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Instrumentation for Thermal Comfort Measurements: The Globe Thermometer

ABSTRACT:

Globe thermometers of varying size and composition were compared in terms of response time and accuracy in predicting mean radiant temperature. It was found that larger globes (150 mm.) were most accurate but that much smaller globes (38 mm.) had signifigantly faster response times while sacrificing little in accuracy.

INTRODUCTION:

The globe thermometer (see photos page #13)is a device used in thermal comfort experiments primarily to estimate mean radiant temperature. It indicates the heat balance between radiative gains and convective losses for a particular environment (e.g., a particular air temperature, air velocity, and temperatures of surrounding surfaces in an office). Depending on size, composition and coating, the instrument can be optimized for accuracy or response time. This paper outlines recent research to determine which globe would be most appropriate for accurately measuring mean radiant temperature in an office environment while only sampling for five minutes.

BACKGROUND:

Current literature on globe thermometers focusses mainly on the issue of general suitability for predicting mammalian response (primarily humans and cattle) irrespective of instrument response time. However,two frequently referenced papers on globe thermometers (E.N. Hey (1968) and M.A. Humphreys (1977)) address quite different aspects of the problem. Hey deals with the physics of globe heat transfer while Humphreys discusses mostly the appropriateness of small vs. large globes to modeling specifically human response patterns. Although both discuss small globes, Hey only gives an approximate conversion to standard (150 mm.) sized globes without any analysis or explanation. Humphreys gives a cooling curve for a 38 mm table tennis ball but doesn't do any actual measurements comparing the 38mm globe to standard (15 cm.) and other sizes in between (eg. 70 mm) in terms of accuracy and response time. Also note that no other ways of estimating mean radiant temperature were used to gauge the accuracy of the measurement.

While Humphreys states that the 38 mm. globe is the optimum instrument for modeling human response, others (Kuehn et al (1970)) maintain that the *minimum* diameter is more like 100mm. With the advent of new technology , notably the Bruel and

Kjaer 1213 indoor climate analyzer, mean radiant temperature can be very accurately measured using the plane radiant sensor and performing an angle factor calculation. Also, the Thermal Comfort Meter (Madsen (1976)), an ellipsoidal shell with a temperature sensing device, an internal heater, and sophisticated electronics, can be used to directly measure operative temperature and thus provides a third route of verification. Operative temperature is the temperature of a uniform isothermal black enclosure in which the occupant exchanges the same amount of heat by radiation and convection as in an actual non-uniform environment

The work leading to this paper was done in response to a specific need for a globe thermometer that would be both fast (reach 63.2% of its' final value in 2 minutes or less) and also small (three globes had to be placed within one meter of each other and make independent measurements of the micro-climate) without sacrificing much in accuracy.

THEORY:

The globe thermometer is essentially a temperature sensing device (mercury thermometer or thermocouple) suspended inside a spherical shell. The temperature measured in the center depends on the heat transferred by convection, conduction and radiation from the surrounding environment to the surface of the sphere, through the shell,and through the air inside the shell to the temperature sensing device. If the globe is in equilibrium with the environment, the radiant gains are exactly balanced by the convective and conductive losses or vice versa. The gain or loss due to conduction is typically 1%-2% and thus will be ignored.

The heat gained or lost due to radiation is:

$$Q_r = \sigma\varepsilon(T_g^4 - T_{mr}^4) \qquad (W/M^2) \qquad (1)$$

where $\sigma = 5.667\times10^{-6}$ (the Stefan-Boltzmann constant) $(W/(M^2\,K^4))$

ε is the emmisivity of the globe

T_g is the globe surface temperature in Kelvins

T_{mr} is the mean radiant temperature of the surrounding space, also in Kelvins.

The heat gained or lost due to convection is:

$$Q_c = h_c(T_g - T_a) \qquad (W/M^2) \qquad (2)$$

where h_c is the convective heat transfer coefficent $(W/(M^2\ C)$

and T_a is the air temperature (C)

Hey gives the relation

$$Nu = .32\ (Re)^{.6}, \qquad (3)$$

valid for a sphere experiencing convective heat loss in a fluid as long as the Reynolds number is in the range 10^2–10^5. In typical indoor environments, the Reynolds number is well within this range. Substituting the definitions for the Nusselt and Reynolds numbers we find

$$h_c D/\kappa = .32(D\rho V/\mu)^{.6} \text{ solving for } h_c$$

$$h_c = .32\ \kappa\ (\rho/\mu)^{.6}\ V^{.6}\ D^{-.4}$$

κ is the thermal conductivity (W/m ^oC)

ρ is the density (kg/m^3)

μ is the viscosity (kg/ms)

V is the air velocity ($^m/_s$)

D is the diameter of the sphere (m)

$\kappa(\rho/\mu)$ for air in the region under consideration is roughly 19.71 which implies

$$h_c = 6.31\ V^{.6}\ D^{-.4}$$

This relation (with minor variations in numerical values) is generally agreed upon in the literature on globes. The most recent version (ASHRAE HANDBOOK (1984)) is given below.

