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A comparison of globe, wet and dry temperature and humidity measuring devices available for heat stress assessment

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ABSTRACT: Various controlled and ambient tests were undertaken to evaluate the performance of a variety of digital heat stress monitors, psychrometers and simpler temperature/relative humidity data loggers that measure, or determine, such parameters as: dry-bulb, natural wet-bulb, psychrometric wet-bulb and globe temperatures. In this comparison, funded by the Deep Mining Research Consortium, it has been found that all the instruments can competently measure dry-bulb temperature but the accuracy of other sensors could introduce significant uncertainty. For example the quality of relative humidity sensors and failure to correct for the barometric pressure difference in deep mines, directly impacts upon the calculation of psychrometric wet-bulb. The comparison has shown that the response of dry-bulb and globe temperature sensors can vary widely under different radiant heat conditions; however this would be negligible in most mines. Of more concern is the differing performance of the natural-wet bulb sensors especially at low relative humidity and low air velocity. Furthermore, from these tests and the currently available theory it was not possible to determine if any of the natural-wet bulb instruments measured that value correctly or validate any relationship between psychrometric and natural wet-bulb temperature at low air speeds where their difference is greatest. Consequently the uninformed use of some of the commercially available environmental heat stress monitors or derivations from other instruments could provide erroneous results affecting the work load category that can be accommodated or the rest ratio regime required.

1 Introduction

In hot conditions, the potential for heat stress is normally controlled through exposure management tied to an environment based temperature index such as the wet-bulb globe temperature (WBGT) used in North America (ACGIH, 2007). For example, the following summation of natural wet-bulb (t_{nwb}) and globe temperatures (t_g) could be used for underground mines:

$$WBGT_{inside} = 0.7t_{nwb} + 0.3t_g$$

In addition to t_{nwb} and t_g other environmental variables that can be included in the determination of a heat stress index are: dry bulb temperature (t_{db}), air velocity and barometric pressure. However common to all indices is the need to measure a wet bulb temperature as this plays one of the most important roles in determining the evaporative and hence cooling potential of the environment.

Depending on the measured environmental conditions and subsequent index value, a worker's activity may be unrestricted, controlled with a work/rest regimen or prohibited. Therefore, instruments used to determine the potential for heat stress conditions must be accurate to ensure the worker is adequately protected and that productivity is not being affected needlessly.

Today, electronic instruments are the norm and due to their precision, the user often assumed comparable accuracy. However, this is not guaranteed. There is also a trend to use "dry" instruments measuring relative humidity (%RH) to determine psychrometric wet-bulb temperature (t_{wb}) and t_{nwb}. Here, the accuracy of the humidity sensor and failing to consider barometric pressure effects can introduce considerable uncertainty.

The following paper details a range of performance comparisons, funded by the Deep Mining Research Consortium, which were undertaken to determine which instruments may be most suitable for use in deep mines. In alphabetical order, the instruments included in this study were:

- Heat Stress SensorLynx, (originally from IST Corp., U.S.A., but no longer available)
- HSM (Heat Stress Monitor) from Calor Instruments, Australia
- Humidity Indicator HMI41/HMP45 from Vaisala, Finland
- Kestrel 4000 Pocket Weather Tracker from Nielsen-Kellerman, U.S.A
- Microtherm Heat Stress WBGT meter from Casella CEL, U.K.
- QUESTemp834 & 836 heat stress monitors from Quest Technologies, U.S.A.
- SmartReader Plus Multi-channel data loggers from ACR Systems Inc., Canada
- Wibget Heat Stress Monitor RSS-214, from 3M™, U.S.A. (originally supplied by IST Corp.).

2 Controlled Environment Comparisons

The instruments evaluated measure a variety of parameters:

- "WBGT" monitors that measure t_{nwb}, t_{db} and t_g directly.

Table 1. Instrument temperature sensor agreement results from 408C tests in a small controlled environment chamber

Instrument	Sensor	Specifications			April 25th/26th/27th, 2005				October 13th/14th, 2005			
		Sensor	Display Resolution	Accuracy +/-	Avg.	Std. Dev.	Result Range Unit	Result Range Group	Avg.	Std. Dev.	Result Range Unit	Result Range Group
			°C	°C	°C	°C	°C	°C	°C	°C	°C	°C
Hart Scientific 1522	Secondary Standard	Platinum RTD	0.001	0.007				1.04	40.05	0.67		0.88
ACR SmartReader Plus #3	Internal	Thermistor	0.07	0.2	39.64	0.08	0.46		39.72	0.39	0.47	
ACR SmartReader Plus #1	External				40.04	0.12			40.05	0.56		
ACR SmartReader Plus #1	Internal				40.10	0.15			40.19	0.42		
Calor HSM	Dry-bulb	Thermistor	0.1	0.2	39.99	0.22	*0.64*		40.07	0.41	0.33	
	Globe				39.34	0.19			39.74	0.76		
Casella Microtherm #1	Dry-bulb	Platinum RTD	0.1	0.2	39.55	0.12	*0.18*		39.85	0.30	0.24	
	Globe				39.61	0.15			40.08	0.32		
	Wet-bulb				39.43	0.14			39.84	0.47		
3M Wibget RSS-214	Dry-bulb	Unspecified	0.1	0.4	39.66	0.15	*0.25*		40.03	0.57	0.57	
	Globe				39.91	0.19			40.60	0.80		
	Wet-bulb				39.78	0.13						
Kestrel 4000		Thermistor	0.1	1.0	*40.38*	*0.25*			40.58	0.68		
QUESTemp°34 (Small Globe Assembly)	Dry-bulb	RTD	0.1	0.5	*39.66*	*0.14*	0.41		39.92	0.34	0.27	
	Globe				*40.07*	*0.12*			40.19	0.60		
	Wet-bulb				*40.04*	*0.17*			40.06	0.50		
IST Sensor Lynx	Dry-bulb	Unspecified	0.1	0.4	*39.58*	*0.21*	0.29		39.72	0.55	0.24	
	Globe				*39.81*	*0.17*			39.96	0.55		
	Wet-bulb				*39.52*	*0.18*			39.74	0.51		
Vaisala HMI41/HMP45	#1	Platinum RTD	0.1	0.3					40.08	0.68	0.21	
	#2								39.87	0.58		

- Other heat index instruments measure t_{db}, possibly t_g, relative humidity, barometric pressure and wind speed. These parameters are then used to calculate either t_{nwb} or t_{wb}.
- Digital psychrometers measure t_{db}, relative humidity and possibly barometric pressure, to then calculate t_{wb}.

