CHAPTER 3

WCT INDEX ALGORITHM ADVANCED DEVELOPMENT, VERIFICATION, AND VALIDATION

3.1 Introduction. From the formation of the JAG/TI in the fall of 2000, all participants were anticipating how their agency could incorporate recommended improvements to their temperature indices as quickly as possible. As a result, the JAG/TI built into their approved advanced research development recommended deadlines for finishing various aspects of the development, including provision of algorithms and completion of verification and validation. Some of these deadlines were adjusted as the research activities progressed. The first JAG/TI goal was to upgrade or replace the WCTI for the 2001/2002 winter season. Funding for the development project was provided by DRDC, OFCM, and CRREL, with project management provided by OFCM. Reports on the WCTI advanced development, verification, human studies and reverification of the WCTI were provided to JAG/TI by IUPUI and DRDC during the February 14-15 and August 2-3, 2001 workshops.

3.2 Advanced Development and Verification Report. After the first JAG/TI Workshop in October 2000, DRDC and IUPUI began working together on a consensus approach to developing an index based on their existing indices (Bluestein and Osczevski 2002). This new WCTI would be easily utilized by weather forecasters. At the February 2001 Workshop, DRDC and IUPUI reported that their plan was to conduct human studies in the July/August 2001 time frame, with the index ready by October 1, 2001, for the winter season. In addition, twelve human volunteers were needed for the studies. MSC said they would assist with the provision of volunteers. The proposed time frame for the development project was a concern to the group because of the lead time needed to complete internal NWS and MSC coordination, public notification of changes (at least 60 days), public education on the replacement index, and necessary reprogramming of the computers used by forecasters before the start of the 2001-2002 winter season. As a result, the group requested provision of the basic theoretical algorithms and assumptions by May 2001. This would permit MSC and NWS to begin developing the computer software programs and the public education package ahead of time. The group agreed that a mid-May 2001 time slot for the human studies would be better than July/August 2001 for completing the project development work. The preliminary index algorithm was needed by early June (later revised to July10th) for development of software changes to the NWS Advanced Weather Interactive Processing System (AWIPS). The final index algorithm was required by both NWS and MSC no later than August 2, 2001 to ensure adequate time for the final software changes and for coordination and public comment before the start of this year's winter season.

3.2.1 WCT Parameters. The adult face, modeled as the front half of a vertical cylinder, was used as the area affected by the wind since the face was usually exposed to the cold weather. An appropriate frontal diameter, 180 mm, was used for the model. The cylinder's length was of little consequence in considering heat loss from the surface to the air.

A typical walking speed was assumed to be 3 mph (1.34 m s^{-1} or 4.8 km h^{-1}). This value was obtained from published studies of pedestrians crossing streets at intersections. As a worst case, it was assumed that the person would be walking into the wind. This walking speed was added to the wind speed for the actual conditions to determine the effect of the wind chill.

DRDC reported that the solar radiation calculation requested by the JAG/TI to be included in the new index was more difficult to do than originally thought. The members recommended using another method such as the Klima-Michel-Model (KMM), and that KMM modelers would be requested to forward their algorithms. The University of Munich, Germany, has radiation measurements and a radiation algorithm used in the KMM. This was provided to DRDC.

3.2.2 Theoretical Calculations. A steady state condition was assumed for the initial calculations. This required a determination of the skin temperature that would result in the same heat loss rate from the interior or core of the body to the skin as from the skin to the outside air. Heat transfer between two points equaled the temperature difference between the points divided by the resistance to heat flow in that path. This resistance was equivalent to the "R" factor utilized in insulation materials. Heat travels outward from the body to the skin by conduction with conduction resistance dependent on the skin temperature. The heat then travels from the skin to the air by convection and radiation. Both processes involve resistance that was again affected by the skin temperature. Since the skin temperature was not known a priori, an iterative mathematical procedure was required to determine the resistance, and thus, the heat transfer rate. In this procedure, a skin temperature was assumed and the heat transfer equations were solved for the actual air conditions yielding a closer approximation to the actual skin temperature. This result was then used in a repeated solution to the equations until the skin temperature converges to a steady value, providing the final steady state heat transfer rate.

