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1. INTRODUCTION

In 1973, the National Weather Service of the U.S. (NWS) adopted the concept of wind chill to describe the effect of the wind on the loss of body heat, resulting in persons feeling colder than would be indicated by the air temperature alone. A chart was issued with equivalent temperatures called wind chill temperatures (WCT) that, with still air, would result in the same rate of heat loss from exposed skin as that under actual conditions of dry bulb temperature and wind speed. The chart was based on the work of Siple and Passel (1945) performed in an Antarctic winter. Subsequently, many researchers concluded that this chart was in error, that it exaggerated the effect of the wind and its WCT's were too cold. These included Bluestein (1998), Buettner (1952), Burton and Edholm (1955), Elsner and Bolstad (1963), Kessler (1993), Milan (1961), Molnar (1960), Osczevski (1995), and Steadman (1971). The major faults in the original work are great variability in the data points, insufficient data at high wind speeds, neglect of the thermal resistance of the container used in the freezing of water in the study, and an assumption of too high a skin temperature. The error is compounded when the calculated WCT is associated with the wind speed as reported at the local weather station. Such speeds are measured 10 m above the ground and are significantly greater than those at face level.

As result of an internet conference on WCT hosted in 2000 by the Canadian weather service, Environment Canada (EC), the NWS convened a group of interested parties and researchers to evaluate the state of the art in WCT determination and to recommend a better approach. This group, called the Joint Action Group for Temperature Indices (JAG/TI) included members of the NWS and the EC and had as its first objective a WCT chart that would be easy to understand, could be utilized by all North American weather services, and would be scientifically valid. The group concluded that the alternative proposals published by Osczevski (1995) and Bluestein and Zecher (1999), using the same heat transfer principles, offered the best opportunity for a more accurate WCT chart. Osczevski and Bluestein, both members of the group, were designated by the JAG/TI to work together to develop a new WCT chart to be ready for the 2001-2002 winter season. This was accomplished and

implemented in the U.S. and Canada in November, 2001. This paper describes the technical basis for this new chart.

2. ASSUMPTIONS

To avoid consideration of clothed individuals, areas of exposed skin were concentrated on. In winter, the area most exposed is the face. The convective heat loss from the face in wind was approximated by calculating the convective heat flow from the upwind side of a vertical cylinder in cross flow. This is more appropriate than the inclusion of the heat transfer from the full cylinder as explained by Osczevski (2000). The diameter of this cylinder was assumed to be 18 cm. Heat transfer was calculated at cylinder locations that are 50 degrees to the wind, equivalent to mid-cheek. Here the convective heat transfer rate is about equal to the average over the front 160 degrees of the cylinder. The face would be facing into the wind in the worst-case scenario. Such a model in a cross flow wind has been studied in the literature. The rate of convective heat loss from such a cylinder was determined by the method reported in Kreith (1976), which fits the range of Reynolds Numbers and Prandtl Numbers encountered. The rate of heat loss by radiation is a function of the temperatures of the cylinder surface and the air as defined in Incropera (1996).

The equivalent air speed for the still air condition was reexamined. Siple and Passel used 1.79 m s^{-1} (4 mph), which was felt to be excessive. A still air speed of 1.34 m s^{-1} (3 mph) was used as it represents an average walking speed. For the new chart, it was assumed that the adult would be walking into the wind in the worst case and so this speed was added to the actual wind speed at face level in developing the wind chill temperature.

Lastly the wind speed at face level was assumed to be two-thirds of that measured at the 10 m height of the weather stations. This was based on the analysis by Steadman (1971) and refers to the ratio in an open field. This was considered a worst case condition even though the ratio in an urban area could be considerably less.

3. METHODS

Using the above definitions of the wind chill temperature and the still air condition, The WCT is found from equation (1).

$$h_o (WCT - T_s) = h (T_a - T_s) \quad (1)$$

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where h_o is the overall heat transfer coefficient at the skin in still air, T_s is the skin surface temperature, T_a is the dry bulb air temperature, and h is the overall heat transfer coefficient at the skin for the actual state of the air. The appropriate units are $W (m^2 K)^{-1}$ for heat transfer coefficients and degrees Kelvin for temperatures. Degrees Celsius may be used here since differential temperatures are being considered. Equation 1 is applied to the exposed face after the steady state has been established. The equation requires the final skin temperature, which is not known a priori. The heat transfer coefficients depend on the skin temperature so this equation cannot be solved outright for WCT. Thus an iterative procedure was selected using an initial estimate of the skin temperature.

The procedure is based on an electrical analogy of the heat transfer path from the internal body to the outside air as shown in Figure 1.