$$h_c = 6.32\ D^{-.4}\ V^{.5} \qquad (4)$$

and thus

$$Q_c = 6.32\ D^{-.4}\ V^{.5}\ (T_g - T_a). \qquad (5)$$

The radiative heat transfer coefficient, h_r, is frequently linearized as

$$h_r = 4\sigma\varepsilon T_{av}^3 \qquad (6)$$

where T_{av} is the average of the mean radiant temperature and the globe surface temperature,

$$(T_g+T_{mr})/2$$

This form is only valid when T_g and T_{mr} are close in value...a fairly typical situation in everyday office environments. See Appendix A for a mathematical justification of this approximation.

At equilibrium, $Q_c = Q_r$

or $\quad h_c (T_g - T_a) = h_r (T_g - T_{mr})$

In this case we wish to find T_{mr} from a measured T_g so we solve for T_{mr}.

$$T_{mr} = T_g - (h_c/h_r)(T_g - T_a) \qquad (7)$$

and finally substituting for h_c and h_r from equations (4) and (6),

$$T_{mr} = T_g - [(6.32\, D^{-.4}\, V^{.5})/(4\, \sigma\varepsilon\, T_{av}^3)](T_g - T_a) \qquad (8)$$

CONSTRUCTION:

A total of six globes were constructed, each of a different size and composition but all spherical. The two smallest globes (38mm.) were both plastic table tennis balls. Next largest was a (68.4 mm.) christmas tree ornament made of very thin glass. It had red reflective metallic paint on it prior to being coated black which shouldn't have affected the globes performance because its' thermal conductivity is quite good. Next largest was a 5 inch (127 mm) thin glass light bulb with the filament removed and the neck sealed. The two largest globes were both 6 inches (152.4 mm) in diameter. One was a thin-walled glass lightbulb similar to the 127 mm bulb, the other was a rather thick-walled (2 mm) lampshade. The lampshade was not quite a complete sphere, having been sliced off along the top.

Each globe was washed and thoroughly heat dried before being sealed. A section of thermocouple wire with a prepared tip was forced through a small (2.5 mm. diameter) pvc pipe to insure stiffness after installation. The pvc tube was glued in place using fast drying cyanoacrylate glue with the thermocouple junction in the exact center of the sphere. All the globes were fitted with K-type thermocouples

EXPERIMENTAL PROCEDURE AND DATA AQUISITION:

In order to measure response times, the globes must be exposed to as sudden a step change in air temperature, radiation or air velocity as possible. To accomplish this, a controlled environment chamber was used. The globes were hung from thin strands on a frame mounted on a mobile platform. The platform was placed in the hall outside the chamber next to an open window while the chamber was heated with a space heater. When the desired temperature difference was obtained, the door was quickly opened and the globes moved in. The environment was kept at a steady temperature and radiant heat by monitoring the climate analyzer and making small adjustments to the heater. When the temperature in the largest globe had remained constant for ~ 20 minutes, the experiment was terminated. This sequence was repeated for several differences in temperature, different wind velocities and different radiant intensities (see table 1).

TABLE 1

EXPERIMENT #	ΔT °c	ΔV m/s	ΔT_r °c
1	4	0	0
2	7	0	8
3	0	.35/.8	0

The globe temperature data was collected using a Campbell Scientific CR21x programmable datalogger in the differential voltage measurement mode (to avoid any possible ground loops). The voltage from each sensor is compared to that from a reference thermocouple and the conversion to temperature is made in the CR21x using a simple program. Each sensor was sampled every ten seconds and the data dumped to tape every few minutes for storage with a time stamp. The climate data (air temperature, air velocity, plane radiant temperature, and plane radiant assymetry) was measured with a Bruel and Kjaer 1213 indoor climate analyzer. Every ten seconds, a burst of data is transmitted which consists of average values over the last ten seconds. It was connected directly to the computer (IBM pc/AT) through the serial port using a small program to catch the incoming data and dump it to a file.

RESULTS AND CONCLUSIONS:

After downloading the Campbell data from tape , Lotus 123 was used for the analysis. Mean radiant temperature was calculated 1) from globe temperature using equation (8) and 2) from the B+K radiant assymetry sensor (see figures 1 and 2). The step function in figure 1 is derived from the data shown in figure 2 using an angle factor calculation. The angle factor calculation takes into account the projected area of the human body onto each surface it receives radiant energy from. The plane radiant temperature measurement of each surface (total of 6) is given a weight corresponding to the proportion of the body that "sees" that radiation. Thus the weighting given to the surface that opposes the front of the body is higher than the weighting given to the surface that opposes the side of the body.

For a sitting person:

$$T_{mr} = \{(.18(T_{pr}[up]+T_{pr}[down])+.22(T_{pr}[right]+T_{pr}[left]+ .3(T_{pr}[front]+T_{pr}[back])\}/2(.18+.22+.3). \qquad (9)$$

where T_{pr}[direction] is the plane radiant temperature of the surface in that direction.

