Programmable Time-Temperature Indicators: new technology for monitoring the commercial storage of fruits, vegetables, and florist and nursery stocks

CliniSense Corporation

Introduction

Postharvest agricultural items, such as fruits, vegetables, florist and nursery stocks, are perishable. Their storage life is usually a function of their thermal history and respiration rate. Agricultural products have a narrow range of acceptable storage temperatures. Exposure to higher temperatures for longer periods of time can cause deterioration and decay, while exposure to sub-freezing temperature can almost instantly render a product unusable due to ice crystal formation. Thus methods to detect damage due to improper temperature exposure are highly important to this industry.

Time-Temperature Indicators (TTI) are one way to detect such damage. TTI are small tags that ride along with a material, and monitor the acceptability of the material's thermal history. Up until the LifeTrack, however, previous TTI units were chemically based, and had many limitations. These earlier chemical TTI units required users to visually assess changes in color indicators, resulting in subjective and inaccurate determinations. Additionally, it was often difficult or impossible to adjust a chemical TTI to enable it to closely match the complex stability characteristics of postharvest products.

Inaccurate TTI's will, at best, result in waste, causing good material to be thrown out. At worse, the user may unknowingly use deteriorated material, resulting (depending upon the material in question) in various levels of customer dissatisfaction. As a result, early generation TTI have not been particularly useful for many agricultural products.

The solution: Programmable, TTI

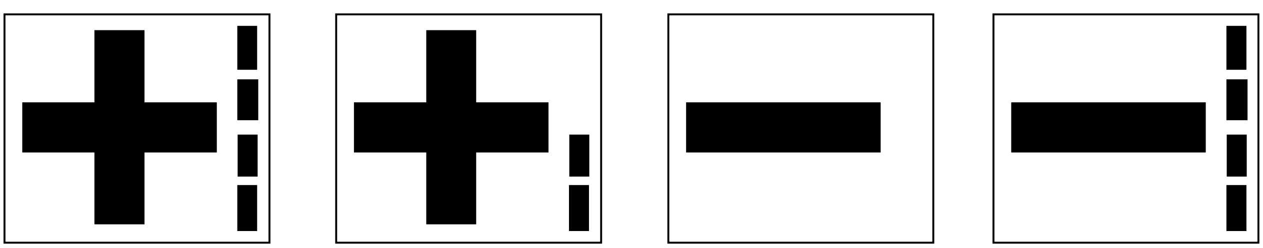
To solve these problems, CliniSense has developed[1] the LifeTrack™ programmable electronic time-temperature indicator (eTTI). This indicator may be easily customized to accurately match the stability profile of nearly any material of interest, including the complex stability profiles of postharvest products. This unit constantly monitors it's thermal history, and displays acceptability status with an unambiguous "+" / "-" visual indicator.

[1] Patent pending

The CliniSense LIfeTrack electronic time-temperature indicator

In addition to displaying thermal history acceptability, the LifeTrack unit can also be configured to display a bar graph showing the percentage of the original shelf-life that is remaining. Optional diagnostic displays, that show if the LifeTrack was subjected to unusually high or unusually low temperature conditions at the time of material lifetime expiration, are also available.

LifeTrack display, showing remaining lifetime graph, and failure diagnostics



Fresh | 50% life remaining | Expired | Expired at high temp.

Wide range of LifeTrack types

Available for most postharvest agricultural products: In order to properly configure a LifeTrack, the stability characteristics of the material that the LifeTrack will be monitoring must be available. For most commercially important agricultural products, this data is available from USDA handbook 66: "The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks". Using this data, and supplemental data (which may be provided by the user), CliniSense can produce custom programmed LifeTrack units calibrated to most agricultural products of interest.

USDA crop data suitable for LifeTrack programming include:

Fruits and Vegetables	Loquat	Killian Daisy
Arazá	Mushroom	Lisianthus
Artichoke	Netted Melons	Jonquil ‘Geranium’
Asparagus	Nopalitos	Narcissus ‘Paperwhite’
Beans (snap, long)	Okra	Ranunculus
Blueberry	Parsley	Rose ‘Ambiance’
Bread Fruit	Pepper	Rose ‘Cara Mia’
Broccoli	Pineapple	Rose ‘Fire and Ice’
Brussels Sprouts	Potato (curing, storage)	Rose ‘First Red’
Carambola	Radicchio	Rose ‘Kardinal’
Cauliflower	Raddish	Rose ‘Preference’
Celeriac	Southern Pea	Rose ‘Raphaella’
Celery	Sprouts	Rose ‘Tineke’
Cherimoya	Sweetcorn	Snapdragon
Chicory		Statice
Cranberry	**Floral Crops and Nursery Stock**	Tulip
Cucumber	**Cut flowers**	
Dates (Delget Noor)	Anemone ‘Mona Lisa’	**Foliage plants**
Eggplant	Aster ‘Matsumoto’	
Endive	Calla Lily	**Nuts**
Garlic	Carnation ‘Imperial White’	Almond
Ginseng	Carnation ‘Ruri’	Pecan
Leeks	Carnation ‘White Sim’	
Lemon	Daffodil ‘King Alfred’	
Lettuce	Gerbera	
Litchi	Iris ‘Madonna’	
Longan	Iris ‘Telstar’	