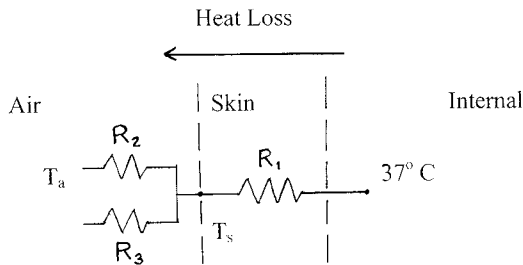


Figure 1. Electrical Analogy for Heat Transfer Path

Each resistance element represents a resistance to heat transfer; from the internal body temperature of 37°C to the skin is conduction (R_1). From the skin to the outside air are two parallel resistances, convection (R_2) and radiation (R_3). Resistances are in units of m^2KW^{-1} . In the steady state, heat transfer from the internal body to the skin must equal that from the skin to the air via the parallel paths of convection and conduction. Note that any incoming solar radiation was not considered as it was not part of the JAG/TI mandate at this point. R_1 was determined by a human trial conducted in a test chamber at the Defence and Civil Institute of Environmental Medicine in Canada (now known as DRDC Toronto). Twelve adult volunteers, aged 22 to 42 with a mean of 33 years, were instrumented for skin and rectal temperatures and subjected to a variety of cold air temperatures and wind speeds at their face while walking on a treadmill at $1.34 ms^{-1}$. Test conditions were continued for 90 minutes. Analysis of the results showed a range of skin conduction resistance. The resistance used in the model was the 95th percentile value of resistance from the experiments, as a worst case. This value, $0.091 m^2KW^{-1}$, is appropriate for a less fit population, which is at greater risk for frostbite.

A steady state internal body temperature of 38°C was assumed in the model, which is appropriate for individuals walking at $1.34 ms^{-1}$, and was verified by the human trial.

WCT for a given air temperature and wind speed is determined as follows:

A reasonable steady state estimate is made for the skin temperature. The Reynolds Number and Prandtl Number for the airflow are determined with density and viscosity based on sea level conditions. The convection heat transfer coefficient h_c is determined from the equations developed by Kreith (1976). Next the radiation heat transfer coefficient h_r is calculated using the Stefan-Boltzmann relationships. These coefficients are the inverses of the resistances R_2 and R_3 respectively. Using the assumed conduction resistance value, the total heat transfer rate Q in watts is given by equation (2).

$$Q = (38 - T_a) [0.091 + (h_c + h_r)^{-1}]^{-1} \quad (2)$$

This equation is solved using the values of the heat transfer coefficients found from the assumption of a skin temperature. In the steady state, this Q is the same as that between the internal body and the skin. Thus a refined value of the skin temperature can now be found by solving the conduction equation (3) for T_s .

$$Q = (38 - T_s) (0.091)^{-1} \quad (3)$$

This calculated skin temperature replaces the original estimate and the above procedure is repeated with new values for the coefficients. The process is repeated again until the skin temperature and heat transfer rate converge to a constant value; this usually occurs quickly.

The values of T_s and Q are now applied to the still air condition so that equation (1) may be solved for the WCT. With a wind speed of $1.34 ms^{-1}$, a Reynolds Number is calculated and used to find a corrected convective heat transfer coefficient. A radiation coefficient is also found, both using the actual air temperature since WCT is not yet known. Now equation (4), representing heat transfer between the skin and the still air, is utilized to solve for WCT.

$$Q = (h_c + h_r) (T_s - WCT) \quad (4)$$

Now the coefficients are corrected using the WCT as the air temperature and this still air equation is solved again. This process is repeated until the WCT converges to a steady value. Using an Excel spreadsheet, the iterations may be done quickly for various combinations of air temperature and wind speed.

4. RESULTS

WCT's were found for the range of 40F to – 40F and 5 to 60 mph in increments of 5 units, and a range of 10C to –50C and 10 to 60 kmh⁻¹ with 5 unit increments in SI units. The results were submitted to the JAG/TI in the summer of 2001.

The results were acceptable to the NWS but the service was unable to utilize the iterative procedure in their computers. A multiple linear regression was carried out to obtain best-fit equations for each unit system, following the form suggested by Quayle and Steadman (1998). The solutions for the combinations of air temperature and wind speed in the desired ranges resulted in the final WCT charts shown in Tables 1 and 2 with the appropriate best-fit equations.

The WCT charts also include estimates of the frostbite risk at various conditions. These are based on a time-dependent model of facial cooling being developed by Tikuisis and Osczevski (2002) and uses a target skin temperature of –4.8C for a 5 percent risk of frostbite onset, as indicated by Danielsson (1996). It should be noted that frostbite risk is not consistent with a fixed WCT but is greater at high wind speeds and moderate temperatures than at low speeds and very cold temperatures. This is because the rate of cooling of the skin is more sensitive to wind speed than to air temperature so the skin temperature drops more sharply with greater wind than with colder air. In two different sets of conditions having the same wind chill temperature, the critical skin temperature of –4.8C will be reached more quickly with a higher wind speed and warmer temperature, although the final steady state skin temperature is the same.

