Heat stress assessment in severe hot work environments: integration of recovery time into the PHS index calculator.

Alice Caporale*, Cristina Mora*, Valentina Ventura*, Riccardo Siena*, Emilio Ferrari*

* *Industrial Engineering Department, University of Bologna, Viale del Risorgimento 2 Bologna, Italy*, *alice.caporale2@unibo.it*, *cristina.mora@unibo.it*, *valentina.ventura7@unibo.it*, *riccardo.siena2@unibo.it*, *emilio.ferrari@unibo.it*

Abstract: This paper presents an updated version of the Predicted Heat Strain (PHS) calculator based on UNI EN ISO 7933: 2023. The structural modification required a comprehensive revision of parameters, entailing the utilization of Java and Visual Studio for code alterations, followed by an exhaustive testing phase. Based on the input values, the redesigned version includes the calculation of Recovery Time (RT) expressed in minutes per hour, a facet absent in the antecedent version. Furthermore, the updated calculator streamlines the determination of acclimatization levels for individuals exposed to environmental conditions by proposing two user-friendly drop-down menus. Additionally, it incorporates an atmospheric pressure calculation contingent on altitude. The redesigned interface also facilitates the input of metabolic energy production and static clothing thermal insulation through a curated list of options, according to UNI EN ISO 8996:2022 and EN ISO 9920:2009 standards. Aside from streamlining the input of complex parameters, the redesign of the PHS calculator represents the pioneering tool for computing the duration of breaks required to safeguard workers exposed to hot environments.

Keywords: Hot environments, Recovery Time, Occupational health and safety

1. Introduction

Nowadays, in many industrial sectors, workers are exposed to hot environments, such as outdoor work in the agricultural, building, and road construction sectors or numerous processes in the ceramic and metalworking industries (Aliabadi et al., 2018). While substantial knowledge about moderate environments is supported by standard UNI EN ISO 7730 (2006), severe environments have received much less attention regarding research and legislation. Exposure to intense heat affects the thermoregulatory system of individuals with negative effects on health, whether direct (e.g., heat stroke, dehydration, cramps, fainting) or indirect, aggravating pre-existing cardiovascular diseases (Yi and Chan, 2017).

In the 1980s, Vogt (1981) proposes the evaluation of heat stress through the required sweat rate (Swreq). This index, based on calculating the evaporative thermal power through the heat balance equation, was adopted by ISO 7933 (1989). However, this standard has been criticized due to a too complex acquisition of parameters such as predicting skin temperature, the impact of clothing on thermal exchanges, the combined influence of clothing and movement, and determining maximum exposure durations.

To address these limitations, the European Union has initiated a research project intending to design and validate a strategy to evaluate heat stress by defining the maximum duration of exposure, improving the prediction of heat exchanges, and predicting skin temperature (Malchaire et al., 2001). This new model, Predicted Heat Strain (PHS), replaced the Swreq in the ISO 7933 (2023).

1.1 Predicted Heat Strain (PHS)

The PHS is a complex analytical model. The iterative calculation procedure allows the human body's physiological response to heat stress to be followed over time, returning as results the temporal trends of the rectal temperature and the total loss of water.

The PHS model is based on the principle that heat stress is more intense the greater the energy gain (i.e., the increase in energy inside the body). Since the 2000s, software developed by the engineering department of Lund University for calculating PHS based on standard UNI EN ISO 7933 has been available online at https://www.eat.lth.se/fileadmin/eat/Termisk_miljoe/PHS/PHS.html. This tool necessitates inputting four environmental factors (i.e., ambient air temperature, mean radiant temperature, relative humidity, and air velocity) and seven individual parameters (i.e., height, weight, metabolic rate, posture, clothing insulation, hydration possibility, and acclimatization).

Data relating to mechanical work, static moisture permeability, fraction of the body covered by reflective clothing, emissivity of reflective clothing, walking speed, and wind direction are also required but not mandatory. Based on the inputs provided, the PHS calculator evaluates the maximum exposure duration by returning four values related to exposure time:

1. Maximum exposure time (minutes).
2. Maximum exposure time (minutes) to maintain the rectal temperature below 38°C.
3. Maximum exposure time (minutes) ensures the quantity of liquid lost is lower than the maximum for 50% of the working population.
4. Maximum exposure time (minutes) to ensure the quantity of liquid lost is lower than the maximum possible for 95% of the working population (more protective limit).