These values of heat loss rate and skin temperature were then used with an assumed wind speed of 3 mph (1.34 m s^{-1} or 4.8 km h^{-1}) to determine what air temperature (the WCT) yielded the same loss rate. This also required iteration since the change in the air temperature from actual to WCT modified the convection and radiation resistances.

The iterative calculation was carried out on a computer, using an Excel^{tm} spreadsheet. It resulted in WCT values for temperature ranges of +45E to –50EF and +10E to –50EC versus wind speeds of 3 to 60 mph and 5 to 80 km h^{-1} (or 1.34-26.8 m s^{-1}) at increments of 5 degrees (F or C), 5 mph and 5 km h^{-1} (or 1.3 m s^{-1}).

3.3 <u>Validation of WCT Algorithms Through Human Studies.</u> While the index development process followed established heat transfer theory, human studies were done to validate the various parameters, including body temperature, skin temperature, and skin resistance, and how these change with time of exposure. The DRDC thermal chamber and wind tunnel facility was chosen by the JAG/TI because it had well-established facilities for such tests and DRDC agreed to partially fund the trials. DRDC conducted the experiments with human volunteers. The results of these trials were used to determine tissue resistance, an essential variable in the mathematical modeling and to validate the theoretical algorithm.

Six men and six women volunteered to be subjects of these studies. These subjects were capable of continuously walking at a moderate rate for 90 min, and were generally more fit than the general population. They ranged in age from 22 to 42 years with a mean of 33 years. The mean Body Mass Index (BMI) was 25.2, which is ideal for the general population from a health standpoint, but is lower than the average BMI of the general population of North America. The

BMIs of the subjects ranged from 18.5 to 32.5. Their percent body fat, measured at four points by calliper, ranged from 18.5 to 32.5% with a mean of 19.6%. The subjects were instrumented with thermocouples to measure the temperatures of the skin of the nose, forehead and both cheeks and ears. Internal temperature was measured with a rectal thermistor. Very thin transducers (RdF 20457-3) were used to measure the heat flow from the cheeks and forehead. At each of three air temperatures, 50EF (+10EC), 32F (0EC) and 14EF (-10EC), the subjects walked on a treadmill for 90 min at 3 mph (1.34 m s^{-1} or 4.8 km h^{-1}), facing into an artificially generated wind of 4.5, 11 or 18 mph (2, 5 or 8 m s^{-1}; 7.2, 17.7, or 29 km h^{-1}). In each experiment, the wind speed was initially set at 4.5 mph (2 m s^{-1} or 7.2 km h^{-1}) and was stepped up to the other two values at 30 min intervals. Skin temperatures were continually monitored to ensure that frostbite did not occur.

The following modifications were made to the initial heat transfer equations as a result of these studies. Over a wide range of temperature and wind speeds, steady state deep body temperature depended on the intensity of exercise and not on the weather. As a result, a body temperature of 38EC (100.4EF) rather than 37EC (98.6EF) was used in the model. This was based on the measurements from the volunteers who were walking at a moderate speed. It was also found that the cheeks usually were the coldest areas of the face, and therefore, should be used for the worst case skin condition. This necessitated a modification to the convective heat transfer calculation. The convective heat transfer component of the computer model was also modified to represent the heat transfer from a location on a cylinder corresponding approximately to the location of the cheek, at a 50E angle from the forward stagnation point. The convective heat transfer coefficient at this angle was equal to the average for the front 160E of a cylinder at any wind speeds that were likely to be encountered. Skin resistance was found by dividing the heat loss rate at the cheek by the temperature difference between the body (38EC or 100.4EF) and the cheek. This yielded a range of resistance values for the 12 subjects. Based on worst case conditions, the skin resistance representing the 95th percentile was used, i.e., the resistance greater than 95 percent of the observed values from the subjects in the trial. Higher resistance was associated with lower skin temperatures and a greater risk of frostbite. There was a tendency for the higher resistances to be associated with subjects who had higher BMIs. While the thermal resistance of the cheek of an individual varied with skin temperature, no correlation was evident for a population. The model was therefore changed to have a constant tissue resistance that corresponded to the 95th percentile value obtained from the experiments. The thermal resistance of the body at skin temperatures near or below the freezing point of skin (-4.8EC or 23.4EF), defined by Danielsson (1996), could not be determined in these human studies because of ethical considerations. Experimental conditions in some subjects did not result in a steady state skin temperature and heat flow from the subjects' cheeks because of Cold Induced Vasodilation (CIVD), which occurs at painfully cold skin temperatures. In CIVD, surface blood vessels open up to allow warm blood to flow from the interior of the body to the skin. This mechanism serves to protect the skin from freezing especially when the body core is warm, but might not occur if the body's temperature is subnormal. One concern with CIVD was that it can make identification of patterns difficult.