5. CONCLUSION

A new wind chill temperature chart has been developed and implemented by the weather services of the U.S. and Canada. It is based on modern heat transfer theory and substantiated by a human trial. The resultant WCT values confirm the conclusions of other researchers that the earlier chart overstated the effects of high wind speeds. The new chart omits consideration of solar radiation effects, which will be evaluated in subsequent research.

6. REFERENCES

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**Table 1. The new Wind Chill Temperature (WCT) Index chart, with
T = Air Temperature in F and V = Wind Speed in mph at 33 feet
elevation, , which is corrected to 5 ft via the equation.**

$$\text{WCT (F)} = 35.74 + 0.6215T - 35.75V^{0.16} + 0.4275TV^{0.16}$$

		Temperature F															
Wind mph	Calm	32	30	25	20	15	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40
	5	27	25	19	13	7	1	-5	-11	-16	-22	-28	-34	-40	-46	-52	-57
	10	24	21	15	9	3	-4	-10	-16	-22	-28	-35	-41	-47	-53	-59	-66
	15	22	19	13	6	0	-7	-13	-19	-26	-32	-39	-45	-51	-58	-64	-71
	20	20	17	11	4	-2	-9	-15	-22	-29	-35	-42	-48	-55	-61	-68	-74
	25	19	16	9	3	-4	-11	-17	-24	-31	-37	-44	-51	-58	-64	-71	-78
	30	18	15	8	1	-5	-12	-19	-26	-33	-39	-46	-53	-60	-67	-73	-80
	35	17	14	7	0	-7	-14	-21	-27	-34	-41	-48	-55	-62	-69	-76	-82
	40	16	13	6	-1	-8	-15	-22	-29	-36	-43	-50	-57	-64	-71	-78	-84
	45	15	12	5	-2	-9	-16	-23	-30	-37	-44	-51	-58	-65	-72	-79	-86
	50	14	12	4	-3	-10	-17	-24	-31	-38	-45	-52	-60	-67	-74	-81	-88
	55	14	11	4	-3	-11	-18	-25	-32	-39	-46	-54	-61	-68	-75	-82	-89
	60	13	10	3	-4	-11	-19	-26	-33	-40	-48	-55	-62	-69	-76	-84	-91

Frostbite may occur in 30 minutes or less

**Table 2. The new Wind Chill Temperature (WCT) Index chart, with
T = Air Temperature in C and V = Wind Speed in km/h at 10m
elevation. WCT (°C) = 13.12 + 0.6215T – 11.37V^{0.16} + 0.3965TV^{0.16}**

		Temperature °C												
Wind km/h	Ca	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45	-50
	10	8.6	2.7	-3.3	-9.3	-15.3	-21.1	-27.2	-33.2	-39.2	-45.1	-51.1	-57.1	-63.0
	15	7.9	1.7	-4.4	-10.6	-16.7	-22.9	-29.1	-35.2	-41.4	-47.6	-51.1	-59.9	-66.1
	20	7.4	1.1	-5.2	-11.6	-17.9	-24.2	-30.5	-36.8	-43.1	-49.4	-55.7	-62.0	-68.3
	25	6.9	0.5	-5.9	-12.3	-18.8	-25.2	-31.6	-38.0	-44.5	-50.9	-57.3	-63.7	-70.2
	30	6.6	0.1	-6.5	-13.0	-19.5	-26.0	-32.6	-39.1	-45.6	-52.1	-58.7	-65.2	-71.7
	35	6.3	-0.4	-7.0	-13.6	-20.2	-26.8	-33.4	-40.0	-46.6	-53.2	-59.8	-66.4	-73.1
	40	6.0	-0.7	-7.4	-14.1	-20.8	-27.4	-34.1	-40.8	-47.5	-54.2	-60.9	-67.6	-74.2
	45	5.7	-1.0	-7.8	-14.5	-21.3	-28.0	-34.8	-41.5	-48.3	-55.1	-61.8	-68.6	-75.3
	50	5.5	-1.3	-8.1	-15.0	-21.8	-28.6	-35.4	-42.2	-49.0	-55.8	-62.7	-69.5	-76.3
	55	5.3	-1.6	-8.5	-15.3	-22.2	-29.1	-36.0	-42.8	-49.7	-56.6	-63.4	-70.3	-77.2
	60	5.1	-1.8	-8.8	-15.7	-22.6	-29.5	-36.5	-43.4	-50.3	-57.2	-64.2	-71.1	-78.0

Frostbite may occur in 30 minutes or less