To date, the PHS calculator represents a computational tool used in occupational health and safety to assess the risk of illness and injury in workers exposed to hot environments. However, once the exposure limit time has been estimated, the PHS index does not indicate the Recovery Time (RT) necessary for workers to restore their thermoregulatory system.

The study by Morris and Kjellstrom (2020) alone suggests a minimum break of 1.5 minutes per half an hour to reduce risk in severely hot environments without adjusting this strategy for different environmental conditions or individual operator differences. Since the literature does not provide a methodology to calculate the break durations within hot environments, this paper provides a method to estimate them.

At the same time, the actual version of the PHS calculator is challenging, even for occupational health, safety, and prevention professionals, due to the absence of practical instructions for determining input values, particularly for complex factors such as metabolic rate. The following sections delve into the new version of the PHS index calculator, which simplifies data entry and implements the function dedicated to calculating recovery time. The new version of the PHS index calculator will be available in the Microclimate section of the Banca delle Soluzioni website (https://www.bancadellesoluzioni.org/it/sezione/9/microclima). This paper aims to facilitate risk assessment in severe hot environments by establishing guidelines for safe working conditions, including adequate rest-work programs.

2. Materials and methods

The actual version of the PHS calculator that has been available online since the 2000s was created by Lund University. Figure 1 displays the software's user interface, where it is possible to enter the necessary input data and obtain the values of the main risk descriptors relative to severe cold environments.

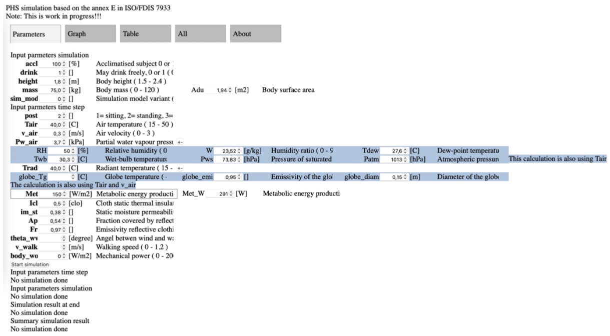

Figure 1: Interface of PHS calculator by Lund University

Many of the required inputs are difficult to estimate and Figure 1 shows the lack of RT between the calculator outputs.

2.1 Recovery time (RT)

The implementation of the RT function within the calculator was based on analyzing the equation in the Insulation Required (IREQ) index for risk analysis in severe cold environments according to UNI EN ISO 11079.

Equation 1 describes the RT calculation in cold environments.

$$RT = \frac{Qlim}{S} \quad [h] \tag{1}$$

Q_{lim}=144Kj=-40 Wh/m² is the maximum tolerable energy loss, while S represents the total heat accumulation.

The implementation of RT in hot environments is based on the maximum tolerable energy increment (Q_{max}) outlined in the standard UNI EN ISO 7933:1989, where the value of Q_{max} is divided for acclimatized and non-acclimatized individuals and individuals in alarm or danger conditions. Meanwhile, S could be transformed in Ereq as it represents the thermal power that requires dissipation.

Therefore, Equation 2 shows the RT calculation for severe hot environments:

$$RT_{ambienti\ caldi} = \frac{Q_{max}}{E_{req}} \text{ [h]} \tag{2}$$

Where:

- Q_{max}=50 Wh/m² for acclimatized subjects and not in alarm conditions;
- Q_{max}=60 Wh/m² for acclimatized subjects and in danger conditions;
- E_{req}=M-W-C_{res}-E_{res}-C-R-dS [W/m²] is the required evaporation rate to maintain heat balance. Then, M is the metabolic heat

production (W/m^2), W is the external work performed (W/m^2), C_{res} is the convective heat loss through respiration (W/m^2), E_{res} is the evaporative heat loss through respiration (W/m^2), C is the convective heat exchange with the environment (W/m^2), R is the radiative heat exchange with the environment (W/m^2), and dS is the change in heat storage in the body (W/m^2)

This formulation's refinement arises from converting the diminishing function to an escalating one. Notably, unlike cold environments where RT diminishes with decreasing air temperature, in hot environments, the recovery time escalates with rising air temperature due to heightened risk factors for the worker.

