NEWTON MANIKIN SOFTWARE FOR EVALUATION OF THERMAL COMFORT USING ISO 14505-2

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Abstract

In this paper authors refer about the Thermal Comfort Analyzer for the evaluation of thermal comfort using thermal manikin Newton. This software was developed in Matlab to automate the routines for evaluation of thermal comfort by ISO 14505-2 standard using the comfort zone diagrams. This method uses equivalent temperature as the objective criteria for investigation of thermal in non-uniform environment i.e. vehicle cabins. Thermal manikin Newton is able to measure thermal resistances of clothing, surface temperatures and heat fluxes for each of his 34 zones. Thermal Comfort Analyzer processed these measured data straightforwardly to obtain resulting local equivalent temperatures, which are visualized in the automatically generated comfort zone diagrams. The software has the post-processing mode for the evaluation of completed tests, the real-time mode for the visualization of the measurement and the calibration mode to identify thermal resistances of clothing.

Keywords: *Thermal comfort, Thermal manikin, ISO 14505-2, Matlab software*

1 Introduction

The problematic of energy efficiency and thermal comfort is important for many of HVAC system manufactures and design engineers. One of the issues is how to objectively evaluate sensation of human subjects when they are using these systems. The thermal sensation is related with the thermal balance of human body, i.e. the balance between the metabolism heat production and the heat losses including the sensible dry heat losses (radiation and convection, or conduction), evaporation and respiration. The sensible heat losses from "human surface" is possible to measure using thermal manikins. The methodology how to perform such kind of measurements is described in ISO 14505 and specifically how to evaluate thermal comfort [1]. This standard uses equivalent temperatures EHT (Equivalent Homogenous Temperature) as the criteria of thermal comfort and it belongs to the most advanced methods for evaluation of thermal comfort in non-uniform environments, e.g. in vehicle cabins. The concept of EHT comes from [2]; later [3] evolved it into the comfort zone diagram method that basis the ISO 14505-2. In the recent version of the standard there are comfort zones diagrams only for summer and winter clothing. However [4] published the set of diagrams for additional types of clothing.

We applied the latter method to evaluate thermal comfort by our thermal manikin Newton manufactured by Measurement Technology NW [5] see **Figure 1**, left. Thermal manikin Newton has human body shape of averaged man and it can control or measure the surface temperatures and heat fluxes for each of his 34 zones. To reduce post-processing time we developed in Matlab a new software Thermal Comfort Analyzer. The main features of the software are presented in this paper, and briefly demonstrated on the real experiment. The presented software allows to automate the measurement post-processing routines and evaluate thermal comfort intuitively by the visualization of equivalent temperatures into comfort zones diagram. The resulting diagrams is possible to export into images and subsequently create video sequences for the further analysis or presentations.

2 Materials and Methods

Thermal Comfort Analyzer (TCA) was developed in Matlab as a standalone executable application with graphical user interface. TCA straightforwardly calculates 18 local and 1 overall equivalent temperatures from the measured parameters and from the knowledge of the local thermal resistance of clothing. The results of evaluated equivalent temperatures are plotted into the comfort zone diagram, which is automatically generated by the software. The software has the post-processing mode for the evaluation of completed tests, the real-time mode for the visualization of the measurement (see **Figure 1**, right) and the calibration mode for post-processing of the calibration measurement. In this chapter the main features of the algorithm are introduced.

Figure 1 Thermal manikin Newton and ThermDac 8 independently supported by TCA software in real time

2.1 Algorithm

The EHT combined with the thermal manikin measurement allows to capture effect of asymmetrical environmental conditions. “The EHT is defined as the temperature of a uniform space, in which all surface temperatures are equal to air temperature, there is no air movement other that the self-convection of the manikin, and the rate of heat loss would be the same as was actually measured” [6]. The EHT temperature T_{eq} is calculated by Eq. (1) from the measured values.

(thermal manikin measurement)

$$T_{eq} = T_s - \frac{\dot{q}_T}{h_{cal}} = T_s - R_T \cdot \dot{q}_T \quad (1)$$

where T_s is manikin surface temperature, which has to be maintained during all test at 34 °C for all manikin segments. R_T is overall thermal resistance including thermal resistance of clothing layer R_{cl} and air layer near the outer the clothing surface R_a (typically around 0.9 clo = 0.1395 m^{2}K/W). $\dot{q}_t$ [W/m^2] is the measured sensible heat flux between manikin and the environment and h_{cal} [W/m^{2}K] is heat transfer coefficient obtained from the calibration procedure.