3.4 <u>WCT Algorithms - Revalidation and Reverification</u>. The initial iterative equation for the WCTI was modified based on the results of the human studies, which required they be revalidated and reverified. In addition, NWS and MSC tried to run the iterative equation on their central and forecaster computers, but soon discerned that it overwhelmed the resources of the smaller computers. This could have jeopardized the implementation of the WCTI. As a result, NWS and MSC requested, and JAG/TI approved, the researchers develop a non-iterative equation for the WCTI.

3.4.1 Revalidation and Reverification Report and Discussion. DRDC reported that the trial results picked up the variation of reaction among the test subjects and noted that the younger subjects demonstrated more reaction than the older subjects. The studies tentatively suggested that physically fit people might tend to have low skin resistance, and therefore, high heat transfer from the inner body to their skin resulting in higher skin temperatures. Additionally, less fit people might have high skin resistance with low heat transfer which prevented the warming of the skin layer. Those people who have a low transfer rate cannot keep their extremities sufficiently warm to avoid freezing of the skin layer and will be more at risk for experiencing wind chill effects. The group decided to use this case since the weather services issue warnings for frostbite and the worst-case scenario. As a result, the resistance factor in the worst case was determined to be 0.09 m^2 K W^{-1}.

It was hypothesized that the high resistance individuals may fare better in hypothermia instances because their core body heat would not be drained as fast as those with higher transfer rates. Previous studies have shown that heavier people lose less heat than thinner people. The group noted that the wind chill should be a heat transfer coefficient based on the convective heat loss due to wind, and that simplified resistance is a function of temperature. If resistance was large then there was a greater temperature gradient across the barrier. Therefore, total resistance was related to the body and convection.

The wind speed effect was not as significant as the skin resistance in the upper wind speeds. The biggest effect occurs with the gentle breezes. Therefore, the new formula was in error at zero wind speed, where the equivalent temperature should equal the air temperature because zero values were not used in the regression. As a result, the recommended starting point for the index was at 5 mph (2.2 m s^{-1} or 8 km h^{-1}), not zero mph or calm winds. The NWS recommended the chart begin at 3 mph (1.3 m s^{-1} or 4.8 km h^{-1}) which was the NWS forecast breakpoint for light and variable or calm wind conditions and the JAG/TI accepted this recommendation. Wind speed was calculated at the face level by applying a two-thirds correction factor to the observed wind speed, which was added to the walking speed to obtain an estimate of the wind speed affecting the face. It was noted that the heat transfer coefficient was proportional to the square root of the wind speed.

DRDC next discussed the results using charts and diagrams. The first chart compared the results of the new index to the old index. The results of the human studies were also presented. As previously mentioned, the twelve subjects ranged from 22 to 42 years in age, from 10 to 27% body fat, and from 18.5 to 32.5 BMI. The wind chill chart incorporated a minimum wind speed of 3 mph, equal to walking speed. The algorithm was run out to 200 km h^{-1} (124.3 mph or 55.6 m s^{-1}) and the regression equation seemed to fit the model calculations reasonably well over the whole range.

The effect of solar radiation was a complex problem due to the number of parameters involved: latitude, longitude, elevation, cloud cover, time of day, and day of year. Development work on incorporating the solar radiation effects could not be completed in time to meet the weather services' operational implementation deadlines. JAG/TI decided that the initial calculation of the WCT would be based on wind alone with a solar radiation factor to be added later.

