Accuracy of metabolic rate estimates from heart rate under heat stress—an empirical validation study concerning ISO 8996

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Abstract: The standard ISO 8996 provides methods for the determination of metabolic rate from measured oxygen consumption \(\text{MVO}_2\), as well as simplified estimation algorithms based on heart rate \(\text{MHR}\). We quantified the accuracy of these methods by comparing \(\text{MHR}\) with \(\text{MVO}_2\) measured in 373 climatic chamber experiments under different workloads and widely varying heat stress conditions. While our results confirmed the 5% accuracy level for \(\text{MVO}_2\), \(\text{MHR}\) considerably overestimated \(\text{MVO}_2\) due to the rise in core temperature concomitantly increasing heart rate by approximately 30 bpm/°C resulting in an overall error of 43%. After individually correcting for this bias the accuracy was 10–15% as stipulated by the standard. Thus, methods correcting for the thermal component of heart rate, e.g. by introducing intermittent resting periods of sufficient length of at least five min when investigating heat stress at workplaces, should become a mandatory element in the ongoing revision of the relevant standards.

Key words: Heat stress, Activity, Metabolic rate, Heart rate, Standards

In addition to the physical parameters of the thermal environment (air temperature, humidity, air velocity, thermal radiation) and the thermal properties of clothing, the rate of metabolic heat production \(M\) associated with occupational activities is a crucial input to assessment procedures for the thermal environment. This applies to the thermal comfort index PMV (Predicted Mean Vote, ISO 7730)1 as well as to the cold stress index IREQ (required clothing insulation, ISO 11079)2 and to heat stress indices like the WBGT (wet bulb globe temperature, ISO 7243)3 and the currently revised PHS (Predicted Heat Strain, ISO/DIS 7933)4).

The international standard ISO 89965 describes methods for the determination of \(M\) at increasing levels of expertise, effort and presumed accuracy. They start at Level 1 (screening) with a simple categorization of workload (resting, low, moderate, high, very high)3, 5), and tables of metabolic rates for different professions6) associated with a ‘very great risk of error’5). Level 2 (observation) uses tables5) or predictive equations of energy consumption for simple activities like walking7) with an assumed accuracy of 20%. Level 3 (analysis) provides algorithms to estimate \(M\) from heart rates (HR) recorded during workplace studies considering the influence of gender, age and body constitution (weight, body fat). A recent review8), which will serve as a guideline document for the ongoing revision of ISO 8996, analysed the uncertainty of the different components of the underlying algorithms using

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Monte Carlo simulations. The authors concluded from the resulting percentage coefficient of variation (CV) that the overall accuracy of metabolic rate estimates based on HR was 10−15%.

For assessing their accuracy, these estimates should be ideally compared to \( M \) determined from measured rates of oxygen consumption (\( VO_2 \)), which are considered Level 4 (expertise) methods and supposed to provide the highest level of accuracy with a typical error of 5%\(^5\).

As \( VO_2 \) measurements require sophisticated equipment and expert knowledge, the recording of heart rates with subsequently applied estimation algorithms are considered as a cost-effective alternative with acceptable accuracy\(^8\) and are recommended for the evaluation of the impact of dynamic work when assessing heat strain at workplaces by the revised draft of the PHS standard\(^9\).

However, the widely acknowledged influence of further components, like static work, thermal and mental load etc., that increase heart rate and thus potentially trigger overestimation errors, is not considered in depth by these documents\(^4, 8\). More specifically, they do not quantify the effects of the rise in core temperature (\( \Delta Tre \)) under heat stress, which will increase both \( M \) and HR. For the first effect, \( Q_{10} \) coefficients\(^9\) describe the percentage change in \( M \) (%\( M \)) due to \( \Delta Tre \) by

\[
\% M = (Q_{10}^{\Delta Tre/10} - 1) \times 100 \quad (1)
\]