The small table tennis balls had response times on the order of 2.5 to 3 minutes (see table 2) while the large glass globes had response times between 8 and 15 minutes or even longer in some cases. The christmas tree ornament was slightly more accurate (i.e. it's temperature was usually closer to the temperatures of the larger globes) than the table tennis balls but its' response time was too long at about 5-7 minutes. The temperature of the table tennis ball tracked the temperature of the larger globes very well once equilibrium was attained - even after the size correction in the mean radiant temperature calculation.

The conversion of globe temperature to operative temperature,

$$T_o=T_a+(h_r/h_c)(T_{mr}-T_a),$$

was also done for comparison to the operative temperative directly measured (see figures 3 and 4) by a Madsen comfort meter (Bruel and Kjaer type 1212 thermal comfort meter). These plots correlate well beyond expectations given the crudity of the measurement. All of the comparisons are favorable for the 38mm table tennis ball and thus it is currently in use as an instrument for collecting data in the field.

TABLE 2

INSTR	ΔTemp °C	t_{resp} minutes	ERROR percent
TTB_1	3.65	2.5	+/- 4%
TTB_2	5.8	2.25	+/- 4.4%
ORN	4.8	5.2	+/- 2 %
127GB	5	8	+/- 1.25%

note: Since different data collection systems were used to sample different sensors, the clocks were not always synchronized. As a result the time axes on figures 1-8 (which follow on the next few pages) are not always matched up.

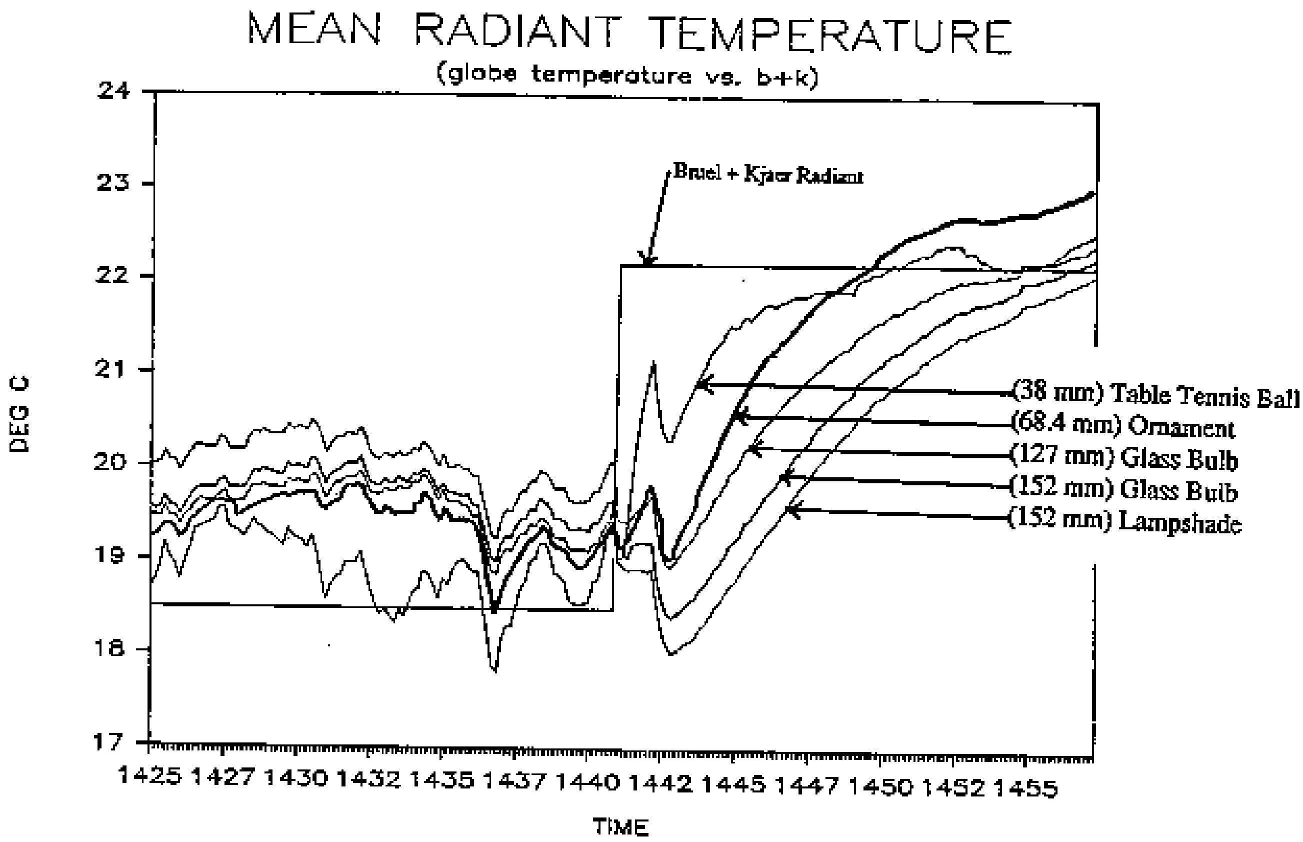

Figure 1. Note the sharp response of the 38 mm. globe to step change. The B+K radiant is calculated using the data below in Figure 2.