3.4.2 WCTI Equations. After making the necessary corrections indicated from the human studies, the researchers ran the iterative model over 800 times with different combinations of wind speed and air temperature. Subsequently, a multiple regression analysis of the results was performed and Equations 3.1a and 3.1b were found to best fit the data. These equations corrected the observed wind speed at 33 ft (10 m) to the height of the face. The wind speed at the level of the face in "calm" conditions was assumed to be 3 mph (4.8 km h^{-1} or 1.3 m s^{-1}). As a result, the WCT should equal the air temperature at this "calm" wind speed. These equations were used to prepare the WCTI charts which were submitted to JAG/TI for review. The weather services requested the charts be modified to identify wind chill temperatures that might be expected to produce frostbite on exposed skin in 30 min or less, in the most susceptible (95th percentile) of the population, and for a worst case scenario (night time clear). This frostbite parameter helped to establish new warning and advisory criteria. The literature suggested that 95% of the population will experience frostbite at a skin temperature of -7.8EC (18EF). Although, about 1-2% of the population might experience it at -1EC (30.2EF) and 5% may be affected at -4.8EC (23.4EF). The resulting WCTI charts (see Tables 3.1 a and b) were given in degrees Fahrenheit and Celsius, and were derived from the appropriate WCT equation. If the wind was measured at face level, the wind speed should be multiplied by 1.5 to use the equation or chart.

$$\mathbf{WCTI=35.74 + 0.6215T-35.75V^{0.16} + 0.4275TV^{0.16}} \qquad \mathbf{3.1a}$$

or

$$\mathbf{WCTI=13.12 + 0.6215T-11.37V^{0.16} + 0.3965TV^{0.16}} \qquad \mathbf{3.1b}$$

where WCTI is the wind chill temperature index, T and V are the air temperature in units of degrees Fahrenheit and wind speed in mph, respectively (3.1a), or degrees Celsius and km h^{-1}, respectively (3.1b).

3.4.3 Frostbite. DRDC continues to work on a time-dependent frost point model. A cylindrical model with 25 layers of concentric circles is being used. Each layer has thermal resistance, heat capacity, and temperature associated with it. Total thermal resistance is spread over 25 layers and adds up to 0.05. Heat is moved from warm to cold. The model is based on a dynamic model of the face and uses a finite difference approximation technique. The preliminary model calculations gave initial times to occurrence of frostbite under certain winds and air temperatures. Based on the best fit to the model results, equations 3.2a and b would be used on the NWS AWIPS computers and in DOD documents, but the equations are only valid when the frostbite time is less than or equal to 30 min and the wind speed is greater than 16 mph (7.2 m s^{-1} or 25 km h^{-1}) and less than or equal to 50 mph (22.3 m s^{-1} or 80.5 km h^{-1}). These results were also provided as a chart (see Table 3.2a and b). Table 3.2b is used by MSC and is on their web site for public use. NWS incorporated the frostbite times into the NOAA Wind Chill Chart (Table 3.3). DOD produced Wind Chill Charts for 3 heights of the anemometer (5, 15, and 33 ft or 1.5, 4.6, and 10m; Tables 3.4a-c) because of various military operational instrument packages. They also incorporated the frostbite times into their Wind Chill Charts.

$$Ft = ((-24.5 \times ((0.667 \times (V10 \times 8/5)) + 4.8)) + 2111) \times (-4.8 - ((Tair - 32) \times 5/9))^{-1.668} \qquad \textbf{3.2a}$$

or

$$Ft = ((-24.5 \times ((0.667 \times V10) + 4.8)) + 2111) \times (-4.8 - Tair)^{-1.668} \qquad \textbf{3.2b}$$

where Ft is the frostbite time in minutes, Tair and V are the air temperature in units of degrees Fahrenheit and wind speed in mph > 16 measured at a height of 33 ft, respectively (3.2a), or degrees Celsius and km h^{-1} > 25 measured at a height of 10 m, respectively (3.2b).

One may note in Table 3.3 that there are several cases where the same wind chill value occurs in different frostbite zones. DRDC found that the wind is a greater factor in time to cooling and frostbite than it is in the steady state equivalent temperature. The time to frost point depends on the integrated heat flow, which is very high when the skin is warm, especially if windy, and becomes lower as the skin cools. The WCT depends on the value of the heat flow after the skin has cooled as low as it is going to go, so it is not surprising that there appears to be inconsistency. It should be kept in mind that frostbite will not actually occur when the air temperature is above the freezing level. It will take greater than two hours for frostbite to occur from the freezing level down to 10EF even with high winds of up to 50 mph (80.5 km h^{-1} or 22.3 m s^{-1}; see Table 3.2a).

