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Thermal Environment Evaluation According to Indices in Industrial Workplaces

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Abstract

Average person spends about one third of day at work. During working hours in industrial workplaces, workers can be exposed to possible heat and cold risks. A significant thermo-hygric microclimate in such workplaces is created by technological equipment. Thermo-hygric microclimate evaluation in workplaces is therefore very important and obtained results should lead to reduction of thermal loads on workers. The need of quick thermal environment assessment based on a few measurements and calculations has led into application of indices in thermal comfort assessment. The most used empirical index for assessment of hot stress potential is WBGT index (wet bulb globe temperature). WBGT index is the most used and accepted index for the assessment of heat stress in industry. This paper deals with monitoring of a workplace with hot microclimate where workers were exposed to stress from heat. The measurement, result processing and interpretation were carried out according to the EN 27243 and ISO 7730.

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Key words: wet bulb globe temperature (WBGT) index; thermo-humidity microclimate; working environment; stress

1. Introduction

There are several thermal comfort indices for evaluation of different thermal environments [1]. Reliable assessment of thermal microclimate should take into consideration all six primary factors affecting thermal comfort: air temperature, radiation, relative humidity, air velocity, thermo-physical properties of clothing and metabolic rate.

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2. View of indices for assessing of different thermal environments

One way of how to evaluate thermal environment is to use thermal comfort indices, which combines two or more parameters of thermal microclimate into one variable. Indices can be divided into [2]:

- **Analytical indices** - based on theoretical concepts,
- **Empirical indices** - based on object measurements or on simplified relationships that do not necessarily follow a theory.

Indicators can be also divided according to class into which the thermal environment is addressed to: moderate, hot and cold environment, Fig.1.

Fig. 1. Indices for assessing of different thermal environments [4].

ISO organization has created a number of important standards which are dealing with categories used by thermal environment indices:

- IREQ – refers to minimum clothing insulation required by workers. The index is used for calculation of clothing ensemble and was applied as an initial attempt at providing thermal comfort. This index represents a method to calculate the thermal stress associated with the exposure to cold environments.

- WCI - Wind Chill Index is the equivalent to perceived temperature that measures the additional loss of thermal comfort of the human body due to the wind (especially) in winter outdoor conditions.

- PMV - Predicted Mean Vote Index. The index predicts the mean response of a larger group of people according to the ASHRAE thermal sensation scale where: +3 hot, +2 warm, +1 slightly warm, 0 neutral, -1 slightly cool, -2 cool, -3 cold (Fig. 2). The PMV index was expressed by P.O. Fanger as:

$$\mathrm{PMV} = (0.303\mathrm{e}^{-0{,}036\mathrm{M}} + 0.028)\,\mathrm{L} \tag{1}$$

where:

M - metabolic rate,

L - thermal load - defined as the difference between the internal heat production and the heat loss to the actual environment - for a person at comfort skin temperature and evaporative heat loss by sweating at the actual activity level.

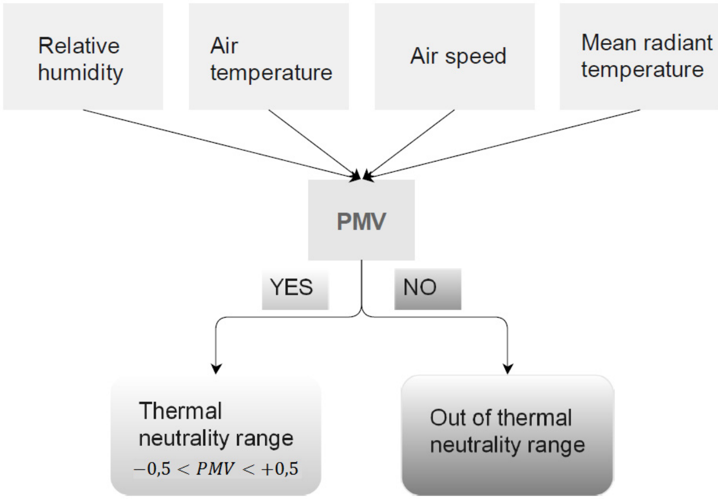

Fig. 2. Assessment of the Predicted Mean Vote.

