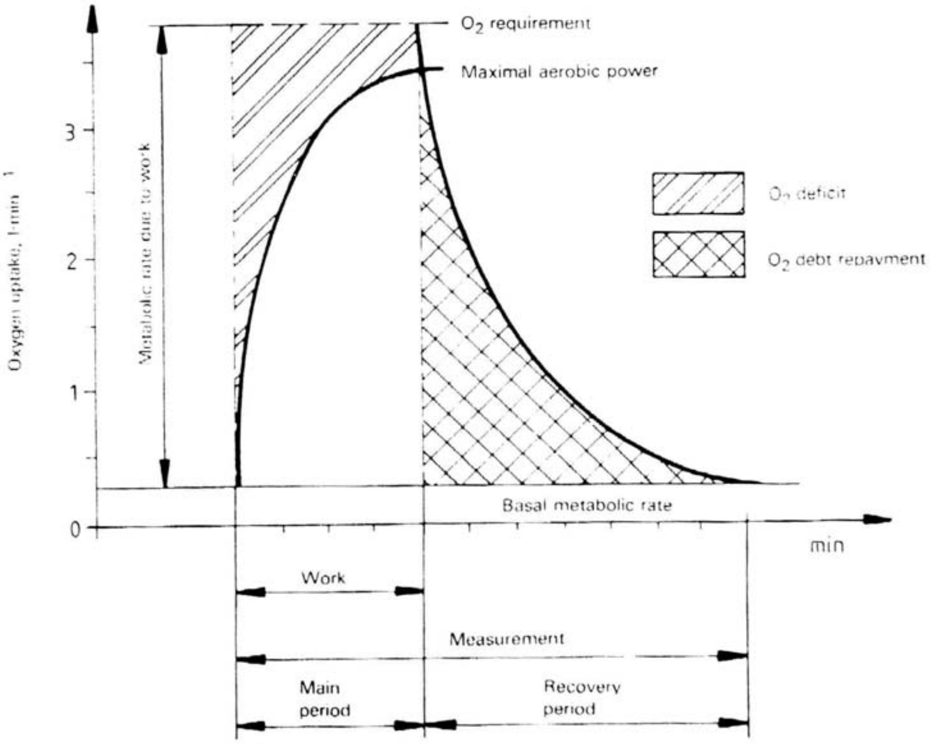


Figure 3 – Measurement of metabolic rate using the integral method

It is necessary to record the course of the work (time study) and the frequency of repeated activities..., for the further evaluation of the results and for the comparison of the metabolic rate with data in the literature. Examples of the calculation of metabolic rate are given in annex D.

7.1.2 Determination of metabolic rate from oxygen consumption

Since the human body can only store very small amounts of oxygen, it must be continuously taken up from the atmosphere by respiration. Muscles can work for a short time without being directly provided with oxygen (anaerobic work), but for longer periods of work, oxidative metabolism is the major energy source.

The metabolic rate can be determined, therefore, by measuring oxygen consumption. The energetic equivalent (EE) for oxygen is used to convert oxygen consumption into metabolic rate.

The energetic equivalent depends on the type of metabolism that is indicated by the respiratory quotient (RQ). In the determination of the metabolic rate, the use of a mean RQ of 0.85 and thereby of an EE of 5,68 W·h / l O_2 is often sufficient. In that case, measurement of carbon dioxide production is not required. The maximum possible error is ± 3,5 %, but generally the error will not exceed 1 %.

The metabolic rate can be determined from the following equations:

$$RQ = \frac{\dot{V}_{CO_2}}{\dot{V}_{O_2}} \quad (2)$$

$$EE = (0,23\ RQ + 0,77) \cdot 5,88 \quad (3)$$

$$M = EE \cdot \dot{V}_{O_2} \cdot \frac{1}{A_{Du}} \quad (4)$$

where

- *EE* is the energetic equivalent, in watts hours per litre of oxygen;
- *RQ* is the respiratory quotient;
- $\dot{V}_{O_2}$ is the oxygen consumption, in litres of oxygen per hour;
- $\dot{V}_{CO_2}$ is the carbon dioxide production, in litres of carbon dioxide per hour;
- *M* is the metabolic rate, in watts per square metre;
- A_{Du} is the body surface, in square metres, according to the Du Bois formula

$$A_{Du} = 0,202 \times W_b^{0,425} \times H_b^{0,725}$$

with

- W_b is the body weight, in kilograms;
- H_b is the body height, in metres.