3.5 <u>Summary Discussion</u>. Freezing cold injury can occur anytime temperatures (air or surface) fall below freezing (32EF and 0EC). However, the likelihood and severity of injury increases with prolonged exposure to lower temperatures and greater relative wind speed, where wind speed may be a combination of actual wind speed, walking speed, and/or vehicle speed. Wind chill is not just a property of the environmental conditions, but of the faces being cooled by it. Cheek thermal resistance varies considerably among individuals. In the human studies, it varied by more than a factor of two. As a result, cheek temperatures in wind, in general, will differ from person to person.

Individuals will feel different degrees of coldness at the same combination of wind and temperature, since the perception of wind chill depends on the skin temperature. Those with high thermal resistance cheeks will have colder faces than those with lower thermal resistance cheeks. The wind chill equivalent temperature for individuals with high thermal resistance cheeks should be relatively high compared to that of individuals having low thermal resistance cheeks. The wind chill equivalent temperature depends on the heat transfer rate, which in the high thermal resistant individual will be relatively low because of the higher internal thermal resistance. However, those individuals with low thermal resistance will feel the cold less because of higher facial skin temperatures. Thus, individuals for whom the wind chill equivalent temperature should be milder, the high thermal resistance group, will perceive the weather to be colder. This apparent paradox calls into question the utility of wind chill equivalent temperatures. In spite of this, once individuals have experienced the range of wind chill and recalibrated the temperature scale to their own sensations, the scale will be useful to them in that they will know what to expect.

Some individuals have leveled criticism at the previous wind chill equivalent temperature scale because the cold equivalent temperatures do not feel the same as a real temperature of that magnitude in still air that they have previously experienced. This criticism will still be heard, because the new scale was not derived for their faces but for the faces of the 95^{th} percentile of cheek thermal resistance. Incidentally, while the population with high thermal resistance is at greater risk of frostbite, they are at lower risk for hypothermia.

Several cautions apply to the use of the WCT model and tables. The exact effect of cold exposure due to wind chill on an individual will vary depending on the type and level of activity, length of exposure, moderating effects of clothing, partial shelter from the wind, solar radiation, and overall physical state of the individual. The model was not designed to determine hypothermia effects since it is based on facial cooling, not on the whole body's temperature cooling. Frostbite will not occur when the air temperature (T) is above freezing (T>32EF or 0EC). In addition, wind chill does not apply to inanimate objects. The only effect that wind will have on inanimate objects is to shorten the time to cool to the actual air temperature.

Table 3.1a The new Wind Chill Temperature (WCT) Index chart, with T = Air Temperature in EC and V = Wind Speed in km h^{-1} at 10 m elevation.

Temperature (EC)

Wind (km h^{-1}) / **Calm**	**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**	**-53.7**	**-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

$$\text{WCT (EC)} = 13.12 + 0.6215T - 11.37V^{0.16} + 0.3965TV^{0.16}$$

Table 3.1b The new Wind Chill Temperature (WCT) Index chart, with T = Air Temperature in EF and V = Wind Speed in mph at 33 ft elevation, which is corrected to 5 ft via the equation.

Temperature (EF)