- PPD index (Predicted Percentage Dissatisfied) is a quantitative measure of the thermal comfort of a group of people at a particular thermal environment. At least approx. 5% of people in a group will be dissatisfied with the thermal climate - even with PMV = 0, see Fig. 3.
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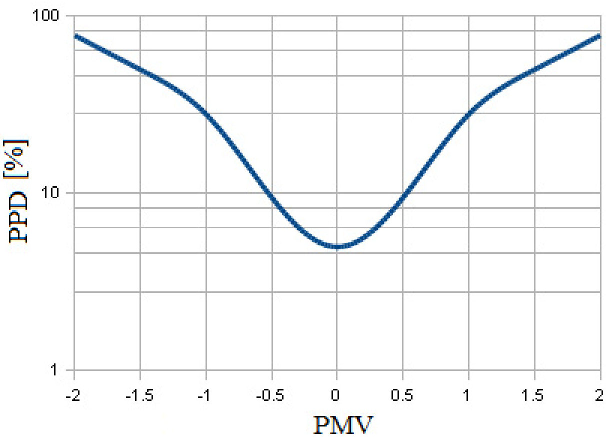

Fig. 3. Evolution of PPD on the basis of PMV.

- The Wet Bulb Globe Temperature (WBGT) is a composite temperature used to estimate the effect of temperature, humidity and solar radiation on humans. The three elements Tw, Tg, and Ta are combined into a weighted average to produce the WBGT. The temperatures may be in either Celsius or Fahrenheit.

$$\mathrm{WBGT} = (0.7 \times \mathrm{Tw}) + (0.2 \times \mathrm{Tg}) + (0.1 \times \mathrm{Ta}) \tag{2}$$

Indoors, or when solar radiation is negligible, the following formula is used:

$$\mathrm{WBGT} = (0.7 \times \mathrm{Tw}) + (0.3 \times \mathrm{Tg}) \tag{3}$$

- PHS (Predicted Heat Strain) index is a rational index, based on the thermal balance equation which uses measured environmental parameters in a series of equations to predict the body response to the heat stress as a raise in core temperature.

3. Practical measurement of thermal microclimate

Monitoring of thermo-hygric microclimate was carried out using the Testo 400, to which tri-functional probe was attached, three-level globe Vernon-Jokl thermometer, and WBGT set. Used equipment meets ISO 7726 requirements for accuracy. Based on the movement of workers during their work shift, two measuring points were selected. These most frequent places were then monitored for 6 hours. Along with measuring points, activities of workers were also analyzed and later served in overall evaluation of the measurement. Because there are two major sources of radiant heat in operation, variable air speed and people moving freely, environment was evaluated as a heterogeneous and non-stationary. Therefore it was necessary to perform measurements at three levels: head (1,7 m), abdomen (1,1 m), ankles (0,1 m). Results obtained from two measurement points were put into table and basic statistic was implied in calculation.

Outside climatic situation of workplace is also a part of the monitoring of thermo-hygric microclimate. During the measurement there was a sunny day and the outdoor air temperature was between 29 and 34 [°C]. Relative humidity was about 40 [%] and air velocity was about 6 [m.s^{-1}].

3.1. Experimental measurements of thermal-moisture microclimate

Three basic physical quantities of thermo-hygic microclimate were measured - R_h relative humidity [%], the dry air temperature t_a [° C] and air velocity v_a [m.s^{-1}] with measuring device Testo 400. Measurements took place in 2 measuring locations M1 and M2 during 6 hours. Measured values of thermo-hygric microclimate were processed in MS Excel. Basic statistical functions such as: min (the lowest value of the set of values), max (maximum value of the set of value|, average (arithmetic mean arguments), stdev (standard deviation), median (middle value of a group of numbers), var (variance values), mode (most frequently occurring value in a group of numbers) were used.

Measured values of dry air temperature, air velocity and relative humidity at both measuring points and at all three levels were statistically processed in MS Excel program. Graphical processing of data obtained by measuring of Testo 400 is shown on the Figure 4 and 5. On the horizontal axis measuring time is shown while on vertical axis are values of dry air temperature, air flow velocity and the relative humidity.