Thus, the common setting \( Q_{10}=27\) implies that a 1°C increase in core temperature will rise \( M \) by approximately 7%, which might increase the variability of \( M \) measured under heat stress. The \( Q_{10} \) effect on \( M \) will then also lead to a concomitant increase in HR for this \( M \) increment. Independently from this effect, the thermoregulatory response to rising body temperature, an increase in blood flow to the skin, will require an increase in HR. This impact of \( \Delta Tre \) on HR, called thermal cardiac reactivity\(^10\) or the thermal component of heart rate (\( AHR_T \))^5,10 or ‘thermal pulses’\(^11, 12\), will increase HR by 30−40 bpm per 1°C rise in \( Tre \)\(^8, 10, 12\). This could introduce an overestimation bias and thus inflate the prediction error of \( M \) estimated from HR\(^8\) under heat stress conditions.

This validation study aimed to assess the claimed levels of accuracy for the different methods to determine \( M \) quantifying the influence of physiological strain under heat stress conditions by comparing \( M \) estimates to measured values from controlled climatic chamber experiments.

We compiled a database from human heat stress experiments performed previously\(^9, 12–15\) in the climatic chamber at IfADo, which had been conducted according to the ethical principles of the Declaration of Helsinki. Data originated from 373 laboratory sessions consisting of 11 individual series with 11 to 78 trials performed by six non-acclimatized young fit males (Table 1) who had provided informed consent to the studies. Their averaged characteristics (mean ± SD) were 20.8 ± 0.9 yr of age, 1.83 ± 0.04 m of body height (\( H_b \)), 72.1 ± 8.4 kg of body weight (\( W_b \)), 1.9 ± 0.1 m\(^2\) of body surface area (\( A_{Du} \)), 21.5 ± 2.5 kg/m\(^2\) of body-mass-index (\( BMI \)), and 55.3 ± 8.1 ml/min/kg of peak oxygen consumption (\( VO_{2max} \)).

Following a one-hour bed rest under neutral conditions, the participants donned a cotton coverall combined with underwear, socks and gym shoes providing a thermal insulation of 0.7 clo\(^13\). Then they moved into the climatic chamber set to heat stress conditions characterized by different combinations of air temperature (range 15−55°C), water vapour pressure (0.4−1.8 kPa), air velocity (0.5−2.0 m/s), and values of mean radiant temperature varying between 0 and 128.5 K above air temperature. The participants performed treadmill work for at least 3 h with three levels of workload: 3 km/h on the level (\( W_1 \)), 4 km/h on the level (\( W_2 \)), and 4 km/h with 2.5° inclination, corresponding to a grade of 4.4% (\( W_3 \)). The protocol included short interruptions (3 min) after each 30 min period for weighing the participants. In addition, rates of oxygen consumption (\( VO_2 \)) in l/min were determined from the expired air collected in Douglas bags towards the end of each full hour according to ISO 8996\(^5\). As physiological responses usually stabilized after two hours\(^12\), we calculated averages over the third hour of exposure from continuously recorded rectal temperatures (\( Tre \)) and HR, thus representing steady-state values. These were matched with \( VO_2 \) measurements from the third exposure hour. We also computed resting values (\( Tre_0 \), HR\(_0 \)) from the last 15 min of the rest period.

We calculated \( Q_{10} \) coefficients from \( Tre \) and \( VO_2 \) for each series as described recently\(^9\) using an expanded version of (1) shown in (2).

\[
VO_2 = VO_{2ref} \times Q_{10}^{(Tre-Tref)/10} \quad (2)
\]

More precisely, \( Q_{10} \) coefficients were obtained by exponentiating the slopes of the logarithmized equation (2) fitted by linear regression to the measured \( VO_2 \) using \( Tre \) as predictor with \( Tre_{ref} = 36.8°C \). It should be noted that choosing a different value for \( Tre_{ref} \) or applying a multiplicative transformation on \( VO_2 \), e.g. calculating metabolic rates using a constant standard energy equiva-
lent as in (3) below, would only affect the intercept \( VO_2,\text{ref} \), but result in identical \( Q_{10} \) values.