These three types of instruments incorporate six parameters that needed to be controlled or accounted for in order to compare their performance. Some of these parameters could be varied while keeping the others constant, whereas others could only be eliminated. For example, t_{db} and barometric pressure could be controlled in a small in-house environmental chamber. However, establishing a range of stable relative humidity/wet-bulb temperature conditions was more difficult. This was due to the size of the enclosure needed for simultaneous comparison of the instruments. Providing a uniform radiant heat load to assess t_g measurement was not possible; this parameter could only be eliminated from influencing other measurements by performing the comparisons in a dark or low-light environment. Similarly, it was not possible to maintain a significant and uniform air velocity over all the instruments while sustaining the stability of the other parameters; this limited the comparison of t_{wb} and t_{nwb} measurements.

2.1 Basic Temperature Measurement

The first comparison of the heat stress instruments evaluated the responses of the temperature sensing elements of the six "heat stress" meters plus other psychrometers inside a small temperature and barometric pressure controlled chamber. Where possible, each instrument's individual temperature sensors were exposed by removing wet-bulb wicks, black globes and radiant shrouds so they would only be measuring t_{db}.

The controlled temperature tests in this small chamber ranged from -20°C through to 40°C. Table 1 lists each instrument's temperature measurement specifications and the results of three tests performed nominally at 40°C. The April 2005 results are combined from two tests each with a limited number of instruments, the October 2005 results are for a single test with all the instruments placed in the chamber. These tests showed that all the instruments agreed amongst themselves with most differences being within the resolution and/or quoted accuracy of the instruments. For instruments with multiple sensors, the averages generally agreed within 0.5°C and for the whole population the averages generally agreed within 1.0°C. During this set of tests, the Wibget t_{nwb} sensor started to malfunction, reporting consistently higher but still linear results. This condition was corrected upon the sensors replacement. Similarly, a delicate high precision Hart Scientific 1522 PRT (platinum resistance thermometer), used as the comparison standard, was similarly not available for all the tests due to it needing repair.

The accuracy of t_{db} and t_g measurement sensors was confirmed in a second series of comparison tests performed inside a walk-in controlled environment chamber. This large chamber, part of the human thermoregulation research facilities at University of Ottawa's School of Human Kinetics, precisely monitored t_{db} and the moisture content of the air entering and leaving the chamber. This second set of tests were limited to nominally 15, 25 & 35°C t_{db}, performed under low-light conditions with negligible radiant heat sources and minimal air velocity, but under various humidity conditions. The results of these comparisons, given in Table 2, shows that when compared to the chamber's PRT standards virtually all the sensors were extremely linear ($R^2 > 0.998$), with gradients near unity (1 ± 0.024), intercepts $< \pm 0.71$°C and regression

Table 2. Regression analysis results from environmental chamber 15, 25 and 35ºC dry-bulb temperature tests

Instrument	Sampling Interval (sec)	Resolution (^{o}C)	# of	Dry-Bulb Regression Analysis			
			Readings	Gradient	Intercept (^{o}C)	R^2	Standard Error
Calor HSM	300	0.1	199	1.007365	-0.245249	0.999911	0.074982
Casella Microtherm #1	60	0.1	1200	1.014741	0.126939	**0.997939**	**0.360179**
Casella Microtherm #2	60	0.1	1199	1.008409	0.001999	0.999033	0.246685
Hart Scientific 1522 (Reference)	60	0.0001	734	0.996742	0.045913	0.999919	0.048714
3M Wibget RSS-214	60	0.1	1151	**0.975540**	**0.710745**	0.999859	0.093742
IST SensorLynx	60	0.05 - 0.1	1203	0.989621	0.265010	0.999934	0.064228
Kestrel 4000	120-300	0.1	359	0.998063	-0.013934	0.999929	0.067363
QUESTemp°34 (Large Globe Assemby)	60	0.1	1212	1.005813	-0.336329	0.999920	0.070938
QUESTemp°34 (Small Globe Assemby)	60	0.1	1212	0.984405	0.365598	0.999954	0.053708
QUESTemp°36 (Small Globe Assemby)	60	0.1	1212	1.005577	-0.193514	0.999958	0.051612
Vaisala HMI41/HMP45 #1	120-180	0.01	562	0.989617	0.273435	0.999971	0.042686
Vaisala HMI41/HMP45 #2	120-180	0.01	561	0.999495	0.091087	0.999969	0.043435
ACR SmartReader Plus #1 (External)	60	0.02	1190	0.997128	0.003386	0.999925	0.068607
ACR SmartReader Plus #1 (Internal)	60	0.02	1190	0.999774	0.077454	0.999928	0.067027
ACR SmartReader Plus #2 (External)	60	0.02	1190	1.001061	0.043006	0.999927	0.067519
ACR SmartReader Plus #2 (Internal)	60	0.02	1190	1.002165	-0.062231	0.999932	0.065529