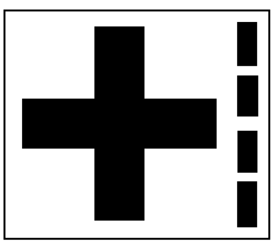
Using a LifeTrack

Example 1: Cut flower storage and vase life:

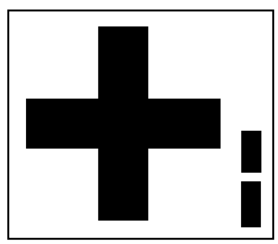
Ideally, most non-tropical cut flowers should be stored at temperatures between 1 and 2 ^{o}C, using preservative solutions and humidity control as appropriate. Most storage and transportation conditions, however, are far from ideal, and cut flowers are usually subjected to higher storage temperatures, and high temperature spikes, during the transport chain. As a result, different batches of flowers may all look good upon receipt, but then yield vastly differing vase lives when removed from cold storage, and subsequently kept at room temperature. This can result in unhappy customers and lost business.

CliniSense LifeTrack units monitor the transport and storage chain, and can let the user know at a glance if a particular batch of cut flowers is likely to have an unusually low vase life. This way, transport and storage problems can be detected, inventory can be used appropriately, and customer satisfaction can be optimized.

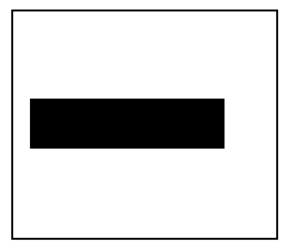
As an example, consider three possible LifeTrack readings, shown below:



A: Fresh



B: 50% life remaining



C: Expired

Reading "A" lets the florist know that the cut flowers have been properly stored and shipped, and will likely have a normal vase life. Reading "B" lets the florist know that the cut flowers have been thermally stressed, and that only about 50% of their normal vase life is remaining. Reading "C" lets the florist know that the cut flowers are likely to cause intense customer dissatisfaction.

Example 2: Asparagus shelf-life

Fresh cut Asparagus has a complex shelf life. The product is damaged by freezing, has about 10 days storage at 0 ^{o}C, 30 days storage at 1-2 ^{o}C, dropping to 18 days at 4 ^{o}C, and only 1-2 days at 20 ^{o}C.

By using a LifeTrack programmed with Asparagus shelf-life parameters, the true remaining shelf life of various lots of Asparagus may also be monitored and instantly assessed.

LifeTrack characteristics[2]:

Size: *2 1/4" x 1 1/2" x 0.5"*
Temperature range:[3] -20 - 70 °C
Temperature accuracy: +/- 0.5 °C at 0 °C, +/- 1 °C elsewhere.
Time resolution: 1 - 60 minutes between each temperature time point
Time delay until monitoring starts: 0 - 1440 minutes
Interface: LCD, reset button, test button, data interface
Battery: CR2032 (3V) coin cell
Battery lifetime: 36 months
EMC optimized design
Humidity: 0 - 95%. The unit may be sealed in watertight covering for high humidity
Cost (basic unit, high volume): ~ $15

Standard options (programmable unit):

Assistance with P(temp) calculations
Quick-turn factory calibration
Optional "cause of expiration" display

Other configurations (high volume customers):

Custom user eTTI programming software
Data interface cable
Alternate display
IR temp logger playback
Extended battery lifetime
Extended temperature range
Alternate case or colors
Embedded

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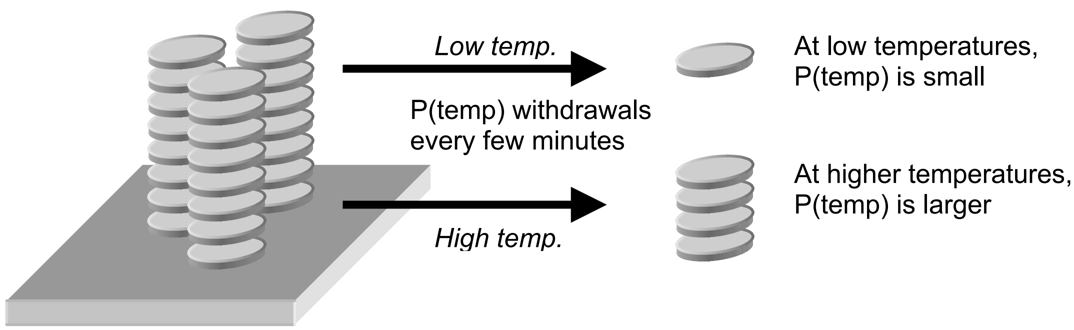
[2] Typical commercial unit. Extended range units are available upon special order.