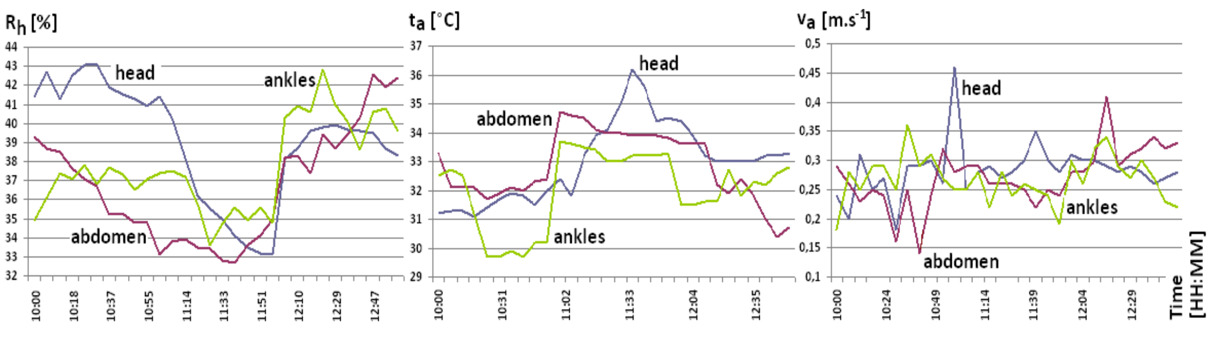

Fig. 4. Development of the dry air temperature, air velocity and relative humidity on place M1.

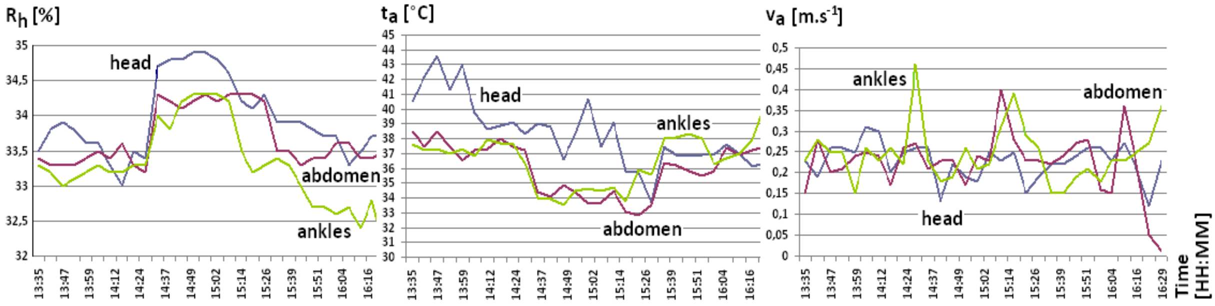

Fig. 5. Development of the dry air temperature, air velocity and relative humidity on M2.

3.2. Globe temperature

Temperature measurement obtained by globe thermometer was conducted in order to determine the approximate amount of mean temperature radiation $t_{r,\ m}$ [°C] by using the three level Vernon-Jokl thermometer. Black ball thermometer is used to derive the approximate value of mean temperature radiation from the observed simultaneous temperatures readings of globe temperature (t_g) [°C], air temperature and air velocity surrounding the sphere [3]. Measurements done with this device were conducted at 2 measuring locations during working shift. The values of global temperature, measured by Vernon-Jokl were statistically processed. Graphical processing of data obtained by measuring of global temperature can be seen in Figure 6. On the horizontal axis measuring time is shown while on vertical axis the final temperature of the globe temperature is shown.