The calibration procedure has to be done before the first experimental investigation of thermal comfort using thermal manikin, because the calibration is valid only for the one specific set of clothing. This procedure requires stable homogenous environment with the air and radiant temperature $T_a = T_r =$ 24 °C. The value of h_{cal} is calculated for each of the segments by the Eq. (2), this parameter determines the width of comfort zones for the individual segment.

(thermal manikin calibration)

$$h_{cal} = \frac{\dot{q}_{cal}}{T_s - T_a} = \frac{\dot{q}_{cal}}{34 - 24} \quad [Wm^{-2}K^{-1}] \quad (2)$$

where $\dot{q}_{cal}$ [W/m^2] is sensible heat flux calibrated for the specific set of clothing. The calibration process should be repeated more times to identify statistical error of the measurement. Air gaps between manikin surface and clothing layer are the main sources of the measurement uncertainties. The shape of air gap is substantially influenced by the manikin posture and the process to getting dressed, more about this topic is in [7].

The equivalent temperatures calculated by the Eq. (1) not express the thermal comfort themselves; they have to be related somehow with the human subjectivity. Comfort zone diagram was established to define correlation between local equivalent temperatures T_{eq} and the mean thermal vote (MTV) for all body segments. Diagrams are formed by the five thresholds of T_{eq} for each of 18 segments corresponding to the mean thermal votes MTV=[-1.5;-0.5;0;+0.5,+1.5]. The MTV scale includes both thermal sensation and thermal comfort together see the **Table 1**. The MTV scale can be associated (similar as PMV index) with the index PPD i.e. predicted percentage of dissatisfied, the minimal value of PPD is 5 % in case of MTV=0.

Table 1 Comfort zones diagrams MTV scale

PPD [%]	Not acceptable	< 20 %, acceptable	< 10 %, comfort	< 20 %, acceptable	Not acceptable
MTV scale	MTV < -1.5	-1.5 ≤ MTV < - 0.5	-0.5 ≤ MTV ≤ + 0.5	+0.5 < MTV ≤ +1.5	MTV > +1.5
	too cold	cold but comfort	Neutral	warm but comfort	too warm

The values of T_{eq} come from experimental investigation on the human subjects and they are valid only for the sedentary activities 70 – 90 W/m^2 and also for the specific set of clothing. Nilsson [4] assembled the Eq. (3) with empirical term (*a+b·MTV*) to obtain relation between dressed clothing and thresholds of local equivalent temperatures.

(comfort zone diagram thresholds) $$T_{eq} = T_s - R_T \cdot (a + b \cdot MTV) \quad [°C] \qquad (3)$$

where *a, b* are regression coefficients from the Nilsson's experiments, for theirs value see Tab. 1 in [4]. The empirical formula in Eq. (3) is valid only for the seated posture and thermal resistance of clothing up to R_{cl} = 1 clo = 0.155 m^{2}K/W i.e. total thermal resistance (clothing + air layer) R_T = 1 – 1.9 clo. The overall thermal comfort is evaluated as the area weighted average of the all local equivalent temperatures. The method assumes that the body parts sensitivity is directly proportional to the area of segments. This assumption has been proved that is simplistic and the weighting coefficients should differ for dominant parts (back, chest, head) and other (hands, arms). This issue has been investigated for instance by [8]. Comfort zone diagrams is a stationary method which not consider transient behaviour of thermal sensation, however a strong point of the method is a dealing with thermal comfort in non-uniform environment.

3 Results and Discussion

The main result of this paper is the development of the own software to reduce post processing time of evaluation thermal comfort by comfort zone diagrams. The software is primary designed for the reading the Newton manikin data files which are processed by the ThermDac manikin software. In this chapter the manual and user interface of the software is introduced see **Figure 2**, where a user interface of TCA software is shown with the illustration of the comfort zone diagram for the winter clothing.