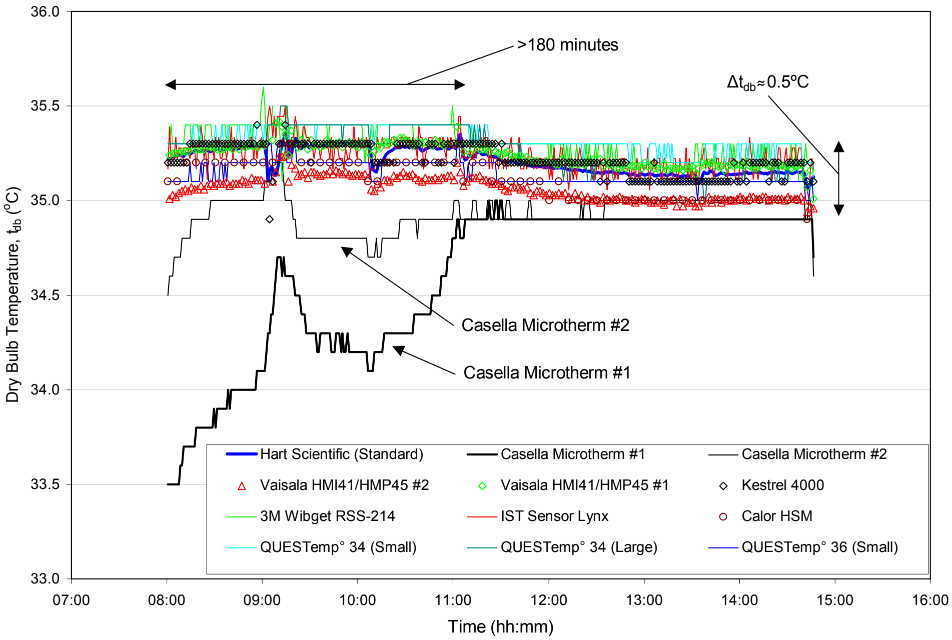

Figure 1. Instrument response example against time during the controlled environmental chamber test at nominally 35ºC

standard errors < 0.360. For any instrument with a t_g sensor, its response was also shown to be identical to the t_{db} sensor under these non-radiant heat conditions. During these controlled environment chamber comparisons, the performance of the two Casella Microtherm units was noticeably different from the other instruments. Figure 1 shows these units as taking much longer to reach the same t_{db} response as the other sensors at 35°C. This delay although not observed at 15°C became increasingly apparent as the temperature increased. The same anomalous performance was also noted for the t_g sensor of both units. The cause for this delay is unknown and was not observed for this instrument in any of the other comparison tests.

2.2 Controlled Relative Humidity Comparisons.

The second comparison of instruments evaluated the responses of relative humidity sensors (typically a thin film) against t_{nwb} sensors (wet wick covered thermometers)

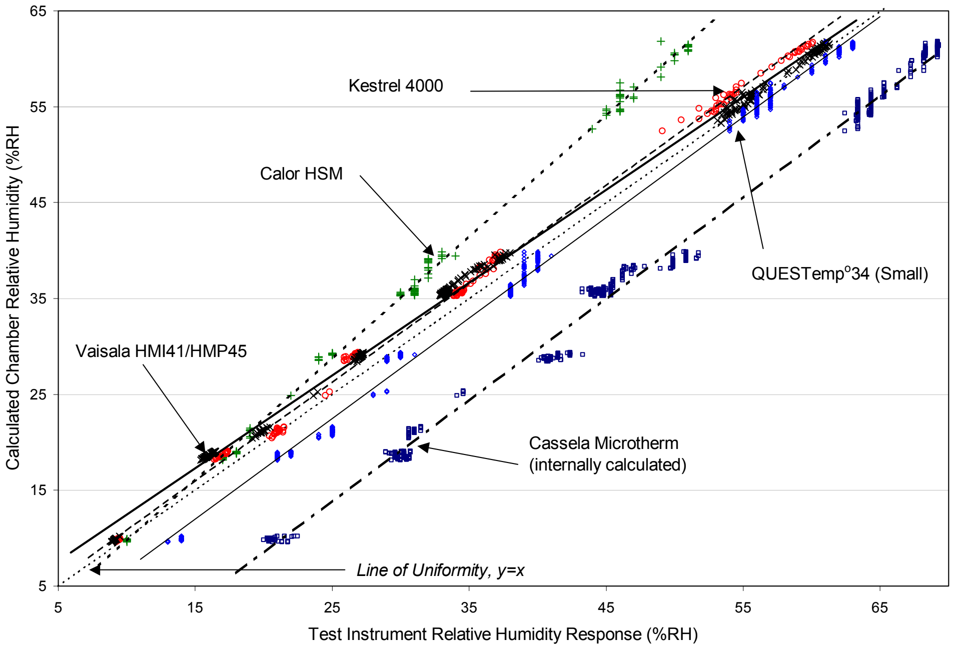

Figure 2. Comparison sample of test instruments relative humidity responses in the controlled environment chamber

and whether the two different types of sensor could be related through theoretical equations.

CANMET's environmental chamber was not designed to generate stable and homogeneous moisture content atmospheres that could be measured with a standard instrument. Consequently, this part of the simultaneous instrument comparison is based upon three days of testing performed inside the University of Ottawa's controlled environment chamber. The moisture content of the air entering and leaving this chamber was monitored with precision dew-point temperature meters. This value was converted to a relative humidity, t_{wb} and then to t_{nwb} using psychrometric software packages.