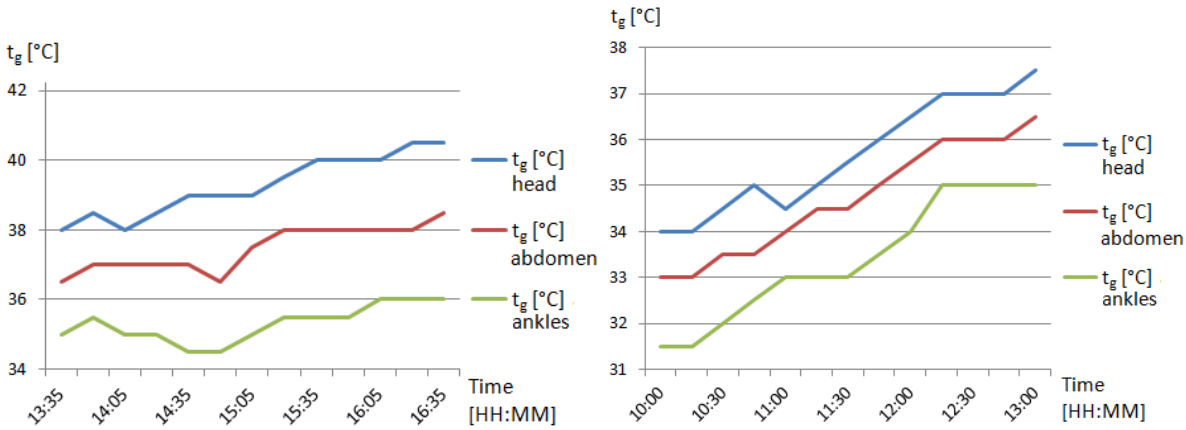

Fig. 6. Development of the globe temperature on workplaces M1 and M2.

3.3. WBGT sensor

The values of WBGT index were obtained by device with WBGT sensor. Measurement was conducted on two measuring places (M1, M2) during 6 hour work shift. During the whole measurement there was 30 minute time used for setting the sensor. Variables such as: black globe temperature t_r [°C], wet bulb temperature t_w [°C] and dry bulb temperature t_a [°C] were measured by this device. Measured values from WBGT sensor were statistically and graphically processed in MS Excel (see Fig. 7 and 8). On the horizontal axis measuring time is shown while on vertical axis is temperature in [°C].

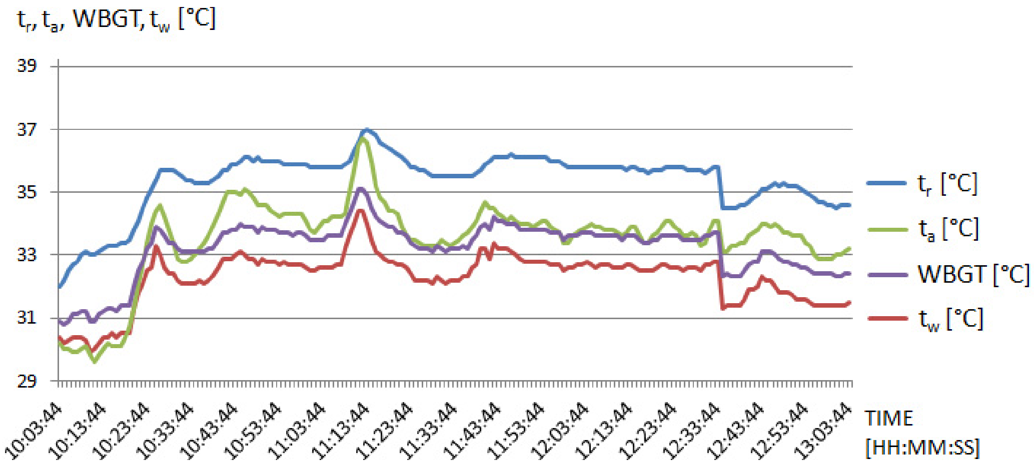

Fig. 7. Development of values measured by WBGT sensor on M1.

