Many stone fruit orchards in Washington are protected against freezing injury of the flower buds by orchard heaters and/or wind machines during the winter when air temperatures fall to \(-20^\circ\text{C}\) or lower. Successful protection against freezing injury under these conditions, however, depends on an accurate estimate of critical flower-bud hardiness temperatures. In the past, critical temperatures have been determined by exposing the flower buds to several temperatures under standard conditions in a freezing chamber, followed by examination of the buds to determine survival percentages (6, 9). The principal disadvantage of this method is the approximate 18-hr delay between sampling and determination of the critical temperatures. During this intervening period, hardiness can change several degrees in response to air temperatures above or below \(0^\circ\text{C}\) to \(-2^\circ\text{C}\) (1, 7, 8). Therefore, it is often necessary to predict current critical hardiness temperatures from previously determined values, plus estimated changes in hardiness based on temperatures during the intervening period.

In 1974, it was found that the cold hardiness of the flower buds of several \textit{Prunus} spp. was related to their capacity to deep supercool (11). The extent to which a population of flower buds deep supercools is measured by differential thermal analysis (DTA) using heat flux plates (2) and is defined by the temperature of the median low-temperature exotherm (LTE\(_{50}\)) of the population. The low-temperature exotherm (LTE) occurs when an extensively supercooled flower primordium within the bud freezes, releasing the latent heat of fusion. Dormant \textit{Prunus} flower primordia remain supercooled below \(-18^\circ\text{C}\) (11), even with ice present in the bud scales and subtending tissues (12). Ice formation in these vegetative tissues is accompanied by high-temperature exotherms, which occur just a few degrees below \(0^\circ\text{C}\) (11). Injury of a flower primordium is associated with its LTE (4). Therefore, the LTE\(_{50}\) of a population of dormant flower buds usually corresponds to the temperature required to kill 50\% of the primordia during laboratory freezing tests (1).

DTA reduces the delay between sampling and the determination of critical hardiness temperatures, but it is still necessary to estimate the current critical hardiness temperature. A model that accurately predicts the hardiness of a field population of flower buds based on laboratory DTA measurements and a readily measurable environmental parameter to which hardiness changes are related would be useful in making freeze-protection decisions. Air temperatures have been related to changes in peach and sweet cherry hardiness (7, 8) and are conveniently measured by commercially available dataloggers. The conceptual model of overwintering sweet cherry flower-bud hardiness presented here is derived empirically from laboratory experiments based upon the effects of temperature on changes in the LTE\(_{50}\) (1). Following refinement, the model may supplement direct measurements of hardiness in assisting orchardists in their freeze-protection decisions.

**Materials and Methods**

Changes in the LTE\(_{50}\) of dormant sweet cherry flower buds are a function of the air temperature (T) to which the buds are exposed, the duration of exposure (1), and the accumulation of chill units (c), based on the Utah model (13). (Table 1 lists the abbreviations and units for parameters used in the model.) The start of chill unit accumulation each autumn corresponds to time zero, i.e., \(t_n = t_0\), in the model. It is unlikely that the beginning of chill unit accumulation and the initiation of the deep-supercooling mechanism in the flower buds each autumn correspond precisely. Therefore, calculations of LTE\(_{50}\) via the model may begin sometime after \(t_0\). Once the deep supercooling mechanism has been established, an LTE\(_{50}\) measured by DTA [(LTE\(_{50}\)\(_{\text{DTA}}\)] will provide an initial value from which subsequent LTE\(_{50}\)s can be calculated [(LTE\(_{50}\)\(_{\text{c}}\)] via the model. As the model is refined, it may be necessary to provide an updated (LTE\(_{50}\)\(_{\text{DTA}}\)) if the (LTE\(_{50}\)\(_{\text{c}}\)) deviates substantially from the measured (LTE\(_{50}\)\(_{\text{DTA}}\)).