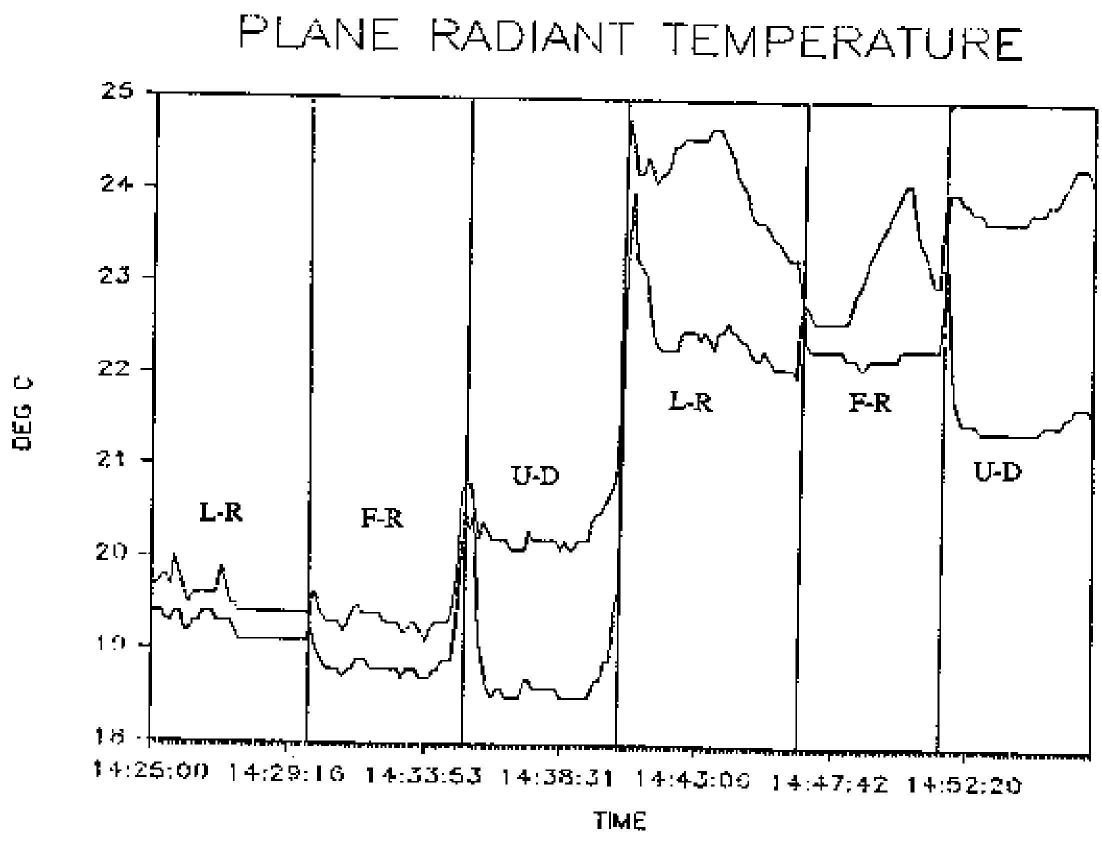

Figure 2. The step function in Figure 1 above is a weighted average of 5 minute samples in each of 6 directions (see eqn. (8)).