Wind (mph) Calm	**40**	**35**	**32**	**30**	**25**	**20**	**15**	**10**	**5**	**0**	**-5**	**-10**	**-15**	**-20**	**-25**	**-30**	**-35**	**-40**	**-45**
5	36	31	27	25	19	13	7	1	-5	-11	-16	**-22**	**-28**	**-34**	**-40**	**-46**	**-52**	**-57**	**-63**
10	34	27	24	21	15	9	3	-4	-10	-16	**-22**	**-28**	**-35**	**-41**	**-47**	**-53**	**-59**	**-66**	**-72**
15	32	25	22	19	13	6	0	-7	-13	**-19**	**-26**	**-32**	**-39**	**-45**	**-51**	**-58**	**-64**	**-71**	**-77**
20	30	24	20	17	11	4	-2	-9	-15	**-22**	**-29**	**-35**	**-42**	**-48**	**-55**	**-61**	**-68**	**-74**	**-81**
25	29	23	19	16	9	3	-4	-11	-17	**-24**	**-31**	**-37**	**-44**	**-51**	**-58**	**-64**	**-71**	**-78**	**-84**
30	28	22	18	15	8	1	-5	-12	**-19**	**-26**	**-33**	**-39**	**-46**	**-53**	**-60**	**-67**	**-73**	**-80**	**-87**
35	28	21	17	14	7	0	-7	-14	**-21**	**-27**	**-34**	**-41**	**-48**	**-55**	**-62**	**-69**	**-76**	**-82**	**-89**
40	27	20	16	13	6	-1	-8	-15	**-22**	**-29**	**-36**	**-43**	**-50**	**-57**	**-64**	**-71**	**-78**	**-84**	**-91**
45	26	19	15	12	5	-2	-9	-16	**-23**	**-30**	**-37**	**-44**	**-51**	**-58**	**-65**	**-72**	**-79**	**-86**	**-93**
50	26	19	14	12	4	-3	-10	-17	**-24**	**-31**	**-38**	**-45**	**-52**	**-60**	**-67**	**-74**	**-81**	**-88**	**-95**
55	25	18	14	11	4	-3	-11	**-18**	**-25**	**-32**	**-39**	**-46**	**-54**	**-61**	**-68**	**-75**	**-82**	**-89**	**-97**
60	25	17	13	10	3	-4	-11	**-19**	**-26**	**-33**	**-40**	**-48**	**-55**	**-62**	**-69**	**-76**	**-84**	**-91**	**-98**

Frostbite may occur in 30 minutes or less

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

Table 3.2a Time to occurrence of frostbite (5% risk of frostbite) in minutes or hours (h) and English units.

Air Temperature (EF)

Wind (mph) Calm	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45	-50
5	>2h	>2h	>2h	>2h	31	22	17	14	12	11	9	8	7
10	>2h	>2h	>2h	28	19	15	12	10	9	7	7	6	5
15	>2h	>2h	33	20	15	12	9	8	7	6	5	4	4
20	>2h	>2h	23	16	12	9	8	8	6	5	4	4	3
25	>2h	42	19	13	10	8	7	6	5	4	4	3	3
30	>2h	28	16	12	9	7	6	5	4	4	3	3	2
35	>2h	23	14	10	8	6	5	4	4	3	3	2	2
40	>2h	20	13	9	7	6	5	4	3	3	2	2	2
45	>2h	18	12	8	7	5	4	4	3	3	2	2	2
50	>2h	16	11	8	6	5	4	3	3	2	2	2	2

Table 3.2b Time to occurrence of frostbite (5% risk of frostbite most susceptible segment of the population) in minutes and metric units.

Air Temperature (EC)

Wind (km/h) Calm	-15	-20	-25	-30	-35	-40	-45	-50
10	x	x	22	15	11	8	7	6
20	x	x	14	10	7	6	5	4
30	x	18	11	8	6	4	4	3
40	42	14	9	6	5	4	3	2
50	27	12	8	5	4	3	2	2
60	22	10	7	5	3	3	2	2
70	18	9	6	4	3	2	2	2
80	16	8	5	4	3	2	2	1

x = Frostbite unlikely

Frostbite possible in 2 minutes or less	1
Frostbite possible in 3 to 5 minutes	3
Frostbite possible in 6 to 10 minutes	6

Table 3.3 NOAA Wind Chill Chart with "time to frostbite" indicated (adapted from Tew et al. 2002).

Wind Chill Chart

Wind (mph)	Temperature (°F)																	
Calm	40	35	30	25	20	15	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45
5	36	31	25	19	13	7	1	-5	-11	-16	-22	-28	-34	-40	-46	-52	-57	-63
10	34	27	21	15	9	3	-4	-10	-16	-22	-28	-35	-41	-47	-53	-59	-66	-72
15	32	25	19	13	6	0	-7	-13	-19	-26	-32	-39	-45	-51	-58	-64	-71	-77
20	30	24	17	11	4	-2	-9	-15	-22	-29	-35	-42	-48	-55	-61	-68	-74	-81
25	29	23	16	9	3	-4	-11	-17	-24	-31	-37	-44	-51	-58	-64	-71	-78	-84
30	28	22	15	8	1	-5	-12	-19	-26	-33	-39	-46	-53	-60	-67	-73	-80	-87
35	28	21	14	7	0	-7	-14	-21	-27	-34	-41	-48	-55	-62	-69	-76	-82	-89
40	27	20	13	6	-1	-8	-15	-22	-29	-36	-43	-50	-57	-64	-71	-78	-84	-91
45	26	29	12	5	-2	-9	-16	-23	-30	-37	-44	-51	-58	-65	-72	-79	-86	-93
50	26	19	12	4	-3	-10	-17	-24	-31	-38	-45	-52	-60	-67	-74	-81	-88	-95
55	25	18	11	4	-3	-11	-18	-25	-32	-39	-46	-54	-61	-68	-75	-82	-89	-97
60	25	17	10	3	-4	-11	-19	-26	-33	-40	-48	-55	-62	-69	-76	-84	-91	-98