A flow diagram of the conceptual model (Fig. 1) shows the
Table 1. Abbreviations and their units.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>c</td>
<td>Chill unit</td>
<td>---</td>
</tr>
<tr>
<td>DTA</td>
<td>Differential thermal analysis</td>
<td>---</td>
</tr>
<tr>
<td>LTE</td>
<td>Low-temperature exotherm</td>
<td>---</td>
</tr>
<tr>
<td>LTE&lt;sub&gt;50&lt;/sub&gt;</td>
<td>Temperature of median LTE</td>
<td>°C</td>
</tr>
<tr>
<td>LTE&lt;sub&gt;50&lt;/sub&gt;&lt;i&gt;c&lt;/i&gt;</td>
<td>Calculated LTE&lt;sub&gt;50&lt;/sub&gt;</td>
<td>°C</td>
</tr>
<tr>
<td>LTE&lt;sub&gt;50&lt;/sub&gt;&lt;i&gt;DTA&lt;/i&gt;</td>
<td>DTA-determined LTE&lt;sub&gt;50&lt;/sub&gt;</td>
<td>°C</td>
</tr>
<tr>
<td>LTE&lt;sub&gt;50&lt;/sub&gt;&lt;i&gt;MAX&lt;/i&gt;</td>
<td>Maximum LTE&lt;sub&gt;50&lt;/sub&gt;</td>
<td>°C</td>
</tr>
<tr>
<td>LTE&lt;sub&gt;50&lt;/sub&gt;&lt;i&gt;MIN&lt;/i&gt;</td>
<td>Minimum LTE&lt;sub&gt;50&lt;/sub&gt;</td>
<td>°C</td>
</tr>
<tr>
<td>LTE&lt;sub&gt;50&lt;/sub&gt;&lt;i&gt;t&lt;/i&gt;</td>
<td>Current (LTE&lt;sub&gt;50&lt;/sub&gt;&lt;i&gt;c&lt;/i&gt;)</td>
<td>°C</td>
</tr>
<tr>
<td>LTE&lt;sub&gt;50&lt;/sub&gt;&lt;i&gt;t&lt;/i&gt;&lt;sub&gt;n=1&lt;/sub&gt;</td>
<td>Previous (LTE&lt;sub&gt;50&lt;/sub&gt;&lt;i&gt;c&lt;/i&gt;)</td>
<td>°C</td>
</tr>
<tr>
<td>t&lt;i&gt;n&lt;/i&gt;</td>
<td>Time at hour &lt;i&gt;n&lt;/i&gt;</td>
<td>hr</td>
</tr>
<tr>
<td>T</td>
<td>Air temp</td>
<td>°C</td>
</tr>
</tbody>
</table>

Decision pathway based on (LTE<sub>50</sub><i>DTA</i>, LTE<sub>50</sub><i>c</i>, and hourly air temperatures (T) for sweet cherry flower-bud LTE<sub>50</sub>s during dormancy. "FIELD" consists of air temperature measurements within the orchard. Hourly air temperature values may be supplied to the model as a single hourly measurement, an hourly average of more frequent measurements, or an interpolation from less-frequent measurements. The hourly air temperature values are transferred to a database at "START", from which calculations of (LTE<sub>50</sub><i>c</i>) are coordinated. Each calculated hourly (LTE<sub>50</sub><i>c</i>) serves as the base for calculating the next (LTE<sub>50</sub><i>c</i>). From the temperature database, a subprogram calculates chill units (c) (13) and provides this value to the program.

During dormancy of sweet cherry flower buds, the LTE<sub>50</sub> does not rise above a certain maximum value ([LTE<sub>50</sub><i>MAX</i>](1)). The (LTE<sub>50</sub><i>MAX</i>)[19] may vary a few degrees during dormancy but usually occurs between −18° and −21°C (1). Specified (LTE<sub>50</sub><i>MAX</i>) is stored in the "START" database to be used in setting limits for (LTE<sub>50</sub><i>c</i>) as described later.