Appendix: LifeTrack technical information

Appendix 1: How it works -- the "stability bank" concept

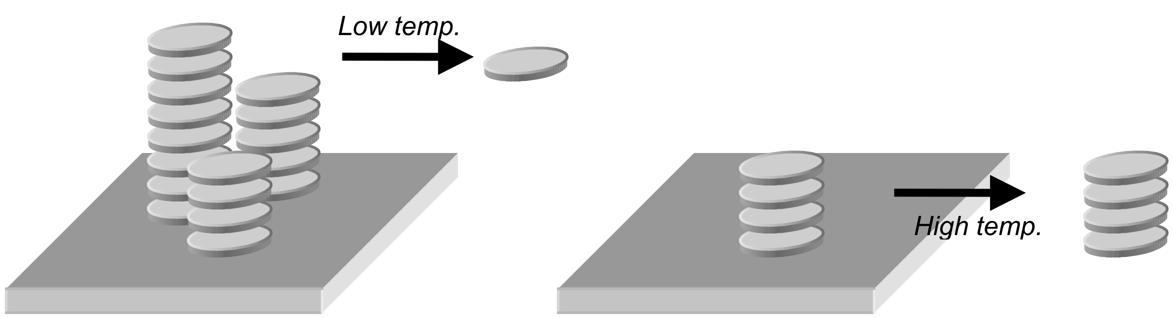
Postharvest plants remain metabolically active, and this metabolism can be detected by the plant's respiration rate. As metabolism continues, the plant ages, and eventually reaches the end of its life. At higher temperatures, respiration increases, and shelf life correspondingly decreases.

The CliniSense LifeTrack uses a new concept, called the "stability bank" model. For plants, this can also be referred to as the "respiration bank". Here, a plant's remaining life is tracked by the status of a respiration bank account (B). This account is opened (for fresh material) with an initial deposit of "F" respiration points. Every few minutes, "P" respiration points are withdrawn from the account. The number of respiration points "P" withdrawn each time is a variable that is a function of temperature, P(temp). At low temperatures, a small number of respiration points "P" are withdrawn from the bank every few minutes. At higher temperatures, a larger number of respiration points "P" are withdrawn from the bank every few minutes.



The stability bank "B", with
an initial deposit of "F" units

As the material ages, the amount of respiration points remaining in the stability bank (B) decreases. When the respiration bank account "B" hits zero, the material has expired.



Stability bank "B" after several minutes at low temperature

Stability bank "B" after several minutes at high temperature

Mathematically, if the respiration bank account "B" of the fresh material is "F", and P(temp) respiration points are withdrawn every minute, then the status of the stability bank account "B" at "Time" (or "T") minutes later is:

$$(1) \quad B = F - \sum_{0}^{Time} P(temp)$$

If B is > 0, then the material is still good. If B <= 0, then the material has expired. Using the respiration bank model, and appropriate selection of "F" and P(temp) values, the stability characteristics of nearly any horticultural material can be accurately modeled.

The CliniSense LifeTrack:

The CliniSense LifeTrack is an electronic device containing a microprocessor, temperature sensor, battery, and display. The microprocessor is programmed to make periodic temperature measurements, convert the measurements into the appropriate P(temp) values, and then perform respiration calculation (1). If the respiration bank "B" value remains positive, the LifeTrack will display a "material good" prompt, such as a "+". If the respiration bank "B" value becomes zero or negative, the LifeTrack will display a "material expired" prompt, such as a "-".

The LifeTrack is available in both programmable and non-programmable models. In the non-programmable model, a predetermined "F" value and table of P(temp) values are programmed into the microprocessor's read only memory (ROM). This is suited to high volume applications where cost is more important than flexibility.

The programmable version of the LifeTrack contains a data input jack, and Flash memory. Thus "F" and P(temp) values may be rapidly downloaded into the unit, and the unit customized to nearly any application. Programmable LifeTrack units are well suited to low and medium volume applications where implementation speed and flexibility are desired.