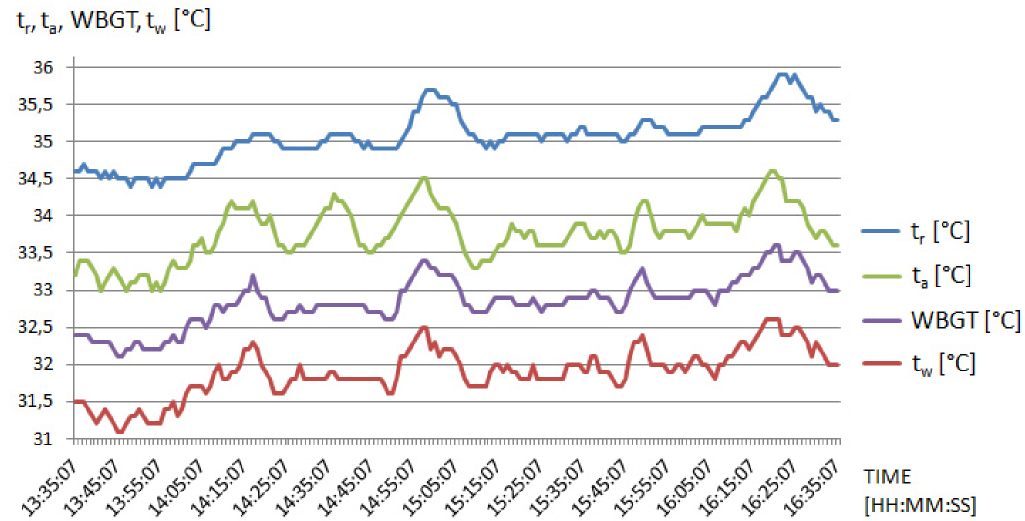

Fig. 8. Development of values measured by WBGT sensor on M2.

4. Processing of evaluation

Evaluation was done by calculating the mean radiant temperature, the PMV index, the determination of metabolic rate and thermal insulation of workers´ clothing.

4.1. Determination of the mean radiant temperature

Mean radiant temperature $t_{r,mi}$ was determined by calculation of the mean radiant temperature measured of black ball for both measured points (Table 1), taking into account that evaluated workplace is a class Stress environment (see equation no. 4) [5]:

$$t_{rmij} = \frac{t_{r,mi,j} + 2 \cdot t_{r,mi,j} + t_{r,mi,j}}{4} [°C] \tag{4}$$

where: $t_{rm\,i,j}$ [°C] – mean radiant temperature,
i = horizontal measurement places ,
j = vertical level (0.1m; 1.1m; 1.7 m).

Mean radiant temperature ($t_{r,mi,j}$) for certain levels for measurement places were calculated from equation (5):

$$t_{r,m\,i,j} = \left[\left(t_{g\,i,j} + 273 \right)^4 + . \frac{1{,}1.10^8 . v_{ai,j}^{0,6}}{\varepsilon_g . D^{0,4}} . \left(t_{g\,i,j} - t_{a\,i,j} \right) \right]^{1/4} - 273 \;[°C] \tag{5}$$

where: $t_{gi,j}$ [°C] – mean value of black ball temperature for given levels of measurement,
$v_{ai,j}$ [m.s^{-1}] – speed of airflow for given levels of measurement,
ε_g [-] – black ball emissivity, ε_g = 0,95 (matte black surface),
D [m] – ball diameter.

Table 1. The mean radiant temperature values for M1 and M2.

WORKPLACE M1				WORKPLACE M2			
$t_{rm1,1}$	$t_{r,m1.2}$	$t_{r,m1.3}$	$t_{r,m1}$	$t_{r,m2.1}$	$t_{rm2.2}$	$t_{r,m2.3}$	$t_{r,m2}$
37,88	36,80	34,90	36,60	44,40	41,09	37,77	41,09

4.2. Computer program for calculating predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD)

PMV can be used to verify if the thermal environment satisfy thermal comfort criteria. PMV is calculated from temperature, mean radiant temperature, air velocity, humidity, energy expenditure and the thermal resistance of clothing [6,11].

Program syntax for PMV and PPD can be found in ISO 7730. Program was rewritten in Java programming language. Thermal clothing insulation and metabolic rate was needed for the calculation.

Thermal clothing insulation (I_{cl}) was calculated according to the different types of clothes stated in ISO 7730.
The resulting thermal clothing insulation of workers is 0.39 clo.

Based on observations of work activities and movement of workers respectively energy expenditure was obtained from the classification table, which is included in the standard EN 27243. According to mean energy expenditure from classification table environment is stated as work class 2. For this class of work is determined by the size of energy expenditure [3]:

- q_M [Wm^{-2}] - per body surface area ($130 < q_M \leq 200$), pertinently,
- M [W] - the average body surface area ($234 < M \leq 360$).

Metabolic expenditure was set at 140 [W/m^2] which represents 2,41 [Met]. In general, the hot environment is defined as PMV > +2.0 (see ASHRAE thermal sensation scale – chapter 2).