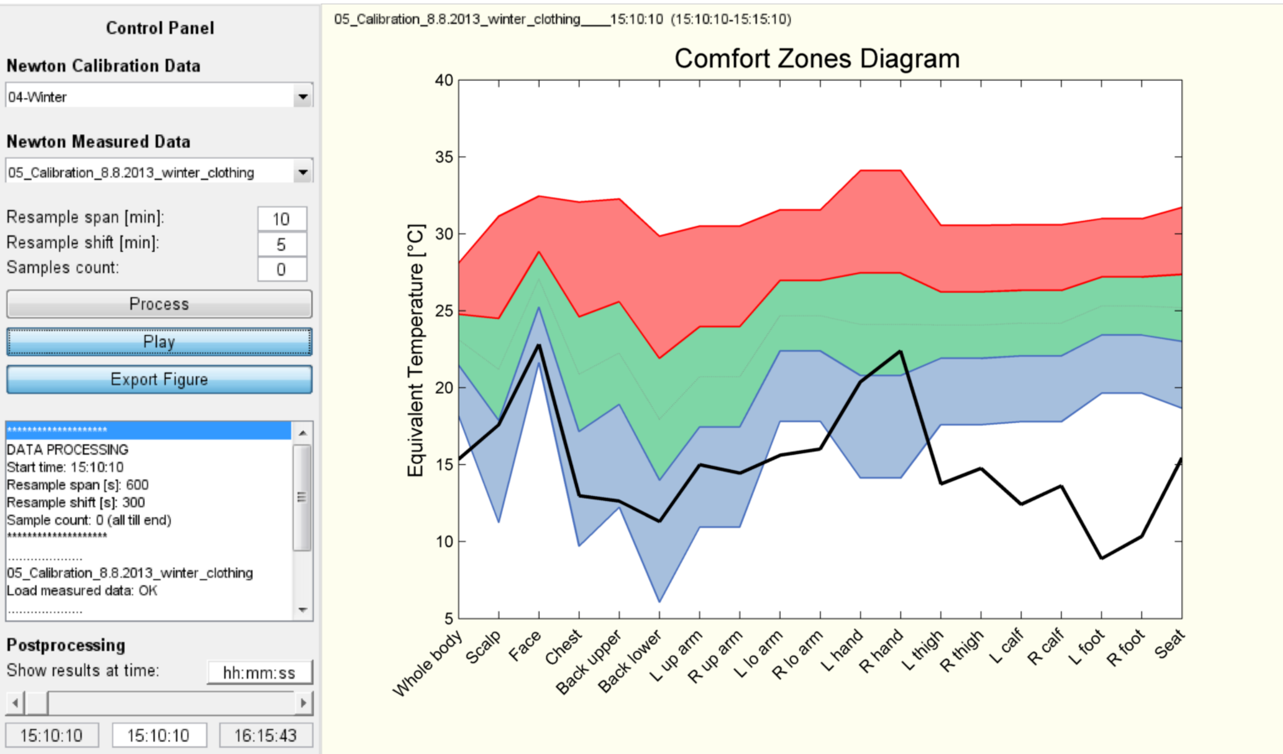

Figure 2 TCA user interface with the comfort zone diagram for winter clothing

TCA allows to resample measured data by interpolation to get averaged data in each resample span. This method is used due to the native inertia of the thermal manikin during measurement, we recommend to resample data to the 10 min. intervals, which are shifted by 5 min. This resampling eliminates oscillation of the measurement caused by the random errors, and local air flow fluctuations. The processed results of equivalent temperatures are stored into xls files in the folder Results. Some of the adjustments can be redefined in the Setup.csv see **Table 2**. The application is split into the diagram and the control panel. The options in the control panel slightly differs according to the selected mode, below is description of most important control elements.

Newton Calibration Data – calibration data (clothing) for which the thermal comfort should be evaluated

Newton Measured Data – experimental data (note: be careful to select corresponding calibration and measurement)

Resample span – the length of the resampling interval in minutes

Resample shift – the distance between the adjacent samples in minutes

Samples count – 0 = process all sample, 1,…N – process N samples

Process – press button to run the processing

Play – toggle button to replay the experimental data

Export Figure – If the toggle button is down the diagrams will be export to the png files for the each new sample

Postprocessing – allows to select specific sample of the processed data using slide bar or edit