The metabolic rates in watts from \( VO_2 \) measured in l/min \((MVO_2)\) were calculated using the standard energy equivalent of 5.68 W/(l/h) according to ISO 89965) as:

\[
M_{\text{VO2}} = VO_2 \times 60 \times 5.68 \quad (3)
\]

Estimates of metabolic rate based on HR \((MHR)\) rely on the linear relationship between metabolic or work capacity with cardiac capacity or cardiac reserve. Detailed algorithms considering different populations depending on gender, age and body constitution are provided in the literature5, 8, 16). Here, we will focus on the equations needed for our sample of young fit males and suggested by the standard5, 8) as follows:

\[
M_{HR} = M_0 + \frac{(MWC - M_0)}{(HR_{\text{max}} - HR_0)} \times (HR - HR_0) \quad (4)
\]

In (4), \( M_0 \) and \( HR_0 \) denote resting values of metabolic rate and heart rate, respectively; \( MWC \) is the maximum work capacity in watts; and \( HR_{\text{max}} \) denotes maximum heart rate. As only \( HR \) and \( HR_0 \) were measured, we estimated the other parameters following the published guidelines 8) under the current revision of ISO 8996. We assumed \( M_0 \) for males as 60 W/m² and converted it to watts by multiplication with \( ADu \). \( HR_{\text{max}} \) was calculated depending on age in years as:

\[
HR_{\text{max}} = 208 - 0.7 \times \text{age} \quad (5)
\]

\( MWC \) can be estimated for males depending on age and lean body mass \((LBM)\) as:

\[
MWC = (19.45 - 0.133 \times \text{age}) \times LBM \quad (5)
\]

As recently reviewed8), there are several options to estimate \( LBM \). We adopted the approach as advised for males in the current draft for the revision of ISO 8996 and calculated \( LBM \) from body weight \((W_b)\) and height \((H_b)\) as:

\[
LBM = \left(1.08 - \frac{W_b}{80 \times H_b}\right) \times W_b \quad (6)
\]

Together with averaged rectal temperature increase \((\Delta T_{\text{re}})\), thermal cardiac reactivity \((TCR)\) representing the slopes from Fig. 1b) and non-dimensional \((nd)\) \( Q_{10} \) coefficients. Percentages of mean prediction error \((%\text{bias})\) and root-mean-squared error \((%\text{rmse})\) for metabolic rates estimated from heart rates \((MHR)\) in comparison to the errors after correcting for bias due to rectal temperature increase \((\Delta T_{\text{re}})\) using the relationship from Fig. 1a), and to predictions from the Pandolf equation \((MPan)\). Subtotals for workload and total figures were calculated from the individual series as means weighted by the number of experiments \( (N_{\text{exp}}) \).

Table 1. Means \((AM)\) and coefficient of variation \((CV)\) of metabolic rate from measured oxygen consumption \((MVO_2)\) measured in 11 series with six participants \((ID1−ID6)\) under different workload conditions \((W1, W2, W3)\)