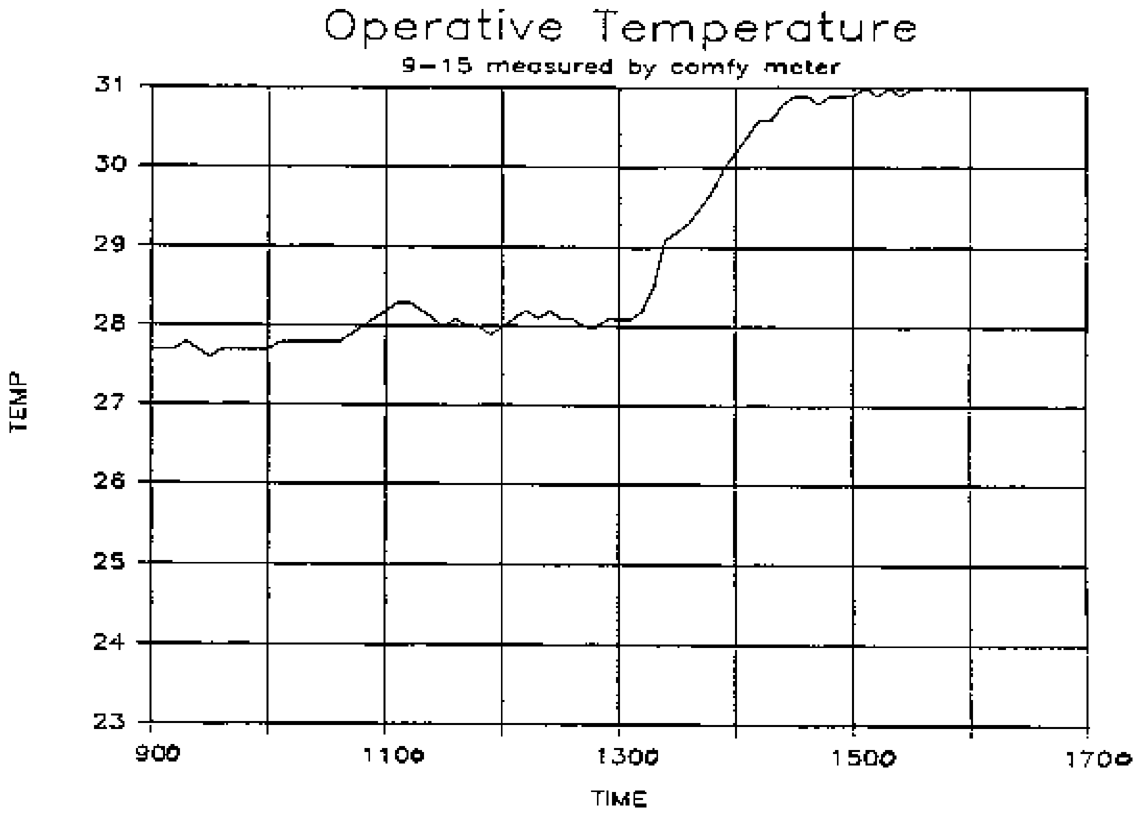

Figure 3. Operative temperature measured by the comfort meter. The data was collected by manually recording the displayed value every minute.

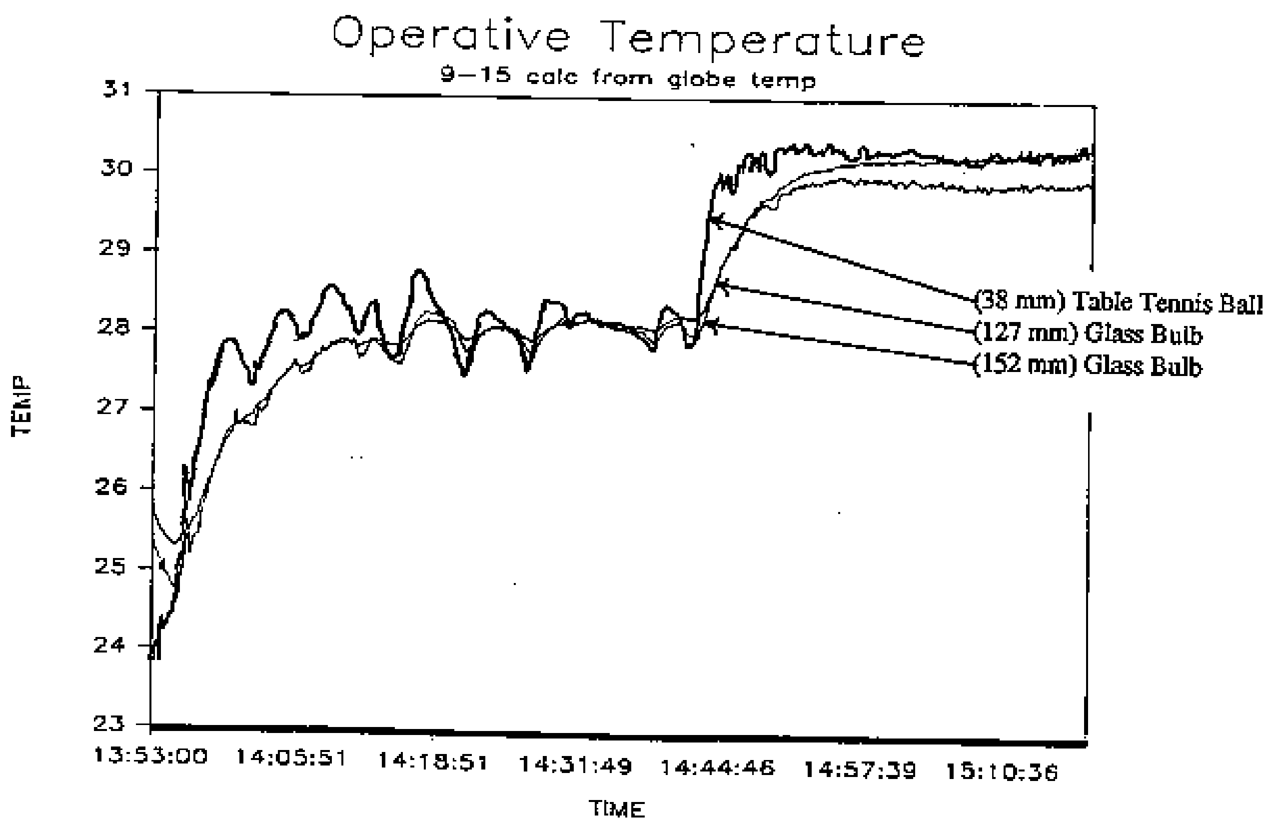

Figure 4. Operative temperature calculated from globe temperature for the same period as in Figure 3 above.