Figurine - If the figurine visualization is on (see **Figure 3**, right) it is possible to select: MTV – mean thermal vote, heat flux, surface temperature, thermal resistance of clothing (there is also option 34 which means visualization of measured data on all 34, otherwise the 34 Newton zones are transformed into 18 zones by the ISO 14505-2). After the end of test is possible to plot results (see **Figure 3**, left)

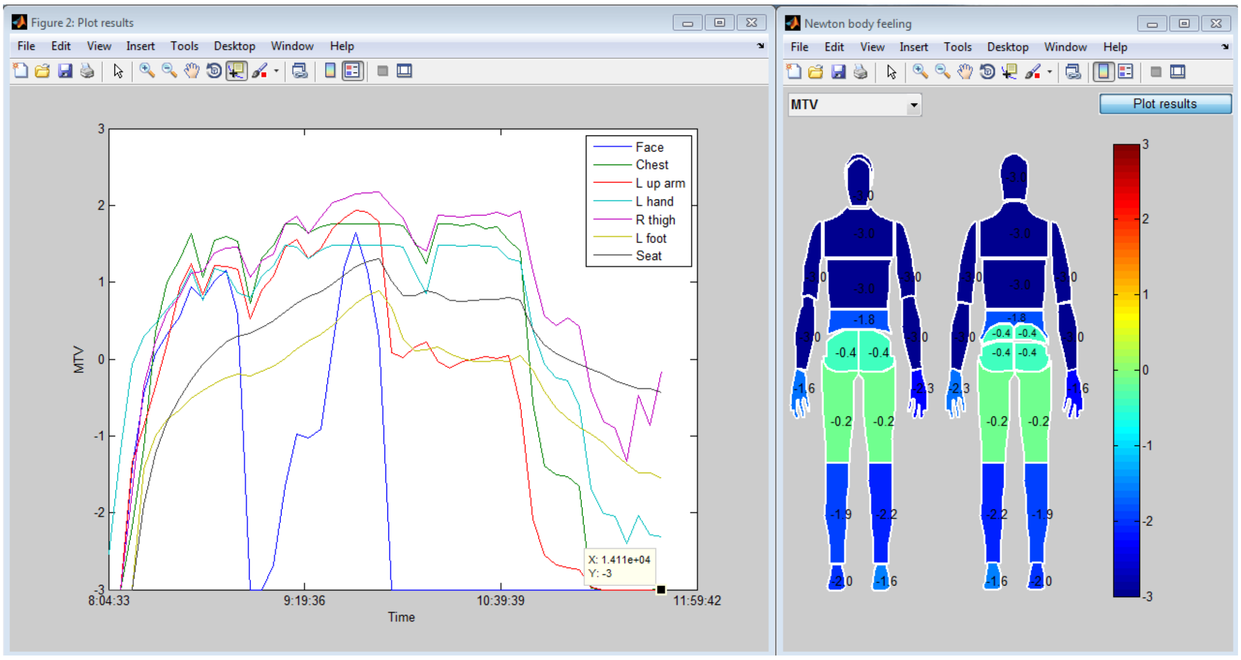

Figure 3 Mean thermal vote and figurine – summer test at time 11:59:42 (see chapter 3.1)

TCA software is possible to download from www.energetickeforum.cz/fsi-vut-v-brne/vysledky-vyzkumu/thermal-comfort-analyzer by cliciking “stažení software”. Before the first start of TCA you need to download and install the Matlab Compiler Runtime (MCR) 2012b (32bit. or 64 bit.) which is free to download from www.mathworks.com/products/compiler/mcr/. The software was compiled into the executable application and after extracting the R-Pokorny_TCA_1_0_instal.zip you can choose between the 32bit and 64bit version. Below is the list of the most important files and subfolders,

- Newton/Calibration – raw data of the calibration measurement file, e.g. „hcal_.csv“
- Newton/Measurement – raw data of the specific experimental test e.g. „Newton_.csv“
- Results – processed data of specific experimental tests: png, xls files
- Setup.csv – setting files with the application options which are possible to edit in text editor, see **Table 2**.
- TCA.exe, TCA.bat – executable files; .bat file runs the application in the console, where is possible to see more detailed information during the processing
- png2avi.m – Matlab script for the creation of .avi file from the image sequences (CAUTION – not functional in the deployed application, only as .m file, i.e. Matlab installation required)