Therefore, the calculation of RT will be carried out with equation 3:

$$RT_{ambienti\ caldi} = \frac{E_{req}}{Q_{max}} \text{[min/h]} \tag{3}$$

Where:

- Q takes the same values as in equation 2;
- E_{req}= (M-W-C_{res}-E_{res}-C-R-dS)*1min [$Wmin/m^2$] as the temperatures calculated within it progress minute by minute.

2.2 Simplification of input parameters

In addition to implementing the RT function, this contribution aims to simplify user selection of input parameters to facilitate risk assessment in hot environments by employers.

The first simplified parameter concerns the acclimatization of workers. UNI EN 7933 (2023) establishes a period of at least 7 days for light activity or 7 to 14 days for heavy work activity to consider exposed individuals as acclimatized.

Therefore, the updated version of the calculator includes two multiple-choice questions. First, choosing the type of activity between light and heavy, and second, whether the worker has been exposed to these conditions for at least 7 or 14 days, as depicted in Figures 2 and 3.

Figure 2: Implementation of acclimatization selection for light activity.

Figure 3: Implementation of acclimatization selection for heavy activity.

This selection affects the difference in heat storage based on metabolism, which for an acclimatized subject is expressed by Equation 4, according to UNI EN ISO 7933 (2023).

$$t_{cr,eq} = 0{,}0036 * (M - 55) + 36{,}8 \, [°C] \tag{4}$$

The standard does not provide a specific function for non-acclimatized subjects, and the current calculator version sets this parameter to zero. However, the study by Périard et al. (2015) indicates that non-acclimatized subjects accumulate 20% less heat than acclimatized individuals.

This apparent paradox arises because non-acclimatized individuals reach heat strain thresholds more rapidly, triggering earlier physiological and behavioral responses to restrict further heat accumulation. Their reduced heat tolerance prompts quicker cessation of activity or enhanced heat dissipation strategies. This results in diminished overall heat accumulation compared to acclimatized counterparts who can endure and sustain performance under greater heat loads for extended durations.

Then, the importance of risk was considered by distinguishing between "alert conditions," in which the subjects' physical condition is suitable for performing the activity, and "hazardous conditions," in which the worker's physical condition is unsuitable. A drop-down menu was implemented to simplify the selection of this parameter, as highlighted in Figure 4.

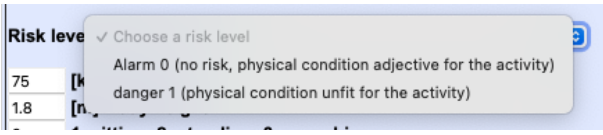

Figure 4: Selection of the worker's physical condition within the PHS updated software.

Indeed, in the definition of RT, the standard states that a subject in "dangerous condition" corresponds to a maximum heat accumulation of 60Wh/m2, while for a subject in "alarm condition," the maximum heat accumulation results in 50 Wh/m2.

After that, the key personal and environmental parameters should be entered. The new calculator suggests their applicability ranges as shown in Figure 5.

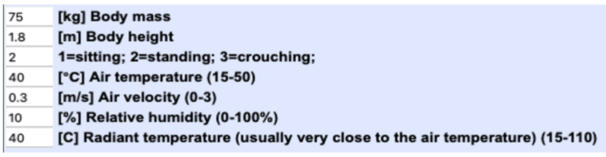

Figure 5: Calculator inputs related to individual and environmental parameters.

Finally, two drop-down menus were made for metabolic rate and clothing insulation to simplify the choice of values in compliance with UNI EN ISO 8996 (2021) and 9920 (2009).

In light of these changes, the new version of the calculator now looks as shown in Figure 6.