The relative humidity generated in the controlled environment chamber ranged from 10% through to 60%. The upper limit of this range decreased as the temperature inside the chamber increased; this was due to the dry condition of the ambient air and the limitations of a humidifier. It should also be noted that it was difficult to maintain, significantly change and then re-establish constant humidity conditions within a day's testing. Consequently, considerable transient or unstable data had to be rejected from the analysis. During this evaluation one of the SmartReader Plus data loggers failed, it started to respond erratically, and was removed from the comparison. Figure 2 compares some of the instrument responses against the relative humidity calculated for the chamber. This Figure highlights the following:

- All the instruments show good linearity ($R^2 > 0.992$); with the majority agreeing with the line of uniformity once their accuracy is considered. The manufacturer quoted accuracies ranged from ±2%RH to ±5%RH despite some instruments having resolutions as precise as 0.01% RH.
- The gradient of most comparisons, similar to t_{db}, was again close to unity (1 ± 0.09).
- The regression standard errors varied considerably, reflecting the resolution of the instruments which ranged from 1% down to 0.01% RH.
- The performance of the Calor HSM was significantly different with a gradient of 1.27. It increasingly underestimated the relative humidity inside the chamber; at 60%RH the Calor HSM only indicated 47%RH.
- A relative humidity value calculated by the Casella Microtherm from its measured parameters was consistently lower than that indicated by the other instruments.
- The QUESTemp°34/36 instruments, after the Calor HSM, had the greatest deviation but this is more a function of its ±5%RH quoted accuracy.

The lower relative humidity accuracy of the Casella Microtherm and QUESTemp°34/36 instruments is not considered critical. This is because it is not used in the subsequent derivation of the WBGT heat stress index.

However the accuracy of the other instruments could be an issue when relative humidity is used to determine t_{wb}. At 50±5%RH, 25°C and 101.3 kPa, the uncertainty of a t_{wb}

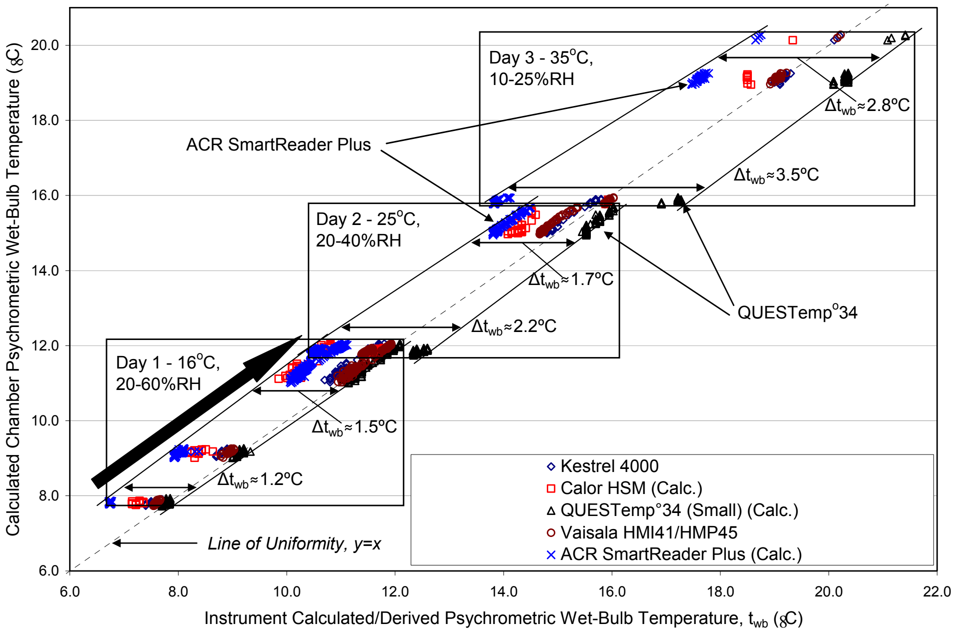

Figure 3. Comparison sample of instrument psychrometric wet-bulb temperature in the controlled environment chamber

calculation is ±0.8°C. At lower humidity this uncertainty increases and at higher humidity it decreases.

2.3 Barometric Pressure Comparison

Barometric pressure is needed to calculate t_{wb} from t_{db} and relative humidity. Most instruments are design for surface applications and consequently assume a standard barometric pressure of 101.3 kPa. However mines are becoming deeper, at 3 km the ambient barometric pressures could reach 140 kPa and failing to consider this can introduce significant errors. For example assuming standard pressure, 35°C and 30, 50 & 70%RH, would result in the t_{wb} being underestimated by 1.4, 0.8 and 0.4°C respectively. Here again the potential error is highest at low humidity. These errors will decrease slightly with increasingly higher t_{db}, at 55°C and 30 & 70%RH, the underestimation drops to 1.2 and 0.25°C, respectively.

Only two of the instruments tested, the Calor HSM and Kestrel 4000, were able to measure barometric pressure. These units were compared over a 110-145 kPa range against a Digiquartz® Model 745 Portable Standard barometer (Paroscientific Inc.). This test was known to exceed the quoted specifications of the instruments. However for the type of silicon piezoresistive sensor used, this was believed to more of a calibration limit, rather than response limit. The comparisons showed both units to be extremely linear with these regression analysis results:

- Kestrel 4000, range 105-127kPa
  Corrected (kPa) = 1.0036 x Reading - 0.290
  R^2 = 0.9999, Standard Error 0.0098
- Calor HSM, range 105-119kPa
  Corrected (kPa) = 1.012 x Reading - 0.783
  R^2 = 0.9999, Standard Error 0.0269

Based on these analyses, both instruments appear to measure pressure with suitable precision and accuracy to determine t_{wb}. If the instruments could measure 140 kPa, their correction would be less than 1 kPa, which is insufficient to affect the calculation accuracy of t_{wb}. However, both instruments showed unique characteristics at some pressure beyond their operational specifications:

- The Calor HSM indicated a believable value of 120 kPa regardless of the degree of over-pressurization. However it continued to calculate the t_{nwb} but the determination seemed to be incorrect for the apparent measured values.
- Initially the Kestrel 4000 indicated what appeared to be random and obviously erroneous values ranging between 25 and 230 kPa. However, with increasing over-pressurization it also displayed credible values that were ≈30 kPa below the true barometric pressure. It also continued to calculate t_{wb} correctly but based upon the apparent measured value.