Table 2 Most important options in the Setup.csv

Value	Label	Recommended values and other remarks
10	DefaultSpan	RealTime =1, Calibration = 30 (in minutes)
5	DefaultShift	RealTime =0.1 Calibration = 10 (in minutes)
0	DefaultSamplesCount	RealTime =0 (not used), Calibration = 1
1	TeqPartsAveraging	Averaging of local eq. temp. for dual parts (L, R) – i.e. legs
C:\Online.csv	RealTimePathDefault	default path to the real-time csv test file
0	RealTime	0-off, 1-on
0	hcal	0-off, 1-on , calibration (only for offline mode). Hint: 30,10,1 → Process
0	Figurine	0-off, 1-on , visualization of data on the figurine

3.1 Experimental test case

The software have used for the various type of tests to investigate thermal comfort. We present one of the performed summer tests with the thermal manikin Newton and Škoda Octavia car to demonstrate the effect of air-conditioning on the thermal comfort. A time schedule of the test is defined in the **Table 3** and the results are plot in figures below.

Table 3 Time schedule of the summer test 12.7.2013, Brno

Real time	Action	Diagram for the specific time
8:04	Start test, manikin start heat up	**Figure 4** - 8:59:39
9:00	Engine run, A/C off, ventilation 3/6	**Figure 4** - 9:59:38
10:00	A/C on - set temp. 22 °C, ventilation 3/6	**Figure 5** - 10:04:38, 10:59:40
11:00	A/C on - max. power, ventilation 6/6	**Figure 6** - 11:04:40, 11:59:42

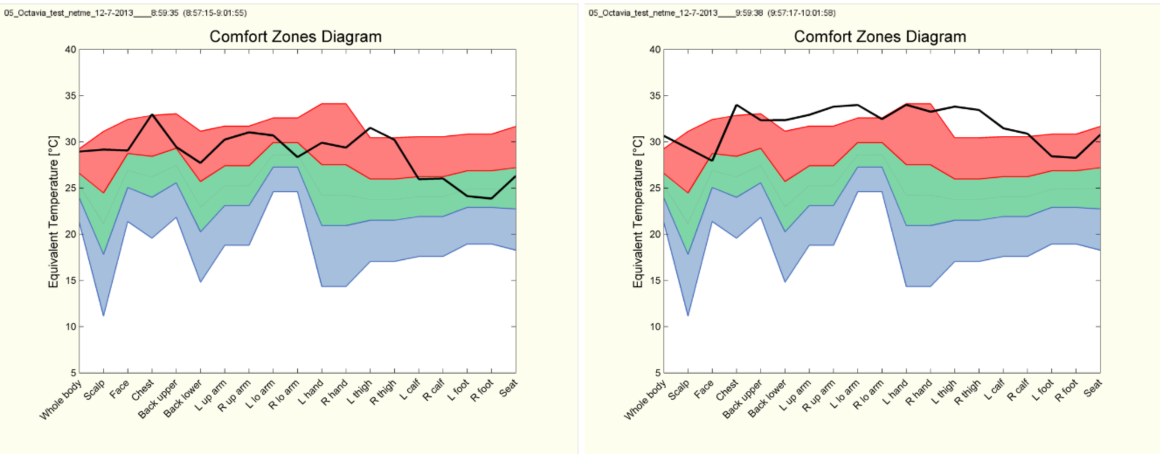

Figure 4 No air-conditioning - 8:59:39 ($T_{air,IN}$=27 °C) and 9:59:38 ($T_{air,IN}$=30.9 °C)