Freezing and thawing are the principal phenomena regulating the model. The LTE<sub>50</sub> of sweet cherry flower buds decreases when the buds are exposed to temperatures low enough to induce ice formation within the bud scales, i.e., below the temperature of the high-temperature exotherm (1). This decrease in LTE<sub>50</sub> was found to be directly proportional to the water content of the flower primordia (1). Apparently, water migrates from the flower primordia to ice sites within the bud when freezing occurs. When frozen sweet cherry flower buds were exposed to temperatures ≥ −2°C, the LTE<sub>50</sub> increased as water moved back into the flower primordia (1). It is assumed that migration of water during freezing and thawing is a response to the water potential gradient between water within the flower primordia and ice within the bud scales. As a result, the rate of water efflux from the flower primordia would be expected to follow an exponential function, with the most rapid loss occurring when the primordia are at their maximum water content and the rate decreasing as the primordia become more dehydrated. During thawing, water influx into the flower primordia would be expected to be more rapid when the water content of the primordia is low, decreasing as the primordia become hydrated. Changes in the LTE<sub>50</sub> during freezing and thawing parallel this dehydration–rehydration relationship. Therefore, changes in the LTE<sub>50</sub> cannot be based simply upon the duration of exposure at a particular temperature, but the current LTE<sub>50</sub> also must be considered.

Fig. 1. Flow diagram for the conceptual model of changes in sweet cherry flower-bud LTE<sub>50</sub> during dormancy (D = decision pathways; E = hourly rate equations).
Other assumptions that were made in constructing this model include: 1) The LTE₅₀ decreases when T \leq -3°C and increases when T \geq -2°C. Previous research found that peach and sweet cherry flower buds gained and lost hardiness when temperatures were below or above -1.1 to -2.2°C, respectively (10). 2) All T \leq -3°C reduce the LTE₅₀ at the same rate at a given chill unit accumulation. 3) Freezing and thawing curves depend upon the current LTE₅₀, which reflects the water content of the flower primordia. 4) Thawing curves do not change during the dormant period; however, freezing curves do change (1) (Fig. 2).

There are linear relationships between the equations of thawing and temperature (Fig. 1). Exponential functions (E5): 6) The freezing cycle is initiated when the LTE₅₀ is at its maximum and the LTE₅₀ to decrease when T \leq -3°C. It was found that a linear decrease in LTE₅₀ occurs when:

\[
\text{(LTE₅₀)}_{t=n} \geq (\text{LTE₅₀})_{\text{MAX}} - 4.3^\circ
\]

where 4.3° represents the decrease in LTE₅₀ below the LTE₅₀+3° for the first 23 hr of freezing at a rate of decrease of 0.185°/hr. [Model decisions (D) and equations (E) are numbered and referenced in Fig. 1.]

Then the hourly decrease in LTE₅₀ is:

\[
(\text{LTE₅₀})_{t=n} = (\text{LTE₅₀})_{t=n-1} - 0.185^\circ
\]

however, when:

\[
(\text{LTE₅₀})_{t=n-1} < (\text{LTE₅₀})_{\text{MAX}} - 4.3^\circ
\]

then the hourly decrease is represented by the asymptotic exponential function (5):

\[
(\text{LTE₅₀})_{t=n} = (\text{LTE₅₀})_{t=n-1} - [0.06 - (8.26 \times 10^{-4}) (1.003^c)]
\]

\[c \text{ = chill units (Fig. 2). Each datum point in Fig. 2 represents the rate of decrease in LTE₅₀ during 10 days of -10°C exposure, exclusive of the first day, in monthly experiments repeated from October through February (1). The c values indicate the chill units accumulated by the date each monthly experiment was begun.}

\text{Thawing.} It is assumed in the model that thawing occurs within the buds and the LTE₅₀ increases when T \geq -2°C (Fig. 1). Since the rate of increase in LTE₅₀ during thawing depends upon temperature (1), D3-D7 are based on temperature. When T = -1°C or -2°C (D3), the LTE₅₀ increased linearly over time (1).