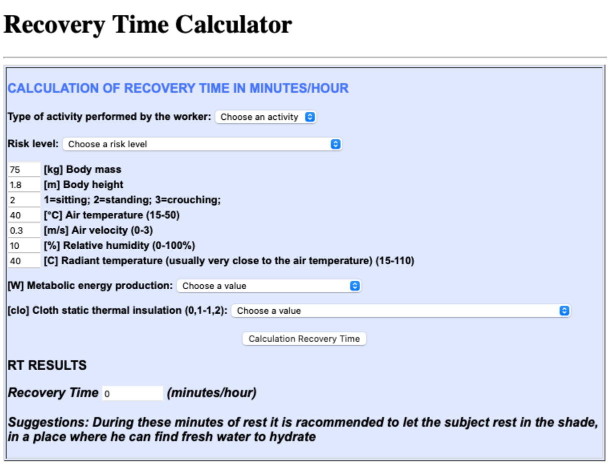

Figure 6: Recovery Time calculator interface.

3. Validation of the RT calculator

The calculator validation was carried out using a test sample included within the UNI EN ISO 7933 (2023) standard, as depicted in Figure 7.

Parameters (units)	Examples of working conditions				
	1	2	3	4	5
Acclimatization	Yes	No	No	No	Yes
Posture	Standing	Standing	Standing	Standing	Sitting
Duration	480	480	480	480	480
T_a (°C)	40	35	30	30	35
T_g (°C)	40	35	45	30	50
V_a (ms^{-1})	0,30	0,10	0,10	1,00	1,00
RH (%)	35	60	35	45	30
M (W)	300	300	300	450	250
W (W)	0	0	0	0	0
I_{cl} (clo)	0,5	0,5	0,8	0,5	1,0
T_r (°C)	40,0	35,0	52,0	30,0	74,6
P_a (kPa)	2,58	3,37	1,48	1,91	1,69
A_p (fraction %)	–	–	30	–	20
F_r (–)	–	–	0,85	–	0,85
Final S_{Wp} (g/h)	813	633	764	547	718
Water loss (g)	6 538	6 345	6 419	4 593	5 813
Final T_{cr} (°C)	37,6	40,8	38,7	38,0	37,5
$D_{limloss}$ (min)	280	250	280	400	310
D_{limTcr} (min)	–	62	149	–	–

Figure 7: Data sample for the PHS calculator test in compliance with UNI EN ISO 7933:2023.

The atmospheric conditions that were present during the winter period did not allow the validation due to the following limits of applicability of the PHS index:

- Air temperature between 15-50°C;
- Air velocity between 0 and 3 m/s;
- Radiant temperature between 15 and 110°C.

The sample of examined values was tested for male and female subjects of the 5th,50th, and 95th percentiles whose weights and heights were derived from Cassola et al., 2011 statistical analysis for the Caucasian population.

Tables 1 and 2 show the calculated RT for female and male operators in cases 1, 2 and 5 of Figure 7, respectively. In both Tables, "Acc" stands for acclimatized subjects, while "Not" stands for non-acclimatized subjects.

Table 1: Validation of the calculator through the UNI EN ISO 7933:2023 test values for female operators.

Case1		Case 2		Case5	
Acc	Not	Acc	Not	Acc	Not
5° Percentile Height: 152,6 Weight: 46,6					
3,404	3,851	3,453	3,901	2,26	2,868
50° Percentile Height: 162,8 Weight: 59,6					
2,134	2,835	3,227	3,72	1,792	2,494
95° Percentile Height: 174,1 Weight: 74,5					
1,645	2,445	3,018	3,553	1,304	2,103

Table 2: Validation of the calculator through the UNI EN ISO 7933:2023 test values for male operators.

Case1		Case 2		Case5	
Acc	Not	Acc	Not	Acc	Not
5° Percentile Height: 163,8 Weight: 57,4					
2,2	2,89	3,287	3,768	1,861	2,549
50° Percentile Height: 174,7 Weight: 71					
1,739	2,52	3,087	3,608	1,398	2,179
95° Percentile Height: 185,6 Weight: 91,6					
1,141	2,041	2,817	3,392	0,8	1,7

Looking at Tables 1 and 2, as body mass and height rise, recovery time value decreases due to increased exertion resistance. Furthermore, the analysis of the different RTs between cases 1 and 5 shows that the airspeed parameter greatly influences the calculation of RT.