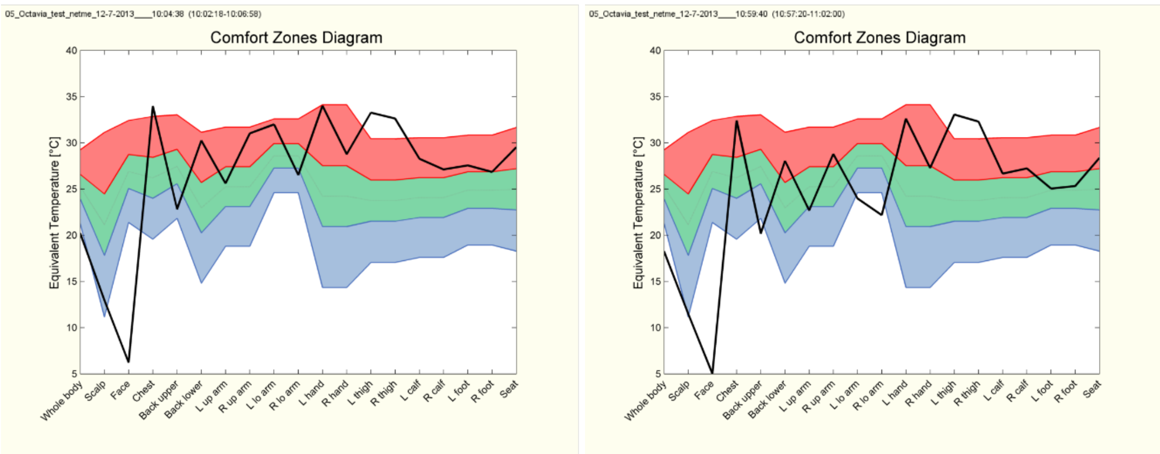

Figure 5 Air conditioning to set point 22 °C - 10:04:38 and 10:59:40 ($T_{air,IN}$=25.5 °C)

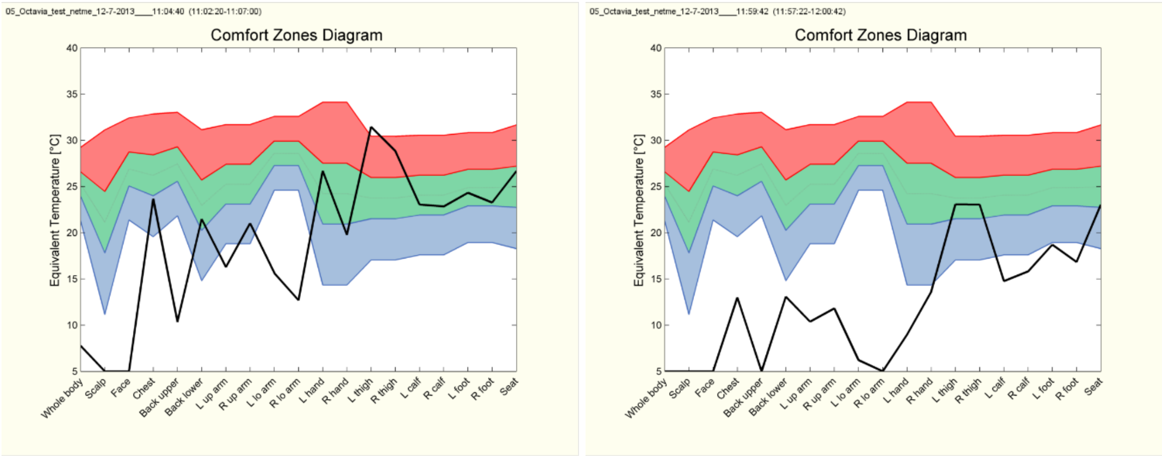

Figure 6 Air conditioning by full power - 11:04:40 and 11:59:42 ($T_{air,IN}$=14.6 °C)

Thermal manikin was dressed into the summer clothing (trousers and t-shirt) see **Figure 1**. At the start of the test the car was parking outside; air temperature was 17.6 °C in the morning and 23.9 °C in the noon and the cloud cover only with few clouds during the whole test. Solar radiation together with the running thermal manikin were heating up the car cabin. Even when the ventilation was switched on, the mean temperature measured at driver feet and head level $T_{air,IN}$ risen from 27 °C up to 30.9 °C see **Figure 4**. It can be noticed apparently on the **Figure 5** which parts were most fan-cooled (face, back upper) when the air-conditioning was turn on. On the contrary part which had contact with the seat (thighs and the seat part) were least fan-cooled parts by the A/C, see **Figure 6**. The mean thermal vote of the selected parts could be seen on the **Figure 3**.

4 Conclusions

It was developed a software for processing of measured data by the thermal manikin Newton to facilitate routines of evaluation of thermal comfort by the ISO 14505. In this paper the algorithm of the used method was introduced and demonstrate on the one experimental test case: thermal comfort in the air-conditioned car cabin. The software has the post-processing mode for the evaluation of completed tests, the real-time mode for the visualization of the measurement and the calibration mode to identify thermal resistances of clothing.

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