7.1.3 Determination of oxygen uptake

The procedure for determining the oxygen uptake is described in the following sections.

7.1.3.1 Calculation of the STPD reduction factor

The determination of the oxygen uptake requires to measure or record the following data:

a) The personal data: sex, weight, height, age;
b) The method of measurement;
c) The duration of the measurement: partial method or integral method as described in section 7.1.1.
d) The atmospheric pressure;
e) The volume of air expired;
f) The temperature of the expired air;
g) The fraction of oxygen in the expired air;
h) The fraction of carbon dioxide in the expired air if determination of RQ is required.

7.1.3.1 Calculation of the STPD reduction factor

The gas volume shall be related to t = 0 °C, p = 101,3 kPa (normal atmospheric pressure) for a dry gas (STPD conditions: Standard condition for Temperature 0 °C, barometric Pressure 101,3 kPa, Dry). As the collected air is saturated with water vapour (the saturation pressure of which is a function of temperature) and its temperature is determined by ambient temperature (ATPS conditions: Atmospheric condition for Temperature and barometric Pressure, Saturated), the reduction factor f can be calculated from the following equation using the partial pressure of the water vapour (see table 2).

$$f = \frac{273 \cdot (p - p_{H_2O})}{(273 + t) \cdot 101{,}3} \quad (5)$$

where

- f is the STPD reduction factor;
- p is the measured atmospheric pressure, in kilopascals;
- t is the temperature of the expired air, in degrees Celsius, measured in the gas-meter or assumed the ambient temperature when a Douglas bag is used.
- p_{H_2O} is the partial pressure of the saturated water vapour, in kilopascals, corresponding to the temperature t (see table 2);

Table 2 - Saturated water vapour pressure (kPa) for temperatures between 10 °C and 37 °C (1 °C steps)

Temperature (°C)	0	1	2	3	4	5	6	7	8	9
10	1,23	1,31	1,40	1,50	1,60	1,70	1,82	1,94	2,06	2,20
20	2,34	2,49	2,64	2,81	2,98	3,17	3,36	3,56	3,78	4,00
30	4,24	4,49	4,75	5,03	5,32	5,62	5,94	6,27	--	--

If the collected expired air is heated up by the environment to a temperature in excess of 37 °C, the pressure of the saturated water vapour of 6.27 kPa at the temperature of 37 °C shall be used.

7.1.3.2 Calculation of the expiration volume for STPD

$$V_{ex}STPD = V_{ex}ATPS \times f \quad (6)$$

where

- $V_{ex}STPD$ is the expiration volume, in litres, at STPD;
- $V_{ex}ATPS$ is the expiration volume, in litres, at ATPS;
- f is as defined in 7.1.3.1.

7.1.3.3 Calculation of the volume flow

$$\dot{V}_{ex} = \frac{V_{ex}STPD}{T} \quad (7)$$

where

- $\dot{V}_{ex}$ is the volume flow, in litres per hour;
- T is the test duration in hours, i.e. the main period for the partial method and the main and recovery period for the integral method.

7.1.3.4 Calculation of oxygen consumption

$$\dot{V}_{O_2} = \dot{V}_{ex} \times (0{,}209 - F_{O_2}) \quad (8)$$

where

- $\dot{V}_{O_2}$ is the oxygen consumption, in litres of oxygen per hour;

- F_{O_2} is the fraction of oxygen in the expired air.

7.1.3.5 Calculation of carbon dioxide production

$$\dot{V}_{CO_2} = \dot{V}_{ex} \times (F_{CO_2} - 0{,}0003) \qquad (9)$$

where

- $\dot{V}_{CO_2}$ is the carbon dioxide production, in litres of carbon dioxide per hour;
- F_{CO_2} is the fraction of carbon dioxide in the expired air.