2.4 Psychrometric Wet-Bulb (t_{wb}) Determination

None of the instruments evaluated measure t_{wb} directly; it was calculated internally from t_{db} and relative humidity

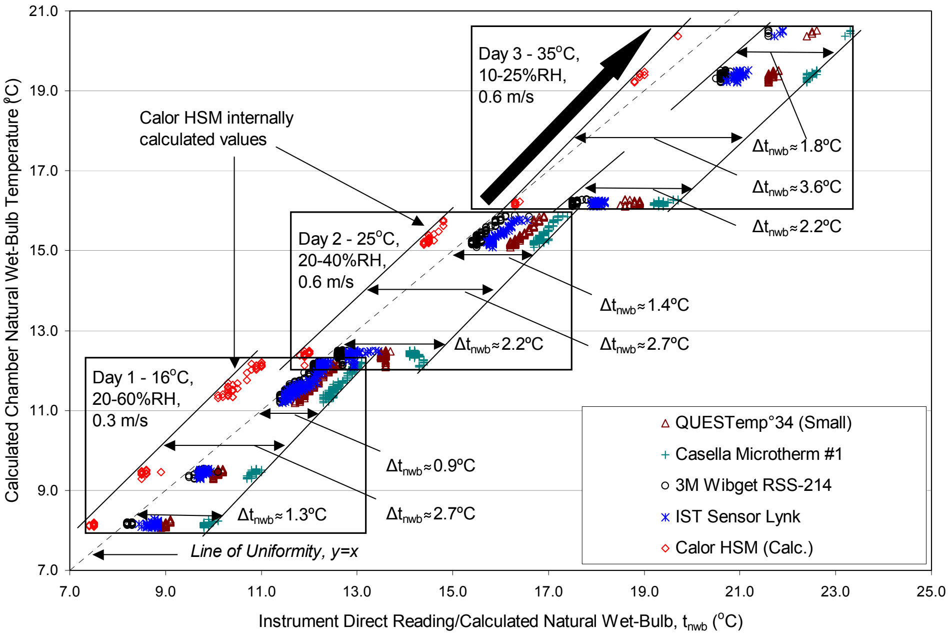

Figure 4. Comparison sample of instrument natural wet-bulb temperature response in the controlled environment chamber

with either a measured, user-entered or standard barometric pressure.

The comparison of derived t_{wb} was again based upon a series of tests performed in the controlled environment chamber at the University of Ottawa. Figure 3 showing some of the instrument response against the t_{wb} calculated for the chamber, highlights some of the trends observed in these tests. Similar to the previous comparisons all the instruments showed good linearity with R^2 typically > 0.9 for the full test range, but with higher standard errors. However, even better linearity was achieved for each individual test day. This can be explained through Figure 3 where the data points are identified by test day:

- Each day each instrument appeared to have a slightly different performance characteristic for each day of testing.
- The spread between maximum and minimum t_{wb} derived for each instruments increased each day with increasing t_{db}.
- Each day, the spread in t_{wb} generally decreased with increasing humidity. The only exception to this being on Day 1 as a consequence of the Calor HSM's different humidity response.

The calibration accuracy of the individual relative humidity sensors is a major contributor to the spread in calculated t_{wb}. The outliers below the line of uniformity are from the QUESTemp°34 with its ±5%RH accuracy, the furthest outliers above the line of uniformity belong to a SmartReader Plus data logger at ±3%RH; neither of these instruments was designed for the determination of t_{wb}.

The truest measuring instruments, i.e. closest to the line of uniformity, were the Vaisala units with a quoted accuracy of ±2%RH and the Kestrel 4000 with ±3%RH. Both of these units were designed to provide t_{wb}.

The Calor HSM, which probably calculates the t_{wb} in order to then derive a t_{nwb}, failed to perform as well as the Vaisala and Kestrel instruments. However, this was a consequence of its differing relative humidity response.

2.5 Natural Wet-Bulb (t_{nwb}) Response

The four "WBGT" instruments measure t_{nwb} directly through evaporation; in the Calor HSM it was internally calculated from other measured parameters. Figure 4 compares some of the instrument responses against the t_{nwb} calculated for the controlled environment chamber. This calculation used the air velocity measured by the Calor HSM. Similar to t_{wb}, all the instruments showed good linearity across the evaluated range but again even better linearity per test day. Figure 4 shows the following:

- All the instruments measuring t_{nwb} directly indicated temperatures higher than that calculated, i.e. they are below the line of uniformity.
- The Calor HSM was the only instrument to give t_{nwb} values lower than those calculated for the controlled environment chamber. This can again be attributed to this unit's different relative humidity response.

- Not all of the spread in measured readings falls within the quoted accuracy of up to ±0.5°C, for the instruments.
- Within each test day, the spread in t_{nwb} measured by the instruments, decreased with increasing relative humidity.
- Across the three days, the spread in t_{nwb} measurements and their deviation from the line of uniformity both increase with increasing t_{db} and air velocity, and decreasing relative humidity.