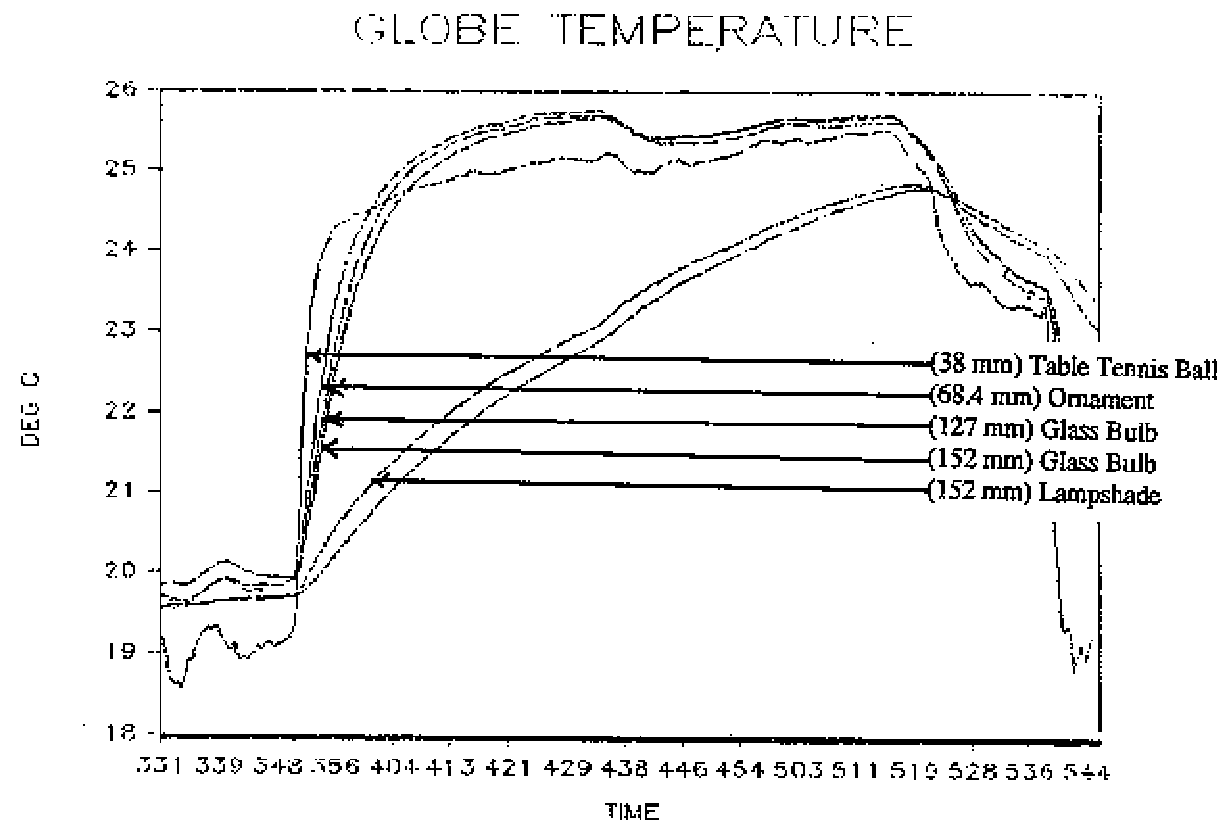

Figure 5. Response of globe temperature to variations in air velocity. Compare to Figure 6 below.