7.1.3.6 The effect of contraction of the expired volume

The inspired and expired volumes are not equal if RQ ≠ 1. Contraction can be taken into account using the following equations:

$$\dot{V}_{O_2} = \dot{V}_{ex}[0{,}265\,(1 - F_{O_2} - F_{CO_2}) - F_{O_2}] \qquad (10)$$

$$\dot{V}_{CO_2} = \dot{V}_{ex}\,[F_{CO_2} - (1 - F_{O_2} - F_{CO_2})\ 0{,}380 \times 10^{-3}] \qquad (11)$$

7.1.4 Calculation of metabolic rate

7.1.4.1 Partial method

The metabolic rate is determined from the oxygen uptake and the energetic equivalent using equation (4).

7.1.4.2 Integral method

The following calculation shall be carried out when using the integral method, as only the difference between the total measured metabolic rate and the known metabolic rate of the activity during the recovery period, i.e. sitting, is related to the work itself.
First, the metabolic rate is derived as in the partial method, and then the following conversion is performed.

$$M = \left(M_P \times \frac{t_m + t_r}{t_m} \right) - \left(M_S \times \frac{t_r}{t_m} \right) \qquad (12)$$

where

- M is the metabolic rate, in watts per square metre;
- M_p is the metabolic rate, in watts per square metre, for the partial method;
- M_s is the metabolic rate, in watts per square metre, when seated;
- t_m is the duration of the main period, in minutes;
- t_r is the duration of the recovery period, in minutes.

7.2 The doubly-labelled water method for long-term measurements

This section describes only the principle of the method.
After collection of a baseline urine sample, the subject drinks an accurately weighed oral loading dose of $^2H_2\,^{18}O$.

- Deuterium (^2H) labels the body water pool and the rate of its disappearance from the body (k_2) provides a measure of water turnover (r_{H_2O}).
- The ^{18}O labels both the water and bicarbonate pools which are in rapid equilibrium through the carbonic anhydrase reaction.

The rate of disappearance of ^{18}O (k_{18}) provides a measure of the combined turnover of water and bicarbonate $(r_{H_2O} + r_{CO_2})$. Therefore, bicarbonate turnover (i.e. the subject's carbon dioxide production rate) can be calculated as the difference between the two rate constants ($k_{18} - k_2$).
Carbon dioxide production can be converted to energy expenditure using classical indirect calorimetric calculations. The initial dilution of the isotopes provides a measure of the ^2H and ^{18}O spaces, which are useful in calculating body composition.
The method requires that the measurements are made over at least two biological half-lives of the isotopes: in children, the minimum test duration is about 6 days, in normal adults, it is about 12-14 days, and in the elderly, it may be longer.
The double-labelled water (DLW) method has been cross validated against whole-body calorimetry or intake/balance procedures in a number of studies. None of these has recorded a significant discrepancy between DLW and the comparator method in subjects under steady-state conditions. The overall precision of the method is about ±3 - 5% depending on circumstances.
Although the DLW technique is simple in concept, there are a number of complex details that must be thoroughly understood by the user.
Further information may be obtained from Murgatroyd et al. (1993) Techniques for the measurement of human energy expenditure: a practical guide, International Journal of Obesity (1993) 17, 549-568

7.3 Direct calorimetry - Principle

Direct calorimetry measures energy expenditure as the rate at which heat is lost from the body to the environment. This heat is transferred through non-evaporative heat loss (radiation, convection, conduction) and through the evaporation of water. Direct calorimetry is usually a whole-body measurement made within the confines of a chamber, but has also been achieved using a heat exchanging body suit. The non-evaporative components of heat exchange are measured passively in terms of the temperature gradient across the walls of a poorly insulated chamber (gradient layer calorimetry), or actively by measuring the rate at which heat must be extracted from a chamber to avoid heat loss through well-insulated walls (heat sink calorimetry). Evaporative heat loss affects the moisture content of the environment and requires independent measurement. It is measured either by condensing the water appearing in the chamber and measuring the latent water content of the air (without condensation) and calculating its associated latent heat of evaporation. Total heat loss is estimated as the sum of the evaporative and non-evaporative components.