<table>
<thead>
<tr>
<th>Work-ID</th>
<th>( N_{\text{exp}} )</th>
<th>( \Delta T_{\text{re}} ) ((^\circ \text{C}))</th>
<th>( TCR ) ((\text{bpm/}^\circ \text{C}))</th>
<th>( Q_{10} ) ((\text{nd}))</th>
<th>( AM ) ((W))</th>
<th>( CV )</th>
<th>( %\text{bias} )</th>
<th>( %\text{rmse} )</th>
<th>( %\text{bias} )</th>
<th>( %\text{rmse} )</th>
<th>( %\text{bias} )</th>
<th>( %\text{rmse} )</th>
<th>( %\text{bias} )</th>
<th>( %\text{rmse} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1-ID1</td>
<td>15</td>
<td>1.0</td>
<td>28.8</td>
<td>1.47</td>
<td>193</td>
<td>11%</td>
<td>63%</td>
<td>66%</td>
<td>0%</td>
<td>14%</td>
<td>−12%</td>
<td>16%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W1-ID2</td>
<td>18</td>
<td>0.9</td>
<td>16.2</td>
<td>1.07</td>
<td>224</td>
<td>4%</td>
<td>41%</td>
<td>45%</td>
<td>0%</td>
<td>14%</td>
<td>−23%</td>
<td>23%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W1-ID3</td>
<td>15</td>
<td>1.0</td>
<td>24.8</td>
<td>1.12</td>
<td>210</td>
<td>7%</td>
<td>61%</td>
<td>63%</td>
<td>0%</td>
<td>11%</td>
<td>−23%</td>
<td>24%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W2-ID1</td>
<td>44</td>
<td>1.0</td>
<td>38.8</td>
<td>1.19</td>
<td>221</td>
<td>11%</td>
<td>56%</td>
<td>60%</td>
<td>0%</td>
<td>14%</td>
<td>1%</td>
<td>11%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W2-ID2</td>
<td>35</td>
<td>1.0</td>
<td>17.9</td>
<td>1.13</td>
<td>265</td>
<td>6%</td>
<td>27%</td>
<td>31%</td>
<td>0%</td>
<td>12%</td>
<td>−14%</td>
<td>15%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W2-ID3</td>
<td>78</td>
<td>1.0</td>
<td>20.9</td>
<td>1.05</td>
<td>242</td>
<td>5%</td>
<td>44%</td>
<td>47%</td>
<td>0%</td>
<td>13%</td>
<td>−11%</td>
<td>12%</td>
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<tr>
<td>W2-ID4</td>
<td>52</td>
<td>0.9</td>
<td>39.3</td>
<td>1.19</td>
<td>289</td>
<td>7%</td>
<td>35%</td>
<td>45%</td>
<td>0%</td>
<td>15%</td>
<td>−0%</td>
<td>7%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W2-ID5</td>
<td>38</td>
<td>0.9</td>
<td>23.3</td>
<td>1.00</td>
<td>272</td>
<td>5%</td>
<td>57%</td>
<td>59%</td>
<td>0%</td>
<td>12%</td>
<td>−7%</td>
<td>8%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W2-ID6</td>
<td>51</td>
<td>0.8</td>
<td>28.7</td>
<td>1.09</td>
<td>277</td>
<td>4%</td>
<td>8%</td>
<td>19%</td>
<td>0%</td>
<td>9%</td>
<td>−5%</td>
<td>7%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W3-ID1</td>
<td>11</td>
<td>0.9</td>
<td>40.4</td>
<td>0.95</td>
<td>323</td>
<td>5%</td>
<td>10%</td>
<td>14%</td>
<td>0%</td>
<td>6%</td>
<td>5%</td>
<td>7%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W3-ID2</td>
<td>16</td>
<td>1.1</td>
<td>11.0</td>
<td>0.97</td>
<td>329</td>
<td>4%</td>
<td>8%</td>
<td>14%</td>
<td>0%</td>
<td>9%</td>
<td>5%</td>
<td>7%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Subtotals for workload

<table>
<thead>
<tr>
<th>Work</th>
<th>( N_{\text{exp}} )</th>
<th>( \Delta T_{\text{re}} ) ((^\circ \text{C}))</th>
<th>( TCR ) ((\text{bpm/}^\circ \text{C}))</th>
<th>( Q_{10} ) ((\text{nd}))</th>
<th>( AM ) ((W))</th>
<th>( CV )</th>
<th>( %\text{bias} )</th>
<th>( %\text{rmse} )</th>
<th>( %\text{bias} )</th>
<th>( %\text{rmse} )</th>
<th>( %\text{bias} )</th>
<th>( %\text{rmse} )</th>
<th>( %\text{bias} )</th>
<th>( %\text{rmse} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>48</td>
<td>1.0</td>
<td>22.8</td>
<td>1.21</td>
<td>210</td>
<td>7%</td>
<td>54%</td>
<td>57%</td>
<td>0%</td>
<td>13%</td>
<td>−20%</td>
<td>21%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W2</td>
<td>298</td>
<td>0.9</td>
<td>28.0</td>
<td>1.10</td>
<td>260</td>
<td>6%</td>
<td>38%</td>
<td>43%</td>
<td>0%</td>
<td>13%</td>
<td>−6%</td>
<td>10%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W3</td>
<td>27</td>
<td>1.0</td>
<td>23.0</td>
<td>0.97</td>
<td>327</td>
<td>4%</td>
<td>9%</td>
<td>14%</td>
<td>0%</td>
<td>8%</td>
<td>5%</td>
<td>7%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Total 373 1.0 27.0 1.11 258 6% 38% 43% 0% 12% −7% 11%
widely used Pandolf equation\(^7\) for treadmill walking. Equation (7) predicts the metabolic rate \(M_{\text{pan}}\) in watts considering body weight \(W_b\), the load due to the weight of clothing and sensors \(L=2\) kg\(^{13}\), the grade of the treadmill \(G\) in %, and walking speed \(v_w\) in m/s, which was calculated by dividing the values given in km/h by 3.6.