One possible cause of each day's differing performance is a potential error in the observed air velocity within the controlled environment chamber. As the flow through the chamber did not change significantly, the velocity should have remained relatively constant at a low value. Upon assuming all tests were performed at 0.3m/s it becomes apparent that a calculated t_{nwb} is very sensitive to air velocity and relative humidity. On Day #3, at 10%RH, using 0.6m/s in the calculation of t_{nwb} for the chamber would have resulted in an underestimation of 0.5°C, and at 25%RH it would have been 0.3°C. With increasing humidity, the underestimation continues to decrease; on Day #2 it would have ranged from 0.2 to 0.3°C. The net effect of these potential underestimations would be to bring the direct measured results from Days #2&3 closer to the line of uniformity.

The other factor that could affect the measured results is the evaporation characteristics of each instrument. At low air velocities, a different saturated micro-climate could exist around the wetted wick of each instrument. This condition, if real, would decrease with increasing air velocity. This possibility was supported in the observed results, the Wibget and SensorLynx (both originally manufactured by IST Corp.) were the closest to the line of uniformity, next were the three QUESTemp°34/36 instruments and the two Casella Microtherm units were the furthest away. Each manufacturer's instrument had a different configuration t_{nwb} sensor.

2.6 Natural Wet-Bulb (t_{nwb}) Calculation

Another possible cause for the discrepancy between the measured and derived t_{nwb} is the calculation employed. This analysis used the theoretical derivation developed by Brake (2001) as employed in the Hotwork™ software package (MVA, 2005); this relationship was based upon psychrometric/evaporation theory. This theoretical derivation was the preferred method as it permitted a sensitivity analysis to determine the effect of increased barometric pressure in deep mines and could be implemented as a "user function" in common data analysis spreadsheets. The only other readily usable method found to determine t_{nwb} was from the work of Bernard and Pourmoghani (1999) as available in a psychrometric spreadsheet (Bernard, 2005). Here the determination of t_{nwb} is based upon an empirical relationship derived from laboratory measurements under standard pressure conditions.

A comparison of these two methods, at standard barometric pressure, shows that they do not agree especially at low relative humidity. At 35°C t_{db} and t_g with 60%RH, the differences are minor, they generally agree within 0.2°C, which is within the accuracy of most instruments. At very low humidity, such as 10%RH the driest condition within the tests, the discrepancy between t_{nwb} determinations can be up to ≈0.6°C. Although still small, this discrepancy can significantly increase the overall uncertainty of any calculation.

The sensitivity analysis also showed another major difference between the empirical and theoretical derived values. Both show that at low air speeds, t_{nwb} is always greater than t_{wb}. As the velocity increases, the empirical t_{nwb} converges toward the t_{wb} with both being identical at 3 m/s or greater. However, with the theoretical t_{nwb} it decreases faster with increasing air speed, drops below the t_{wb} and settling at a fairly stable value beyond 3 m/s. This could be a failing of the current theoretical method.

3 Ambient Environment Comparisons

Two further sets of performance comparisons were carried out under what might be considered typical or expected ambient environment operating conditions. These two sets of tests explored:

- The sensitivity of the instruments to three differing radiant heat loads.
- Performance in an underground mine at above standard barometric pressures.

3.1 Globe (t_g) and Dry-bulb (t_{db}) Response to Radiant Heat

All the "WBGT" instruments and the Calor HSM employ a temperature sensor inside a blackened hollow globe to provide a t_g measurement. This is representative of heat given off by radiant heat sources such as the sun. Many of these instruments use a small globe to speed-up the response time of the unit; however all are quoted as being corrected to match the performance of a "standard" 150 mm Vernon globe.

Figure 5 provides a sample from the outdoor comparison of the t_g response for some of the commercial instruments. Also included are t_g values from the high precision Hart Scientific temperature probe inserted to the centre of a "standard" 150 mm black hollow copper globe and the shrouded t_{db} measured by a QUESTemp°34. Figure 5 shows the t_g sensors responded at different speeds and there was a 5-12°C spread in instrument responses. Despite the lack of consistency in the outdoor conditions the Casella Microtherm is an obvious outlier with a much lower response. In other tests, the Calor HSM also indicated noticeably lower t_g values compared to the majority of instruments but not to the same degree as the Casella Microtherm.

The outdoor series of tests also indicated that the t_{db} response of virtually all the units evaluated was affected, to varying degrees, by radiant heat exposure. The only exceptions were the QUESTemp°34 sensors which

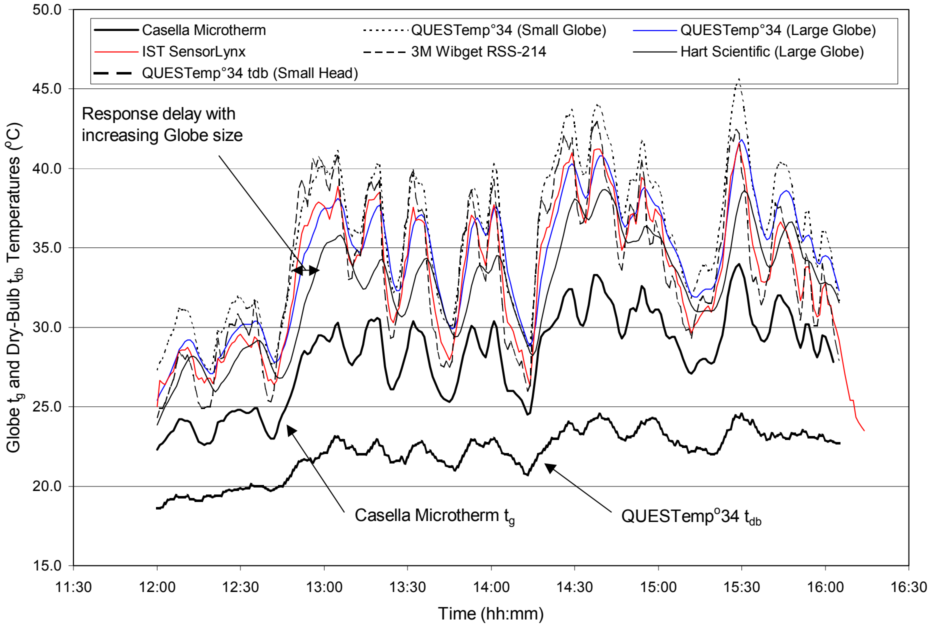

Figure 5. An example of instrument tested outdoor globe temperatures responses during intermittent sun conditions

outdoor data shown in Figure 5, there was up to a 6°C spread in t_{db} instrument response.