Further information may be obtained from Murgatroyd et al. (1993), Techniques for the measurement of human energy expenditure: a practical guide, International Journal of Obesity 17, 549-568.

Annex A (informative):
Evaluation of the metabolic rate at the level 1, Screening

This annex provides the data to use for simply and easily characterizing the mean workload for a given occupation or for a given activity according to the two methods prepared for the level 1, Screening:

- Method A: classification according to occupation
- Method B: classification according to the kind of activity.

Table A.1. - Metabolic rate for various occupations

Occupations		Metabolic rate (Wm^{-2})
Office work	Sedentary work	55 - 65
	Clerical work	65 - 100
	Janitor	80 - 115
Craftsmen	Bricklayer	110 - 160
	Carpenter	110 - 175
	Glazier	90 - 125
	Painter	100 - 130
	Baker	110 - 140
	Butcher	105 - 140
	Clock and watch repairer	55 - 70
Mining industry	Haulage Operator	70 to 85
	Coal hewer	110
	Cokeoven worker	115 - 175
Iron and steel industry	Blast furnace worker	170 - 220
	Electric furnace worker	125 - 145
	Hand moulder	140 - 240
	Machine moulder	105 - 165
	Foundry man	140 - 240
Iron and metal working industry	Smith	90 - 200
	Welder	75 - 125
	Turner	75 - 125
	Drilling machine operator	80 - 140
	Precision mechanic	70 - 110
Graphic occupation	Hand compositor	70 - 95
	Book-binder	75 - 100
Agriculture	Gardener	115 - 190
	Tractor driver	85 - 110
Traffic	Car driver	70 - 100
	Bus driver	75 - 125
	Tramway driver	80 - 115
	Crane operator	65 - 145
Various occupations	Laboratory assistant	85 - 100
	Teacher	85 - 100
	Shop-girl	100 - 120
	Secretary	70 - 85

Table A.2 - Classification of metabolic rate by category

Class	Average metabolic rate (Range)		Examples
	Wm^{-2}	W	
0 Resting	65 **(60-70)**	115 **(105-125)**	Resting
1 Low metabolic rate	100 **(70-130)**	180 **(125-235)**	Sitting at ease: light manual work (writing, typing. drawing. sewing, book-keeping); hand and arm work (small bench tools, inspection, assembly or sorting of light materials); arm and leg work (driving vehicle in normal conditions, operating foot switch or pedal). Standing drilling (small parts); milling machine (small parts); coil winding; small armature winding; machining with low power tools; casual walking (speed up to 3,5 km/h).
2 Moderate metabolic rate	165 **(130-200)**	295 **(235-360)**	Sustained hand and arm work (hammering in nails, filing); arm and leg work (off-road operation of lorries, tractors or construction equipment); arm and trunk work (work with pneumatic hammer, tractor assembly, plastering, intermittent handling of moderately heavy material, weeding, hoeing, picking fruits or vegetables, pushing or pulling light-weight carts or wheelbarrows, walking at a speed of 3,5 km/h to 5,5 km/h, forging).
3 High metabolic rate	230 **(200-260)**	415 **(360-465)**	Intense arm and trunk work; carrying heavy material; shovelling; sledgehammer work; sawing; planning or chiselling hard wood; hand mowing; digging; walking at a speed of 5,5 km/h to 7 km/h. Pushing or pulling heavily loaded hand carts or wheelbarrows; chipping castings; concrete block laying.
4 Very high metabolic rate	290 **(>260)**	520 **(>465)**	Very intense activity at fast to maximum pace; working with an axe; intense shovelling or digging; climbing stairs, ramp or ladder; walking quickly with small steps; running; walking at a speed greater than 7 km/h.