Although the radiant temperature in case 5 is 10°C higher than in case 1, the RT is about one minute lower for all female subjects and half a minute lower for all male subjects analyzed, acclimatized, and non-acclimatized due to a higher air velocity. Case 2, on the other hand, highlights the impact of relative humidity on the RT calculation. Although case 2 considers a lower air and radiant temperature, for all workers analyzed, the RT is higher than case 5 due to a large increase in relative humidity and a dramatic decrease in wind speed.

The absence of a previous tool for evaluating TRs does not allow a direct comparison of results to check their reliability. However, such a calculator was designed based on the current regulations, and the test results are consistent with the expected outcomes.

Therefore, the RT calculator was applied to a case study assessing the heat stress of agricultural workers engaged in strawberry and eggplant harvesting activities inside greenhouses during the summer period (Diano et al., 2015).

The available parameters in this contribution include:

- the energy metabolism of workers is estimated at 170.0 W/m²;
- the thermal insulation of clothing at 0.6clo is equivalent to panties, socks, long-sleeved cotton T-shirts, long cotton pants, and work shoes.

Values of environmental parameters, measured in May 2015, have been replaced with environmental data from the visual crossing web portal (https://www.visualcrossing.com/weather-history) for a typical day in August 2023. Table 3 shows the hourly values converted to be used by the RT calculator.

Table 3: Hourly evolution of microclimate parameters on an August day in 2023.

Time	Ta [°C]	Tr [°C]	HR %	Va[m/s]
7:00	20	20	82,8	2,1
8:00	22	22	73,3	2,6
9:00	24	24	69,1	1,5
10:00	26	26	65,3	2,1
11:00	28,5	28,5	58	1,5
12:00	30	30	48,6	1,5
13:00	31	31	43	0,5
14:00	32	32	40,7	1
15:00	33	33	40,7	2,1

The TR calculation depicted in Table 4 was performed considering a male subject belonging to the Caucasian 50th percentile (Cassola et al., 2011) considering:

- weight 75kg;
- height 1.80m.

Table 4: RT calculation during the working day.

Time	RT [min/h]	
	Acclimatized	**Non-Acclimatized**
7:00	2,10	2,42
8:00	2,11	2,43
9:00	2,12	2,44
10:00	2,14	2,45
11:00	2,15	2,46
12:00	2,14	2,46
13:00	2,14	2,45
14:00	2,14	2,45
15:00	2,15	2,46

The results highlighted that, on average, non-acclimatized subjects need half a minute of additional rest per hour under the same environmental conditions and individual parameters.

4. Results and discussion

In both analyzed cases, the RT values obtained were compared with the recommendation from Morris and Kjellstrom's (2020) study of 1.5 minutes of rest for every half hour of work. In most cases, the recovery times suggested by the calculator were less than 3 minutes per hour. These results, however, are heavily influenced by the operators' personal factors. Both case studies emphasize the critical role of individual parameters in determining RT.

When considering the RTs of each subject individually, they do not vary over the course of the workday. In contrast, comparing operators by gender or percentile results in RT values with variations of up to 2 minutes per hour. This underscores the importance of adjusting work/rest schedules and modifying work practices to accommodate individual physiological needs for heat stress recovery. During recovery periods, workers should rest in shaded, cool areas and have access to water for hydration.

The analysis is limited by the presence of only one comparison element. Therefore, further literature review and field studies are planned to determine accurate recovery times based on personal parameters and physiological differences.

Moreover, the new PHS calculator remains a complex tool that requires precise input parameters for accurate results. Users are advised to seek expert guidance when determining these parameters, particularly clothing insulation, metabolic rates, and environmental conditions. Interpretations of calculator outputs should consider the specific context and limitations of the model. Addressing these aspects through comprehensive training, leadership buy-in, and continuous improvement of the RT calculator will enhance its practical utility and effectiveness in preventing heat-related illnesses in diverse work environments.

5. Conclusions

Implementing the recovery time (RT) calculator marks a significant advancement in preventing heat exposure illnesses in severe hot environments. This tool enables precise RT assessments by considering environmental and personal variables, assisting employers in risk analysis and reducing heat-related illnesses. The comparison of RT calculator results with literature values often shows lower RT estimates, which can enhance productivity and motivate employers to adopt the tool. However, resistance may arise due to insufficient training, lack of understanding, and concerns over resource allocation and system integration. Overcoming these challenges through comprehensive training and strong leadership support is essential for successful implementation.