\[
M_{\text{pan}}=1.5 \times W_b + 2 \times (W_b + L) \times (L/W_b)^2 + (W_b + L) \times (1.5 \times v_w^2 + 0.35v_w \times G) \quad (7)
\]

For each of the 11 series, based on calculations for each individual session, we determined intra-series means and CV as presented in Table 1. Mean \(M_{\text{VO2}}\) increased with workload from 210 W \((W1)\) over 260 W \((W2)\) to 327 W \((W3)\), whereas \(CV\) showed slightly decreasing values with 7\% \((W1)\), 6\% \((W2)\) and 4\% \((W3)\). A closer inspection revealed that \(CV\) significantly increased with \(Q_{10}\) (r=0.81, p=0.002). Though rectal temperature increase from rest \((\Delta T_{\text{re}})\) varied between 0.1−1.7°C (Fig. 1a), we observed similar averages of approximately 1°C in all series (Table 1), indicating prevailing steady-state conditions. Together with the overall \(Q_{10}\) of 1.11, this implies an average increase in \(M_{\text{VO2}}\) of about 1% due to \(\Delta T_{\text{re}}\) (1), contributing to 6% overall \(CV\), with \(CV\) values conforming to the accuracy level of 5% claimed by the standard\(^5\) for \(Q_{10} \approx 1\), i.e. if \(M\) were independent of \(\Delta T_{\text{re}}\).

We calculated the prediction error \(M_{\text{HR}}-M_{\text{VO2}}\) for all 373 experiments and computed intra-series mean error (bias) and root-mean-squared error (rmse) summary statistics presented in Table 1 as percentage values relative to mean \(M_{\text{VO2}}\). Metabolic rates calculated from heart rates considerably overestimated \(M_{\text{VO2}}\) (Table 1) with mean \%bias ranging from 54\% \((W1)\) over 38\% \((W2)\) to 9\% \((W3)\). Consequently, overall \%rmse amounted to 43\% (Table 1), which further increased to 64\% when replacing lean body mass \((LBM)\) by body weight \((W_b)\) in eq. (5), as suggested\(^8\) for the prevailing lean persons in our study. These figures were far above the accuracy level of 10−15% stipulated by
the standard\textsuperscript{5}) and guideline document\textsuperscript{8}).

The error was highly sensitive to $\Delta Tre$ as illustrated by Fig. 1a. However, the slopes exhibited a considerable inter-series variability, which mirrored the variation in thermal cardiac reactivity ($TCR$), i.e. the increase in heart rate ($\Delta HR=HR-HR_0$) due to core temperature rise ($\Delta Tre$) shown in Fig. 1b and summarized in Table 1. $TCR$ varied between 11.0−40.4 bpm/°C, whereas the overall average (27.0 bpm/°C) was close to the value of 33 bpm/°C reported in ISO standard 9886\textsuperscript{10}). The slopes of Fig. 1a significantly correlated with TCR ($r=0.96$, $p<0.001$), suggesting that the bias was largely attributable to the thermal component of heart rate ($\Delta HR_T$)\textsuperscript{5, 10}), also termed ‘thermal pulses’\textsuperscript{11, 12}), which were neglected by the proposed algorithms\textsuperscript{8}).