Calculation of PMV for both measuring points was done by the computer program for calculating PMV and PPD

(Fig. 9). The results obtained from the calculation are: PMV (M1) = 3.42, PMV (M2) = 3.66.

Fig. 9. PMV calculation – results.

From the results PMV (M1) = 3.42, PMV (M2) = 3.66 obtained by calculation it can be stated that the measured thermal environment was hot. For evaluating hot environment WBGT index was used. The average values of WBGT were obtained by statistical processing of measured data for both measurement points (Tab. 2).

Table 2. Statistical processing of WBGT index for M1 and M2.

Measurement point M1				
function	**t_r [°C]**	**t_w [°C]**	**t_a [°C]**	**WBGT [°C]**
min	32	29,9	29,6	30,8
max	37	34,4	36,7	35,1
avg	35,38	32,29	33,53	33,22
stdev	0,94	0,84	1,32	0,86
median	35,7	32,6	33,8	33,5
variance	0,88	0,7	1,74	0,74
modus	35,8	32,7	33,9	33,6
Measurement point M2				
function	**t_r [°C]**	**t_w [°C]**	**t_a [°C]**	**WBGT [°C]**
min	34,4	31,1	33	32,1
max	35,9	32,6	34,6	33,6
avg	35,07	31,89	33,76	32,84
stdev	0,34	0,33	0,36	0,33
median	35,1	31,9	33,8	32,8
variance	0,12	0,11	0,13	0,11
modus	35,1	31,8	33,8	32,8

An average WBGT (M1) = 33.22 °C and WBGT (M2) = 32.84 °C were compared with a referential value (refer WBGT = 28° C) found in the table in EN 27243. From this we can state that WBGT reference value is exceeded.

5. Discussion

Exceeding of referential values shows that it is necessary to reduce heat load on workers. There are several ways for doing that [1]:

- Apply more detailed analysis of thermal load by more accurate methods,
- Reduce the heat load in a given workplace by using personal protective equipment, adjusting the

environment, reduction of time spent in the environment.

For determination of degree of physical human body burden it is necessary to take into account the summary of all thermo-hygric microclimate parameters (high air temperature is worse to bear when there is also a high humidity or air velocity affects the heat transfer between the organism and its environment). Generally, the more negative factors are in the work environment the greater negative impact they will have on the health of the worker. In this way evaluated facility was designed. Is it possible that because of these factors high values from WBGT were obtained. For a deeper analysis of extremely hot environment, it is recommended to use the PHS index (Predicted Heat Strain) - index of thermal strain, which was developed for the evaluation of transition conditions in hot working environments [4].

6. Summary

For an indoor air quality study, there are a number of empirical equations used by some authors over the last few years. Indices, such as the predicted percentage of dissatisfied with local thermal comfort, thermal sensation and indoor air acceptability, are determined in terms of some measured parameter, such as dry bulb temperature, relative humidity and speed of air (ISO 7730) [7].

The problem of high temperatures of air inside industrial workplaces occurs particularly during hot summer days. Assessed workplace showed high dry air temperatures (between 32 °C and 35 °C), and high globe temperatures (between 31 and 40 °C). This indicated high level of thermal load, occurred at workplace. By PMV index calculation, it was proved that workers are exposed to thermal stress. The workplace was therefore assessed by WBGT index. The average values of WBGT were obtained by statistical processing of measured data for both measurement points. Results of statistical processing shows average values of WBGT (M1) = 33.22 °C and WBGT (M2) = 32.84 °C. These values were compared with a referential value (refer WBGT = 28°C) found in the table in EN 27243. From this we can state that WBGT reference value is exceeded. That means it is necessary to reduce the heat load in the given workplace in the future.

Hot summer days are increasing the temperature inside of the building. That is why ventilation and air conditioning systems are common. Ventilation and air condition systems are supplying or removing large volumes of air. Ventilation can also serve to adjust the humidity and other conditions in the work environment. In many manufacturing plants temperature and relative humidity are provided by air conditions. In these system is adjusted by filtration, preheating or cooling or it can be humidified or dehumidified. If hot industrial facilities are not able to provide air condition they must provide at least natural ventilation and mostly by air conditions [8].
Nowadays tropical days are more frequent and because of that it is recommended to use air conditioning in hot industrial plants in the future.

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