The instruments were exposed to more severe radiant heat loads at a mine's smelting facility. In this test the instruments were located within 3-4 m of a furnace at 300°C. Although this location provided a consistent radiant heat load, it was not possible to ensure each instrument was the same distance from the heat source. Consequently, any difference in t_g response was more likely due to the distance from the heat source rather than differing performance. However, within the furnace test, the results seemed to indicate that even the shrouded t_{db} sensor of the QUESTemp°34 could be affected in close proximity to high radiant heat sources.

In the underground tests performed to date, there was little difference between the temperatures of the air and surrounding rock. Consequently, there was no significant difference between the measured t_{db} and t_g temperatures.

3.2 Mine Environment Comparisons – Direct Readings

Throughout four underground evaluations with t_{db} ranging from 22 to 29°C, after considering their quoted accuracy all the tested instruments indicated the same t_{db}. Across the ten to fifteen instruments compared on any day, generally they all agreed within 1°C; this performance was comparable to the controlled environment tests.

Similarly, the four to seven t_g measuring instruments also agreed within 1-1.5°C in the underground comparisons. Under these non-radiant conditions, the t_g effectively became a slow responding t_{db} sensor.

The direct reading t_{nwb} instruments showed variable agreement dependant upon the relative humidity. Across the four underground test sites, the t_{nwb} ranged from 16 to 22°C, however on any individual day the agreement ranged from within 0.5°C at 85%RH through to within 2°C at 30%RH. It was also noted that the instruments response followed the same order as observed in the controlled tests, the Wibget and SensorLynx reading lowest, followed by the QUESTemp units and the Casella Microtherm instruments indicating the highest t_{nwb}.

In the underground tests the direct reading relative humidity meters also showed variable performance. With the exception of one day, two Vaisala and the Kestrel instruments showed good agreement, typically within a 2-3%RH spread. However, for some unknown reason, both Vaisala units gave consistent but anomalous results during one underground test. The QUESTemp instruments, up to three units, also generally agreed with the Kestrel and Vaisala units but the spread increased to 5-6%RH, a function of their lower calibration accuracy. The Calor HSM always underestimated the humidity compared to the other instruments; at 20%RH it underestimated by 2-3%RH, and at 85%RH it read 15% lower. This field performance of the Calor HSM was in-line with that observed in the controlled tests.

Several SmartReader Plus data loggers included in the underground tests displayed a wide spread of responses, these ranged from nearly identical to the Vaisala and Kestrel units, through to a 5-6%RH difference. Two other SmartReader Plus units also had to be removed from the comparison due to erratic responses.

3.3 Mine Environment Comparisons – Derived Values

The two derived values of interest in this comparison were an instrument's ability to determine either t_{wb} or t_{nwb} in the absence of a direct measurement.

The Kestrel 4000 and Vaisala instruments calculate t_{wb} from t_{db}, %RH and barometric pressure. Measured values are used except for the barometric pressure by the Vaisala instruments, they used an assumed standard or user entered value. Throughout the comparisons to pressures reaching 126 kPa, the Kestel 4000 calculated the t_{wb} correctly.

The Calor HSM calculates t_{nwb} from t_{db}, t_g, %RH, wind speed and barometric pressure. Throughout all the tests the Calor HSM gave t_{nwb} values significantly lower than those measured directly; this is in part a result of the units %RH sensor underestimating compared to the other instruments. However it was also found that the unit, when compared to the Hotwork™ software using the same input parameters, seemed to be calculating a significantly lower t_{nwb} value by up to 1°C. It was also noted that the Calor HSM appeared to be using a very low barometric pressure (<80 kPa) in its calculation starting somewhere above its specified pressure range. This was despite the unit displaying 120 kPa, which was credible for the test location.

4 Discussion

This series of comparison tests has shown that certain instrument responses are affected to varying degrees by radiant heat and relative humidity conditions. Furthermore, it has also shown that some instruments could produce erroneous results due to the assumption of a standard pressure or through what appears to be incorrect calculation of derived values. However, the severity to which these instrument characteristics affect their applicability to determining a heat stress index is dependant upon their application.

The laboratory tests have shown that all instruments should be able to accurately measure t_{db} provided they are protected from radiant heat effects. This requirement is stipulated in the documentation supporting the use of the WBGT (ACGIH, 2001) but is rarely mentioned elsewhere. The only instruments adequately protected from radiant heat effects, providing they are not extreme, are the QUESTemp°34 & 36. However, in underground environments this should not be an issue.

The laboratory tests have also shown that for instruments employing temperature sensors to determine t_g and t_{nwb}, these sensors are as accurate as and agree with the t_{db} sensors. However, their individual performance starts to differ when configured to measure t_g and t_{nwb}.

According to the manufacturer specifications the t_g of each instrument has, where applicable, have been normalized to reflect that inside a standard 150 mm (6") diameter matt black painted copper sphere. As expected the outdoor tests showed the different sized globes affected the response speed. It was also noted that the Calor HSM and Casella indicated a much lower t_g, often in excess of -5°C, when compared to the other instruments. The reasons for this were not investigated. However, from the underground tests performed to date the variable performance of the globe sensors is not an issue. This is due to the lack of any significant difference between t_g and t_{db} in these underground environments.