There are procedures to correct for $\Delta HR_T$, either using the correlation with core temperature, if those measurements were available\textsuperscript{11}), or by estimating $\Delta HR_T$ from HR recorded during resting periods intermitting the heat exposure\textsuperscript{10, 17–19}). The latter method is advantageous under field conditions, as it does not require any core temperature measurements. The basic idea is to calculate $\Delta HR_T$ as the difference of the HR recorded after at least five minutes break from work to $HR_0$, which could be measured before start of work or estimated by the 1st percentile of all measured HR\textsuperscript{5}). Linear interpolation approximates intermediate values of $\Delta HR_T$ over the working periods, which are then subtracted from recorded HR before estimating $M HR$\textsuperscript{17–19}).

As Tre was available in our study, we applied a bias correction to the $M HR$ estimates for each series using the individual regression functions from Fig. 1a. As shown in Table 1, this did not only remove the bias, but also reduced $\%rmse$ considerably to values between 9−15%, thus conforming to the requested accuracy level of 10−15%\textsuperscript{5, 8}).

Interestingly, in our study a comparable overall performance was observed for the simple estimates $M_{Pan}$ (Table 1) using the Pandolf equation\textsuperscript{7}) (7), which represents a Level 2 method\textsuperscript{5}) for this type of treadmill work in the laboratory.

A recent field study on forest workers\textsuperscript{18}) achieved a similar level of accuracy by estimating $\Delta HR_T$ from intermittent resting periods\textsuperscript{7}) and using individual M-to-HR relations calibrated with procedures deemed representative for forest work\textsuperscript{18}). This is important, as the M-to-HR relationship intra-individually depends on the type of work: for the same heart rate, work with great muscles (legs) shows a metabolic rate 23−30%\textsuperscript{8}) higher than activities involving smaller muscles (work with arms), and the difference may even increase for static muscular work. So the overestimation bias shown in Table 1 for $M HR$\textsuperscript{8}) may be actually higher in field situations frequently including work of small muscle groups and also static muscular work than for our comparison with walking subjects predominantly concerning leg muscles.

This validation study followed the concept of expressing accuracy levels as $CV$\textsuperscript{5, 8}), but supplemented this by calculating bias in combination with rmse, as these quantities provide more appropriate error figures in case of non-zero bias. Adhering to this concept, we could largely confirm the accuracy level of 5% for $M_{T02}$ as stipulated by the standard\textsuperscript{5}), although the influence of body temperature on $VO_2$ was smaller ($Q_{10}=1.11$) compared to recent studies\textsuperscript{9}) with semi-nude subjects showing $Q_{10}=2$.

However, we observed large overestimation by the $M HR$ algorithm due to thermal cardiac reactivity inflating the overall error up to 43% on average and above 60% for single series. After bias correction at the individual level, the error conformed to the accuracy level of 10−15% found in the recent simulation study assuming zero bias\textsuperscript{8}).

Our results reinforce recent findings\textsuperscript{11, 16–19}) on two essential requirements for the application of $M HR$ estimation algorithms to work scenarios. First, individual HR-to-M-relationships derived from controlled cardiac stress tests are desirable, that should reflect the actual workload and type of work under consideration\textsuperscript{5, 11, 18}). Secondly, a correction for the thermal heart rate component is necessary, especially under heat stress conditions. Thus a bias correction, e.g. by introducing intermittent resting periods of sufficient length of at least five minutes\textsuperscript{10, 17–19}) should become mandatory for Level 3 studies in ISO 8996\textsuperscript{5}) and PHS\textsuperscript{4}). Otherwise, the accuracy of Level 3 studies might fall behind simpler Level 2 methods, as indicated by the smaller error for $M_{Pan}$ in our study.

Finally, we like to add that measurement repetition is one method to reach a requested level of accuracy. Based on the $CV$ of an unbiased estimate, the formula (actual accuracy level/requested accuracy level)$^2$ approximates the required number of repetitions. This implies that two measurements would be necessary to achieve the 10% accuracy level with a method actually providing 14%, while four repetitions would be needed with 20% accuracy, and even 9 with 30%, making such a method inefficient for field applications.

References

Determination and interpretation of cold stress when using required clothing insulation (IREQ) and local cooling effects. International Organisation for Standardisation, Geneva.