Frostbite Times 30 minutes 10 minutes 5 minutes

$$\text{Wind Chill (°F)} = 35.74 + .06215T - 35.75(V^{0.16}) + 0.4275T(V^{0.16})$$

Where, T= Air Temperature (°F) V= Wind Speed (mph)

Effective 11/01/01

Table 3.4a DOD Wind Chill Chart with frostbite times for an anemometer height of 5ft.

New Wind Chill Chart in Fahrenheit and MPH

Use this chart for winds from 5 foot anemometer height (handheld)

Wind Speed (mph)	Temperature (°F)																			
Calm	40	35	30	25	20	15	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45	-50
5	35	29	23	17	11	5	-1	-8	-14	-20	-26	-32	-38	-44	-50	-56	-62	-68	-74
10	32	25	19	13	6	0	-7	-13	-19	-26	-32	-39	-45	-51	-58	-64	-71	-77	-83
15	30	23	17	10	3	-3	-10	-16	-23	-30	-36	-43	-50	-56	-63	-69	-76	-83	-89
20	28	22	15	8	1	-5	-12	-19	-26	-33	-39	-46	-53	-60	-67	-73	-80	-87	-94
25	27	20	13	7	0	-7	-14	-21	-28	-35	-42	-49	-56	-63	-70	-77	-84	-90	-97
30	26	19	12	5	-2	-9	-16	-23	-30	-37	-44	-51	-58	-65	-72	-79	-86	-93	-100
35	25	18	11	4	-3	-10	-17	-24	-32	-39	-46	-53	-60	-67	-74	-82	-89	-96	-103
40	25	17	10	3	-4	-11	-19	-26	-33	-40	-48	-55	-62	-69	-76	-84	-91	-98	-105
45	24	17	9	2	-5	-12	-20	-27	-34	-42	-49	-56	-64	-71	-78	-86	-93	-100	-107
50	23	16	9	1	-6	-13	-21	-28	-36	-43	-50	-58	-65	-72	-80	-87	-95	-102	-109
55	23	15	8	1	-7	-14	-22	-29	-37	-44	-52	-59	-66	-74	-81	-89	-96	-104	-111
60	22	15	7	0	-8	-15	-23	-30	-38	-45	-53	-60	-68	-75	-83	-90	-98	-105	-113
65	22	14	7	-1	-8	-16	-24	-31	-39	-46	-54	-61	-69	-76	-84	-92	-99	-107	-114
70	21	14	6	-1	-9	-17	-24	-32	-40	-47	-55	-62	-70	-78	-85	-93	-100	-108	-116
75	21	13	6	-2	-10	-17	-25	-33	-40	-48	-56	-63	-71	-79	-86	-94	-102	-109	-117

Risk of frostbite within	*30 minutes*	*10 minutes*	*5 minutes*

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Table 3.4b DOD Wind Chill Chart with frostbite times for an anemometer height of 15 ft.