Annex B (informative):
Evaluation of the metabolic rate at the level 2, Observation

This annex provides the data to use for characterizing in average a working situation at a specific time according to the two methods prepared for the level 2 Observation:

- Method A: the metabolic rate is determined by adding to the basal metabolic rate the metabolic rate for body posture, the metabolic rate for type of work and the metabolic rate for body motion related to work speed (tables of group assessment).
- Method B: the metabolic rate is determined by means of the tabulated values for various activities.

Table B.1.a Metabolic rate (Wm^{-2}) for a seated subject, as a function of work intensity and body segment involved

		Work intensity		
Body segments		**Light**	**Medium**	**Heavy**
Both hands	**Mean**	**70**	**85**	**95**
	Range	**<75**	**75-90**	**>90**
One arm	**Mean**	**90**	**110**	**130**
	Range	**<100**	**100-120**	**>120**
Both arms	**Mean**	**120**	**140**	**160**
	Range	**<130**	**130-150**	**>150**
The body	**Mean**	**180**	**245**	**335**
	Range	**<210**	**210-285**	**>285**

Table B.1.b Supplement of metabolic rate (Wm^{-2}) for body postures

Body posture	***Metabolic rate (Wm^{-2})***
Sitting	0
Kneeling	10
Crouching	10
Standing	15
Standing stooped	20

Table B.2. Metabolic rate related to work speed; basal metabolism (45 W/m^2) is to be added to the resulting values

Type of work	Metabolic rate related to work speed Wm^{-2} / (ms^{-1})
Metabolic rate related to walking speed in ms^{-1}	
Walking, 0,55 to 1,40 ms^{-1}(2 to 5 km/h)	110
Walking uphill, 0,55 to 1,40 ms^{-1}(2 to 5 km/h)	
Slope 5°	180
Slope 10°	280
Walking downhill, 0,55 to 1,40 ms^{-1}(2 to 5 km/h)	
Slope 5°	60
Slope 10°	50
Walking with load on back, 1,1ms^{-1} (4 km/h)	
10 kg load	125
30 kg load	185
Metabolic rate related to climbing speed in ms^{-1} (vertical distance per second)	
Walking upstairs	1800
Walking downstairs	525
Mounting inclined ladder	
Without load	1700
10 kg load	1900

20 kg load	2200
Mounting vertical ladder	
Without load	2100
10 kg load	2400
20 kg load	2700

Table B.3. Metabolic rate for specific activities

Activities			W m^{-2}
Sleeping			40
Reclining			45
At rest, sitting			55
At rest; standing			70
Walking on the level, even path, solid			
	1. without load	at 2 km/h	110
		at 3 km/h	140
		at 4 km/h	165
		at 5 km/h	200
	2. with load	10 kg, 4 km/h	185
		30 kg, 4 km/h	250
Walking uphill, even path, solid			
	1. without load	5° inclination, 4 km/h	180
		15° inclination, 3 km/h	210
		25° inclination, 3 km/h	300
	2. with load of 20 kg	15° inclination, 4 km/h	270
		25° inclination, 4 km/h	410
Walking downhill at 5 km/h, without load		5° inclination	135
		15° inclination	140
		25° inclination	180
Ladder at 70° going up at a rate of 11,2 m/min			
		without load	290
		with a 20 kg load	360
Pushing or pulling a tip-wagon, 3,6 km/h, even path, solid			
		pushing force: 12 kg	290
		pulling force: 16 kg	375
Pushing a wheelbarrow, even path, 4,5 km/h, rubber tires, 100 kg load			230
Filing iron	42 file strokes/min		100
	60 file strokes/min		190
Work with a hammer, 2 hands, weight of the hammer 4,4 kg, 15 strokes/min			290
Carpentry work	hand sawing		220
	machine sawing		100
	hand planning		300
Brick-laying, 5 bricks/min			170
Screw driving			100
Digging a trench			290
Sedentary activity (office, dwelling, school, laboratory)			70
Standing light activity (shopping, laboratory, light industry)			93
Standing, medium activity (shop assistant, domestic work, machine work)			116
Work on a machine tool			
	Light (adjusting, assembling)		100
	Medium (loading		140
	Heavy		210
Work with a hand tool			
	Light (light polishing)		100
	Medium (polishing)		160
	Heavy (heavy drilling)		230