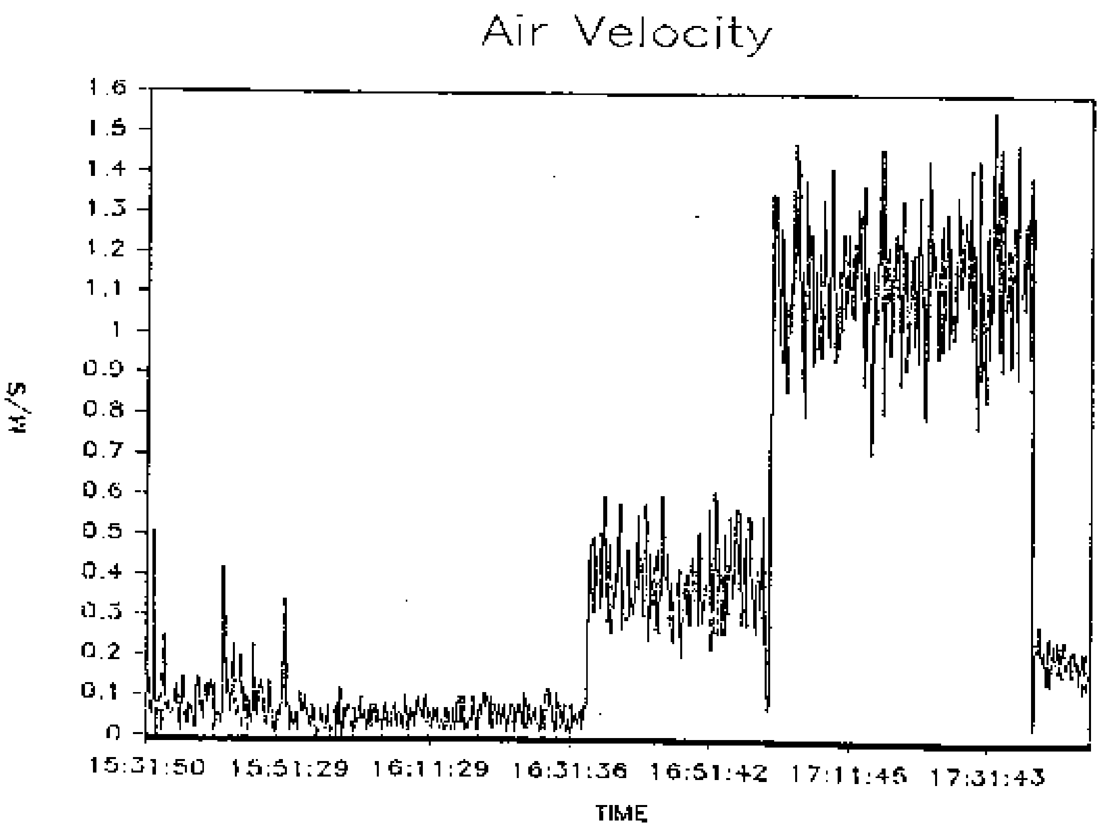

Figure 6. Air velocity corresponding to globe temperature measurements in Figure 5 above. Note dips in globe temperature when air velocity increases.

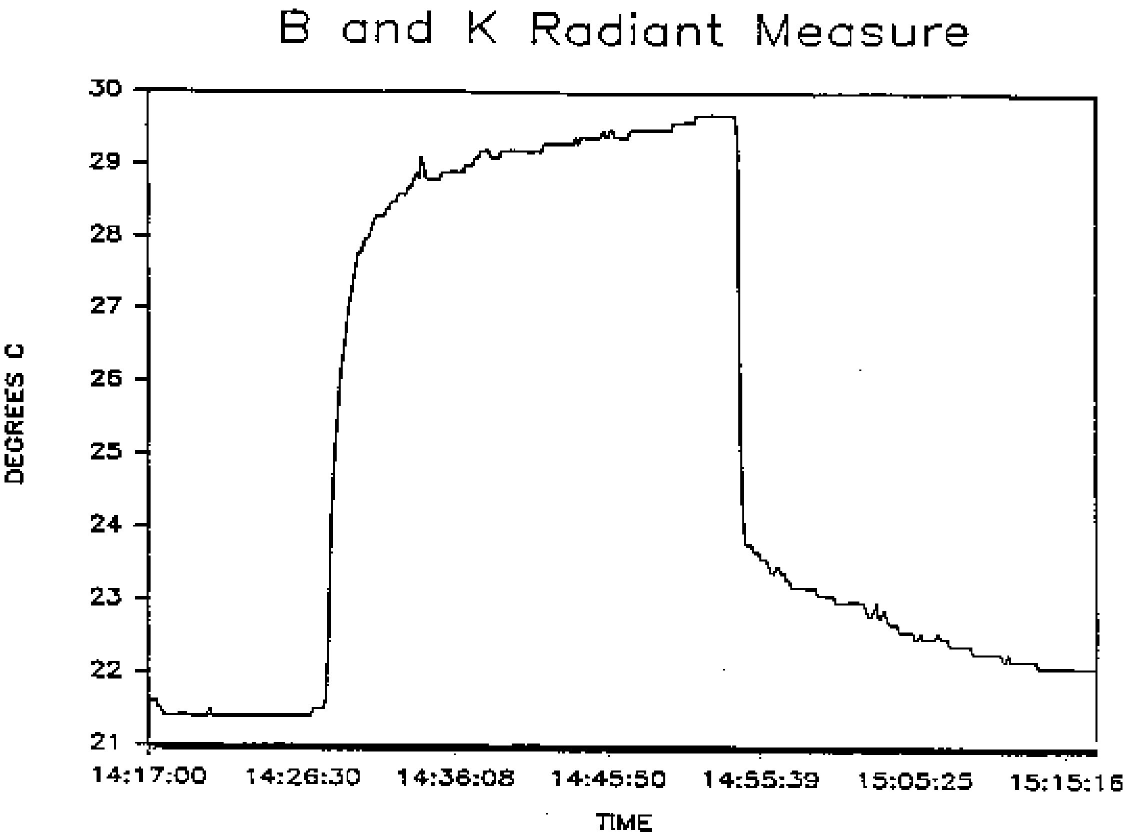

Figure 7. Measurement of radiant sensor corresponding to globe temperature in Figure 8 below.