New Wind Chill Chart in Fahrenheit and MPH

Use this chart for winds from 15 foot anemometer height

Wind Speed (mph)	Temperature (°F)																		
Calm	40	35	30	25	20	15	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45	-50
5	36	30	24	18	12	6	0	-6	-12	-18	-24	-30	-36	-42	-48	-54	-60	-65	-71
10	33	27	20	14	8	1	-5	-11	-17	-24	-30	-36	-43	-49	-55	-61	-68	-74	-80
15	31	24	18	11	5	-2	-8	-15	-21	-28	-34	-41	-47	-54	-60	-67	-73	-80	-86
20	30	23	16	10	3	-4	-10	-17	-24	-30	-37	-44	-50	-57	-64	-70	-77	-84	-90
25	28	22	15	8	1	-5	-12	-19	-26	-33	-39	-46	-53	-60	-67	-73	-80	-87	-94
30	28	21	14	7	0	-7	-14	-21	-28	-35	-41	-48	-55	-62	-69	-76	-83	-90	-97
35	27	20	13	6	-1	-8	-15	-22	-29	-36	-43	-50	-57	-64	-71	-78	-85	-92	-99
40	26	19	12	5	-2	-9	-17	-24	-31	-38	-45	-52	-59	-66	-73	-80	-87	-94	-101
45	25	18	11	4	-3	-10	-18	-25	-32	-39	-46	-53	-61	-68	-75	-82	-89	-96	-103
50	25	17	10	3	-4	-11	-19	-26	-33	-40	-48	-55	-62	-69	-76	-84	-91	-98	-105
55	24	17	10	2	-5	-12	-20	-27	-34	-41	-49	-56	-63	-71	-78	-85	-92	-100	-107
60	24	16	9	2	-6	-13	-20	-28	-35	-42	-50	-57	-65	-72	-79	-87	-94	-101	-109
65	23	16	8	1	-6	-14	-21	-29	-36	-43	-51	-58	-66	-73	-80	-88	-95	-103	-110
70	23	15	8	0	-7	-15	-22	-29	-37	-44	-52	-59	-67	-74	-82	-89	-97	-104	-111
75	22	15	7	0	-8	-15	-23	-30	-38	-45	-53	-60	-68	-75	-83	-90	-98	-105	-113

Risk of frostbite within: *30 minutes* (yellow) | *10 minutes* (magenta) | *5 minutes* (red)

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Table 3.4c DOD Wind Chill Chart with frostbite times for an anemometer height of 33 ft.

New Wind Chill Chart in Fahrenheit and MPH

Use this chart for winds from 33 foot anemometer height

Temperature (°F) / Wind Speed (mph)

Calm	40	35	30	25	20	15	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45	-50
5	36	31	25	19	13	7	1	-5	-11	-16	-22	-28	-34	-40	-46	-52	-57	-63	-69
10	34	27	21	15	9	3	-4	-10	-16	-22	-28	-35	-41	-47	-53	-59	-66	-72	-78
15	32	25	19	13	6	0	-7	-13	-19	-26	-32	-39	-45	-51	-58	-64	-71	-77	-83
20	30	24	17	11	4	-2	-9	-15	-22	-29	-35	-42	-48	-55	-61	-68	-74	-81	-88
25	29	23	16	9	3	-4	-11	-17	-24	-31	-37	-44	-51	-58	-64	-71	-78	-84	-91
30	28	22	15	8	1	-5	-12	-19	-26	-33	-39	-46	-53	-60	-67	-73	-80	-87	-94
35	28	21	14	7	0	-7	-14	-21	-27	-34	-41	-48	-55	-62	-69	-76	-82	-89	-96
40	27	20	13	6	-1	-8	-15	-22	-29	-36	-43	-50	-57	-64	-71	-78	-84	-91	-98
45	26	19	12	5	-2	-9	-16	-23	-30	-37	-44	-51	-58	-65	-72	-79	-86	-93	-100
50	26	19	12	4	-3	-10	-17	-24	-31	-38	-45	-52	-60	-67	-74	-81	-88	-95	-102
55	25	18	11	4	-3	-11	-18	-25	-32	-39	-46	-54	-61	-68	-75	-82	-89	-97	-104
60	25	17	10	3	-4	-11	-19	-26	-33	-40	-48	-55	-62	-69	-76	-84	-91	-98	-105
65	24	17	10	2	-5	-12	-19	-27	-34	-41	-49	-56	-63	-70	-78	-85	-92	-99	-107
70	24	16	9	2	-6	-13	-20	-27	-35	-42	-49	-57	-64	-71	-79	-86	-93	-101	-108
75	23	16	9	1	-6	-13	-21	-28	-36	-43	-50	-58	-65	-72	-80	-87	-95	-102	-109

Risk of frostbite within *30 minutes* (yellow) *10 minutes* (magenta) *5 minutes* (red)

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