Table B.4. - Diary-form for recording activities

Date	
Subject	
Workplace	
Air temperature °C	
Globe temperature °C	
Air humidity RH%	
Air velocity m/s	
Clothing clo	

Table B.5 – Table summarising the diary results

Occupation/work task___________Date:____/

Category		**M**		**Time**		**Total**
		Wm^{-2}		min		
1	Task 1	M_1	x		=	
2	Task 2	M_2	x		=	
…	…	…	x		=	
i	Task i	M_i	x		=	
…	…	…	x		=	
n	Task n	M_n	x		=	
	Total			……		……
	Time-weighted average metabolic rate					**……**

Hour	Min	Task number				
		1	2	3	---	n
…						
…						

ANNEX C (informative)

Evaluation of the metabolic rate at the level 3, Analysis

This annex provides the data to use for estimating the metabolic rate from heart rate recordings over a representative period according to the method prepared for the level 3, Analysis:

Table C.1.: Relationship between Metabolic Rate (in Wm^{-2}) and Heart Rate (in bpm), predicted as a function of the age and the weight of the subject (for women and men)

Women	**Weight (kg)**				
AGE (years)	**50 kg**	**60 kg**	**70 kg**	**80 kg**	**90 kg**
20	2.9 HR-150	3.4 HR-181	3.8 HR-210	4.2 HR-237	4.5 HR-263
30	2.8 HR-143	3.3 HR-173	3.7 HR-201	4.0 HR-228	4.4 HR-254
40	2.7 HR-136	3.1 HR-165	3.5 HR-192	3.9 HR-218	4.3 HR-244
50	2.6 HR-127	3.0 HR-155	3.4 HR-182	3.7 HR-207	4.1 HR-232
60	2.5 HR-117	2.9 HR-145	3.2 HR-170	3.6 HR-195	3.9 HR-219
Men					
20	3.7 HR-201	4.2 HR-238	4.7 HR-273	5.2 HR-307	5.6 HR-339
30	3.6 HR-197	4.1 HR-233	4.6 HR-268	5.1 HR-301	5.5 HR-333
40	3.5 HR-192	4.0 HR-228	4.5 HR-262	5.0 HR-295	5.4 HR-326
50	3.4 HR-186	4.0 HR-222	4.4 HR-256	4.9 HR-288	5.3 HR-319
60	3.4 HR- 180	3.9 HR-215	4.5 HR-249	4.8 HR-280	5.2 HR-311

ANNEX D (informative)
Evaluation of the metabolic rate at the level 4, Expertise

Examples of the calculation of metabolic rate based on measured data

An example of the calculation of metabolic rate for both the partial and the integral methods is given below. A gas-meter was used for the collection of expired gases.

D.1 Calculation of metabolic the partial method

D.1.1 Personal data

Sex: male
Age: 35 years
Height: 1,75 m
Weight: 75 kg
A_{Du}: 1,90 m²

D.1.2 Duration of measurement

Preliminary period: 0.05 h (3 min)
Main period: 0,2 h (12 min)

D.1.3 Atmospheric pressure: P = 100.8 kPa

D.1.4 Measured values

D.1.4.1. Gas-meter

Correction factor for the gas-meter = 0.998
Temperature of the gas-meter (i.e. temperature, t, of the expired air) = 26.8 °C
Final reading of the gas-meter = 7981.2 litres
Initial reading of the gas-meter = 7775.0 litres
Ventilation 206,2 litres

D.1.4.2. Fraction of oxygen and carbon dioxide in the expired air

Fraction of oxygen F_{O2} = 0.162
Fraction of carbon dioxide F_{CO2} = 0.042

D.1.5. Calculation of the expired volume

The expired volume V_{ex}ATPS is calculated from the ventilation and the correction factor of the gas-meter.