Future improvements could enhance the RT calculator's accuracy by refining the energy metabolism parameter. Instead of a fixed input, future versions could use UNI EN ISO 7933:2023 formulas, incorporating age and gender factors for individualized recovery time estimates. This would ensure more effective prevention of heat-related illnesses by providing tailored rest periods for each worker.

Given the increasing frequency and severity of heatwaves due to climate change, enhanced RT calculators are critical for managing risks in hotter work environments. Employers can better protect workers from extreme heat by offering more precise and responsive guidelines. Future enhancements might also integrate real-time data from wearable devices monitoring physiological parameters like body temperature and heart rate, allowing for dynamic RT adjustments based on real-time conditions.

Lastly, integrating the latest research findings into educational and training programs will keep employees and supervisors well-informed about heat stress risks and mitigation strategies, ensuring effective implementation and adherence to safety practices. Future enhancements can bolster awareness campaigns, highlighting the importance of personalized recovery times and the benefits of using advanced tools like the RT calculator.

Aknowledgments

The authors sincerely thank Amelia Garreffa for her valuable contribution to this research.

References

Aliabadi, M., Farhadian, M., Jalali, M., Jahangiri, M., Negahban, A.R. (2018). A new empirical approach for predicting heat strain in workers exposed to hot indoor environments. *Indoor Built Environ.* 27, 597–605.

Cassola, V.F., Milian, F.M., Kramer, R., De Oliveira Lira, C.A.B., Khoury, H.J. (2011). Standing adult human phantoms based on 10th, 50th and 90th mass and height percentiles of male and female Caucasian populations. *Phys. Med. Biol.* 56, 3749–3772.

Diano, M., Valentini, M., Di Gesu, I., Samele, P. (2015). Lo stress termico dei lavoratori impegnati nelle lavorazioni in serra: studio della variabilità del rischio in funzione delle condizioni di lavoro.

EN ISO 9920:2009 - Ergonomics of the thermal environment - Estimation of thermal insulation and water vapour resistance of a clothing ensemble.

Malchaire, J., Piette, A., Kampmann, B., Mehnert, P., Gebhardt, H., Havenith, G., Den Hartog, E., Holmer, I., Parsons, K., Alfano, G., Griefahn, B. (2001). Development and validation of the predicted heat strain model. *Ann. Occup. Hyg.* 45, 123–135.

Morris, N.B., Kjellstrom, T. (2020). Sintesi sulle soluzioni per mitigare lo stress da calore tra i lavoratori del settore agricolo e del settore delle costruzioni 1–7.

Périard, J.D., Racinais, S., Sawka, M.N. (2015). Adaptations and mechanisms of human heat acclimation: Applications for competitive athletes and sports. *Scand. J. Med. Sci. Sport.* 25, 20–38.

UNI EN ISO 11079:2008 - Ergonomics of thermal environments - Determination and interpretation of cold thermal stress using the thermal insulation of clothing required (IREQ) and local cooling effects

UNI EN ISO 7730:2006 - Ergonomics of thermal environments - Analytical determination and interpretation of thermal comfort through the calculation of PMV and PPD indices and local thermal comfort criteria.

UNI EN ISO 7933:1989 - Hot environments - Analytical determination and interpretation of thermal stress using calculation of required sweat rate.

UNI EN ISO 7933:2023 - Ergonomics of the thermal environment - Analytical determination and interpretation of heat stress using calculation of the predicted heat strain.

UNI EN ISO 8996:2022 - Ergonomics of the thermal environment - determination of metabolic rate.

UNI EN ISO 9920 - Ergonomics of the thermal environment - Evaluation of thermal insulation and evaporative resistance of clothing.

Vogt, J. J., Candas, V., Libert, J. P. and Daull, F. (1981) Required sweat rate as an index of thermal stress in industry. *In Bioengineering, Thermal Physiology and Comfort*, eds K. Cena and J. A. Clark, pp. 99±110. Elsevier, Amsterdam.

Yi, W., Chan, A.P.C. (2017). Effects of heat stress on construction labor productivity in Hong Kong: A case study of rebar workers. *Int. J. Environ. Res. Public Health* 14.