The instruments that measured t_{nwb} directly also displayed differing response characteristics especially at low to negligible airspeeds. However the magnitude of difference was a function of the relative humidity. At high humidity, regardless of wind speed, all the instruments generally showed good agreement, i.e. at 85%RH a spread of 0.5°C. Whereas at low air speed and low humidity, i.e. 10%RH, the spread increased to >2°C. This humidity is below what could be expected in an underground mine, but even for the lowest observed mine condition of 30%RH the spread still approached 2°C. This could be significant in the determination of a work-to-rest ratio. A potential reason for the discrepancy could be the different evaporation characteristics or sensor configuration of the instruments. This possibility is supported by the instruments agreeing by manufacturer, but then disagreeing between manufacturers.

The application of available theory also showed that the measurement of t_{nwb} was extremely sensitive to air speed consequently slight spatial variation in the air speed between each instrument's measurement location could also contribute to this difference.

Using the available theory it was unable to confirm which instrument provided the correct t_{nwb}. Throughout, there were noticeable differences between the theoretical derivations from basic parameters and the measured t_{nwb} values. Similar to the spread in t_{nwb} readings, the lack of agreement with theory increased with decreasing relative humidity. Therefore, based upon the tests and analysis performed to date it is impossible to state which instrument should be used to determine t_{nwb} at low relative humidity.

Several of the instruments tested measured %RH and some then used this value to determine t_{wb} or t_{nwb}. Here the tests showed that most of the instruments agreed with each other and independently derived theoretical values. However, the degree to which they agreed, i.e. the spread in readings or deviation from theoretical values, was a function of their calibration accuracy. The truest %RH instruments were those with quoted accuracies of ±2-3%RH. The only instrument with a significantly different %RH response was the Calor HSM, it increasingly reported lower values as the relative humidity increased. At 20%RH this instrument would be comparable with the others however when it indicated 50%RH, the other instruments and theory gave 70%RH.

The accuracy of the %RH determination has also been shown to affect the subsequent precision of an instrument's t_{wb} or t_{nwb} calculation. At 50% ±5%RH the uncertainty of a t_{wb} calculation can be ±0.8°C; again this would increase with lower relative humidity. Consequently only those instruments with high accuracies such as ±2-3%RH should be considered when trying to determine t_{wb}. In this series of tests only the Vaisala and Kestrel 4000 instruments were confirmed to be of this order of accuracy and their calculation of t_{wb} shown to agree with theory. Based upon the observed %RH performance, the Calor HSM would not provide an accurate determination of t_{wb}, furthermore due to the lack of appropriate theory it was not possible to determine if its subsequent calculation of t_{nwb} was correct.

In deep underground mines, barometric pressure needs to be included in the calculation of t_{wb} or t_{nwb} from %RH. At 140 kPa as may be encountered at 3000 m below surface, it has been shown that t_{wb} could be underestimated by 0.25 to 1.4°C depending on the %RH and t_{db}. Here again, the %RH is the most dominant factor and is most noticeable at low humidity. Of the units tested, the Calor HSM and Kestrel 4000 contained a barometer that was of suitable precision for the calculation of t_{wb}. However the currently calibrated range of these units, as tested, is not sufficient for deep mines. Furthermore, it is possible for these instruments to display t_{wb} incorrectly. The Kestrel 4000 calculates a "correct" value based upon the apparent observed barometric pressure, above 127 kPa the unit tested started to give erroneous pressure results but still continued to calculate t_{wb}. Some of these pressures could appear credible if they weren't verified against a high range barometer. The Calor HSM appears to be using its observed pressure correctly despite the limitations of the theory up to a certain pressure. However, upon over-pressurization it displays 120 kPa, which again could be credible, but in its subsequent calculations it appears to be using a much lower barometric pressure. Based upon these findings, it is recommended that these two instruments not be used beyond their manufacturer's or otherwise verified barometric pressure specifications.

An alternative to the direct barometric pressure reading units is the Vaisala Humidity Indicator; this instrument has the option for the user-input of barometric pressure. This negates the potential incorrect determination of t_{wb} based upon an erroneous apparent barometric pressure.

5 Conclusions

This study has shown that the determination of a heat stress index based upon measured environmental parameters is not straightforward. Although all the instrument sensors tested can measure temperature accurately, significant discrepancies start to appear in their response when configured to measure globe and natural wet-bulb temperatures. Furthermore without protection, dry-bulb temperatures can be affected by radiant heat.

The discrepancies in natural wet-bulb temperature is greatest at low relative humidity, this includes 30%RH which can occur in underground mines. At high humidity the discrepancy can become negligible as it is comparable to the specified accuracy of the instruments.

In the absence of a suitable radiant heat test, and a lack of appropriate theory to calculate natural wet-bulb temperature at low air speeds, it was not possible to state which sensors/instruments were correct. Consequently with the instruments as tested, there can be considerable uncertainty in any heat index determination using globe and/or natural wet-bulb temperatures at low airspeeds.

With increasing air velocities the natural wet-bulb temperatures show improving agreement and trend towards the psychrometric wet-bulb temperature. However, at this point "dry" instruments can be considered.

This study has shown that certain instruments measuring relative humidity to within ±2-3%RH can then determine the psychrometric wet-bulb with suitable precision. However when used in mines it is important to ensure changes in barometric pressure are also considered.

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Disclaimer

The authors would like to stress that the findings presented in this paper are based upon the tests performed and the instruments as tested. All new instruments were purchased with their standard calibration certificate; loaned instruments were checked where possible against secondary standards. Some of the instruments have also been returned for recalibration however any improvement in performance has not yet been verified.

Furthermore, the views expressed in this paper are purely those of the authors, they are provided for educational purposes only, as such they not do represent the views of the Government of Canada.

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