At T = -1°C (D4), the hourly increase in LTE₅₀ is:

\[
(\text{LTE₅₀})_{t=n} = (\text{LTE₅₀})_{t=n-1} + 0.48^\circ
\]

At T = -2°C (D5), the hourly increase in LTE₅₀ is:

\[
(\text{LTE₅₀})_{t=n} = (\text{LTE₅₀})_{t=n-1} + 0.13^\circ
\]

When T \geq 0°C, the LTE₅₀ increases exponentially if the (LTE₅₀)_{t=n-1} is above a certain value; however, when (LTE₅₀)_{t=n-1} is below this value, the LTE₅₀ increases at a more rapid linear rate. Both the exponential and linear rates are temperature-dependent, thought to be due to the direct dependence of the LTE on the water content of the flower primordium (1). Therefore, at a low water content, the water potential gradient between the primordium and the thawing bud scales is extremely steep, resulting in a rapid linear increase in primordium water content and LTE. Since the change in LTE₅₀ was measured only at thawing temperatures of 0°, 2°, and 20°C (1), the inflection LTE₅₀ for the gradual exponential increase, must be calculated by interpolation between these temperatures. This calculation is achieved in D8 and D9 when T = 0° - 2°C (Fig. 1).

When:

\[
(\text{LTE₅₀})_{t=n-1} \leq 0.35 T - 29.8^\circ
\]

then, the hourly increase in LTE₅₀ at T = 0° - 2°C is:

\[
(\text{LTE₅₀})_{t=n} = (\text{LTE₅₀})_{t=n-1} + (T + 3)^\circ
\]

where T + 3° is simply the linear relationship between the thawing temperature and the ΔLTE₅₀/hr at 0° and 2° (Fig. 3).

The right side of the decision equation (D8) was derived by subtracting half the rate of increase in LTE50, i.e., \((T + 3°)/2\), from the inflection LTE50.

When:

\[(LTE50)_{t_i} > 0.35 T - 29.8° \quad [D9]\]

the LTE50 increases exponentially as follows:

When \(T = 0°\):

\[(LTE50)_{t_i} = (LTE50)_{t_i - 1} + 0.82^t \quad [E6]\]

when \(T = 1°\):

\[(LTE50)_{t_i} = (LTE50)_{t_i - 1} + 0.90^t \quad [E7]\]

when \(T = 2°\):

\[(LTE50)_{t_i} = (LTE50)_{t_i - 1} + 0.97^t \quad [E8]\]

where \(t\) = consecutive hr when \(T \geq 0°\).

The inflection \((LTE50)_{t_i - 1}\), which separates the rapid linear increase in LTE50 from the exponential increase when \(T \geq 3°C\) (D7), is determined by D13 and D14 (Fig. 1).

When:

\[(LTE50)_{t_i} \leq 0.034 T - 29.2° \quad [D13]\]

then, the hourly increase in LTE50 at \(T = 3°\) is:

\[(LTE50)_{t_i} = (LTE50)_{t_i - 1} + 0.067T + 4.9° \quad [E9]\]

where 0.067T + 4.9° is simply the linear relationship between the thawing temperature and the \(\Delta LTE50/hr\) at 2° and 20° (Fig. 3). The right side of the decision equation (D13) was derived by subtracting half the rate of increase in LTE50, i.e. \((0.067T + 4.9°)/2\), from the inflection LTE50.

When:

\[(LTE50)_{t_i} > 0.34T - 29.2° \quad [D14]\]

then:

\[(LTE50)_{t_i} = (LTE50)_{t_i - 1} + 0.97^t \quad [E10]\]

where \(t\) = consecutive hr when \(T \geq 0°\).

**Limits.** Two limits are placed on the \((LTE50)_{t_i - 1}\). The \((LTE50)_{\text{MAX}}\) (described previously) and the \((LTE50)_{\text{MIN}}\) are specified initially in the model. The lowest measured LTE for sweet cherry buds was near \(-35°C\) after 10 days of exposure to \(-10°\) in Oct. 1983 (1). Therefore, as a lower limit, the \((LTE50)_{\text{MIN}}\) should be no less than \(-35°\). The \((LTE50)_{\text{MAX}}\) varied between \(-18°\) and \(-21°\) during the 1983-84 winter, but usually was near \(-20°\) in laboratory experiments (1).