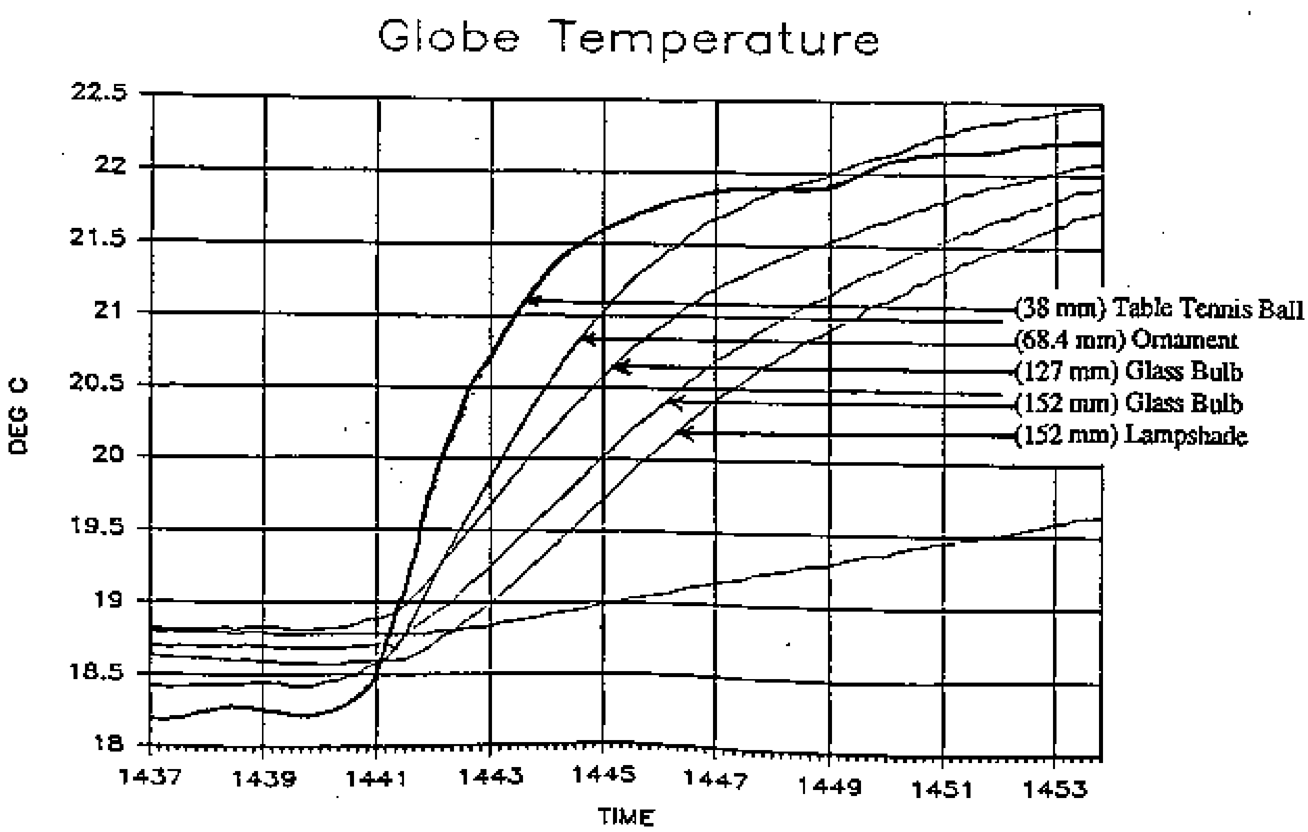

Figure 8. Response of globes to step change

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APPENDIX A

We wish to approximate the heat transfer by

radiation, $Q_r = \sigma\varepsilon\,(T_g^4 - T_r^4)$ as a linear function $Q_r' = 4\sigma\varepsilon((T_r+T_g)/2)^3\,(T_g - T_r)$.

Neglecting factors of $\sigma\varepsilon$, we have

$$(T_g^4 - T_r^4) \approx 4(T_{av})^3(T_g - T_r)$$

where $T_{av}=(T_g+T_r)/2$

$$(T_g^2 - T_r^2)(T_g^2+T_r^2) \approx 4(T_{av})^3(T_g - T_r)$$

$$(T_g - T_r)(T_g+T_r)(T_g^2+T_r^2) \approx 4(T_{av})^3(T_g - T_r)$$

factors of $(T_g - T_r)$ vanish,

$$(T_g^3+T_rT_g^2+T_r^2T_g+T_r^3) \approx 4(T_{av})^3$$

if $T_r \approx T_g$ then the above statment is true.