V_{ex}ATPS = 206.2 x 0.998 = 205.8 litres

The STPD reduction factor is calculated from equation 5:

$$f = \frac{273 \times (100.8 - 3.52)}{(273 + 26.8) \times 101.3} = 0.874$$

V_{ex}STPD = V_{ex}ATPS x f = 205.8 x 0.874 = 179,9 litres

D.1.6. Calculation of the volume flow

Vex = VexSTPD / t = 179.9 / 0.2 = 899.5 l/h

D.1.7 Calculation of the oxygen consumption

$V_{O2} = V_{ex}\,(0.209 - F_{O2})$ = 899.5 (0.209 – 0.162) = 42.3 l O_2/h

D.1.8 Calculation of the carbon dioxide production

$V_{CO2} = V_{ex}\,(F_{CO2} – 0.0003)$ = 899,5 (0,042 - 0,0003) = 37.5 l CO_2/h

D.1.9 Consideration of the shrinkage of the expired volume

$V_{O2} = V_{ex}\,[0.265\,(1 - F_{O2} - F_{CO2}) - F_{O2}]$
= 899,5 [0.265 (1 – 0.162 – 0.042) - 0,162] = 44.0 l O_2/h

$V_{CO2} = V_{ex}\,[F_{CO2}) – 0.00038\,(1 - F_{O2} - F_{CO2})]$
= 899,5 [0.042 – 0.00038 (1 – 0.162 – 0.042)] = 37,5 l CO_2/h

D.1.10 Calculation of the metabolic rate

RQ = V_{CO2} / V_{O2} = 37.5 / 44.0 = 0.852
EE = (0.23 RQ + 0.77) x 5.88 = 5,68 Wh/l 0_2
M = EE x V_{O2} / A_{Du} = 5.68 x 44.0 /1.9 = 131.5 Wm^{-2}

Due to the limits of accuracy attainable, the result may be rounded to 132 Wm^{-2}

D.2. Calculation of the metabolic rate using the integral method

Contraction of the expired volume and calculation of RQ using CO_2 production are omitted in this example, because these corrections have no important effect on the final result.

D.2.1. Personal data: same data as in D.1.1.

D.2.2 Duration of measurement

Main period = 0.05 h (3 min)
Recovery period = 0.15 h (9 min)
Test duration = 0.2 h (12 min)

D.2.3. Atmospheric pressure: p = 100.8 kPa

D.2.4. Measured values

D.2.4.1. Gas-meter

Correction factor for the gas-meter = 0.998
Temperature of the gas-meter = 26.8 °C
Final reading of the gas-meter = 5877.5 litres
Initial reading of the gas-meter = 5707.0 litres
Ventilation = 170.5 liters

D.2.4.2. Fraction of oxygen in the expired air

Fraction of oxygen F_{O2} = 0,155

D.2.5 Calculation of the expired volume

The expired volume V_{ex}ATPS is calculated from the ventilation and the correction factor of the gas-meter.

V_{ex}ATPS = 170,5 x 0,998 = 170,2 litres

The STPD reduction factor has the same value as in D.1.5.

V_{ex}STPD = V_{ex}ATPS x f = 170,2 x 0,874 = 148.8 litres

D.2.6. Calculation of the volume flow

V_{ex} = V_{ex}STPD / t = 148.8 / 0.2 = 744.0 l/h

D.2.7. Calculation of the oxygen consumption

$V_{O2} = V_{ex} (0{,}209 - F_{O2})$ = 40,2 l O_2/h

D.2.8. Calculation of the metabolic rate

Using a mean RQ of 0.85 and thereby an energetic equivalent of 5.68 Wh/l O_2, the following result obtained:

$M = EE \times V_{O2} / A_{Du}$ = 5.68 x 40,2 / 1.9 = 120.2 Wm^{-2}

In order to relate the metabolic rate to the main period, the conversion according to equation (12) is performed.

The metabolic rate for sitting being 55 Wm^{-2} (Table B.3.)

M = 120.2 x 0.2 / 0.05 - 55 x 0.15 / 0.05 = 318,8 Wm^{-2}

Due to the limits of accuracy attainable, the result may be rounded to 320 Wm^{-2}.