If the \((LTE50)_{t_i - 1}\) is between the \((LTE50)_{\text{MAX}}\) and \((LTE50)_{\text{MIN}}\) (D15), it becomes the \((LTE50)_{t_i - 1}\), and is stored in the START data set (Fig. 1). However, if the \((LTE50)_{t_i - 1} \geq (LTE50)_{\text{MAX}}\) (D16) or \(\leq (LTE50)_{\text{MIN}}\) (D17), the \((LTE50)_{t_i - 1}\) becomes the \((LTE50)_{\text{MAX}}\) or \((LTE50)_{\text{MIN}}\), respectively. The \((LTE50)_{t_i - 1}\) becomes the next \((LTE50)c\) iteration.

**Validation.** A comparison of sweet cherry flower-bud LTE50s measured by DTA (1) and LTE50 values calculated by the model was made in the autumn and winter of 1984–85 and 1985–86 (Fig. 4). Calculated LTE50s were started with an assumed \((LTE50)_{\text{MAX}}\) and hourly temperatures, which were determined from daily maximum-minimum air temperatures according to the model of Richardson et al. (13). LTE50 values calculated by the model corresponded to measured LTE50s reasonably well (Fig. 4); however, there were several obvious discrepancies. Most obvious were differences between the measured maximum LTE50s and the \((LTE50)_{\text{MAX}}\) limit set in the model. The other significant deviations between measured and calculated LTE50s occurred during periods of subzero temperatures. This deviation is most apparent during the periods when the measured LTE50s were higher than the LTE50 calculated by the model during mid-Jan. 1985 (Fig. 4A) and late Dec. 1985 (Fig. 4B).

**Discussion**

The conceptual model of dormant sweet cherry flower-bud deep supercooling presented here is a prototype. A more comprehensive model of flower-bud hardiness also should include fall acclimation and spring deacclimation. Therefore, extending this model beyond the limits of the dormant period should be one of the objectives of future research. Besides changes in LTE50, the percentage of flower primordia exhibiting deep supercooling may fluctuate dramatically during spring deacclimation (1). Spring deacclimation is further complicated as the flower bud’s mechanism of freeze resistance changes. As the flower buds lose the capacity to deep supercool, they apparently adopt a freeze-tolerance mechanism, eventually becoming freeze-sensitive as the petal tips emerge through the calyx (3).

Several assumptions used in the model require further testing. The discrepancy between the measured maximum LTE50 and the \((LTE50)_{\text{MAX}}\) set in the model may be due to differences in the maximum LTE50 between seasons or changes in the maximum LTE50 during a given season. Discrepancies between the measured and calculated LTE50s may be due to differences in temperature in the microenvironment of the flower buds, both spatially and temporally, compared to the location and infrequency of diurnally measured maximum–minimum tempera-

![Fig. 4. Comparison of the sweet cherry flower-bud LTE50s calculated by the model (-----) and measured by DTA (□) during the autumn and winter of 1984–85 (A) and 1985–86 (B).](image-url)
tures. It is expected also that rates of freezing and thawing of water in the flower buds would be more complicated than those predicted by the model when temperatures are near the freezing point, i.e., $T = -1^\circ$ to $-3^\circ$C. Some of these assumptions, however, may be tested by introducing them as variables within the model.

The actual environmental and physiological parameters affecting flower-bud hardiness in an orchard are obviously more complex than those considered in this model. Whether a model that takes into account all of these factors is a desirable objective depends on the purpose for which the model was intended. While the model presented here will undoubtedly undergo refinements, it satisfies the requirement for a model that estimates critical flower-bud hardiness temperatures using a readily measurable environmental parameter such as air temperature.

This conceptual model has been coded in BASIC (MDOS 2.01) and can be obtained from the Irrigated Agriculture Research and Extension Center, Prosser, Wash.

**Literature Cited**