Specifying the appropriate LifeTrack program: Typically, each different agricultural product will have its own unique set of temperature shelf-life characteristics, and each will have its own unique type of programmed LifeTrack unit. To select the appropriate LifeTrack program, the shelf-of the product at various storage conditions must be specified. This can be done by either supplying this data directly, or by specifying the appropriate USDA reference shelf-life data. This data is available for hundreds of different agricultural products, and is available online at: http://www.ba.ars.usda.gov/hb66/contents.html

Cut flower vase-life example: As an example, consider a LifeTrack programmed to determine the vase life for sunflowers (asteraceae), following the data of Celikel and

Reid[3]. Here, the respiration of cut sunflowers was measured, and found to fit the equation: $y = 22.186e^{0.073T}$ ml CO_2/kg-hour, where "T" is the temperature in ^oC. Further, it was found that the vase-life of the sunflowers at continuous 20 ^oC storage was 6.3 days. Here, the "respiratory bank" of the sunflowers is assumed to be the observed vase-life at 20 ^oC, times the respiratory rate at 20 ^oC, which is 6.3 days x 95.53 ml CO_2 /kg-hour, or in hours: 6.3 x 24 x 95.53 = 14,444 respiration units.

Assuming that the sunflowers only have a set amount of respiration units before reaching the end of their vase life, then at 0 ^oC, the temperature of maximum stability, where respiration is only 22.186 ml CO_2 /kg-hour, the sunflowers would have a predicted vase-life of 14,444/22.186 = 651 hours or 27.13 days. The respiration predicted vase-life at other temperatures is shown in the left hand side of table 1 below:

Table 1: Respiration predicted sunflower vase-life at constant temperature

Temp	Respiration	Life(days)	Life(min)	Points/min	Total Points
0	22.2	27.1	39064	10	390640
1	23.9	25.2	36314	11	390640
2	25.7	23.4	33757	12	390640
3	27.6	21.8	31381	12	390640
4	29.7	20.3	29172	13	390640
5	32.0	18.8	27118	14	390640
6	34.4	17.5	25209	15	390640
7	37.0	16.3	23434	17	390640
8	39.8	15.1	21784	18	390640
9	42.8	14.1	20251	19	390640
10	46.0	13.1	18825	21	390640
11	49.5	12.2	17500	22	390640
12	53.3	11.3	16268	24	390640
13	57.3	10.5	15123	26	390640
14	61.6	9.8	14058	28	390640
15	66.3	9.1	13068	30	390640
16	71.3	8.4	12148	32	390640
17	76.7	7.8	11293	35	390640
18	82.6	7.3	10498	37	390640
19	88.8	6.8	9759	40	390640
20	95.5	6.3	9072	43	390640

Additionally, although it is not shown on table 1, it is also known that sunflowers are rapidly damaged by freezing, and rapidly damaged by extreme heat. These "boundary conditions" will be discussed shortly.

Returning to table 1, note that at the point of maximum stability (0 ^oC), the sunflowers have a fresh lifetime "F" of 27.1 days, or 39064 minutes. Thus, in this example, using minutes for the time units:

[3] Celiekel, Reid, Storage Temperature Affects the Quality of Cut Flowers from the Asteraceae HORTSCIENCE 37(1):148–150. 2002

F = number of time units at optimum stability temperature = 39064 units. Since the LifeTrack uses integer arithmetic, this will be multiplied by 10 in order to give enough precision for subsequent calculations. Thus F=39064 * 10 = 390640

So the stability bank "B" for fresh material will have an initial deposit of "F" (390640) units. Moreover, if the sunflowers are kept at a constant 0 ^{o}C temperature, $P(temp_{0C})$ should deduct 10 points per hour from the stability bank "B", and the stability equation (1) is:

(2) $B = F - \sum_{0}^{Time} P(temp_{0c})$ thus: $B = 390640 - \sum_{0}^{Time} 10$ or equivalently:

$$B = 390640 - 10 \cdot Time$$

To determine the P(temp) values for various temperatures, it is important to note that at a constant temperature, $temp_c$, equation (1) becomes:

(3) $B = F - P(temp_c)T$

Now by definition, the stability lifetime is the time "T" when the stability bank "B" first hits zero, so at the stability lifetime limit where B=0, equation (3) becomes:

(4) $0 = F - P(temp_c)T$ so solving for $P(temp_c)$, then

(5) $P(temp_c) = \frac{F}{T}$

Thus for any given temperature, $P(temp_c)$ is equivalent to the lifetime of the material "F" at the optimal stability temperature, divided by the calculated lifetime of the material at the particular given temperature ($temp_c$).

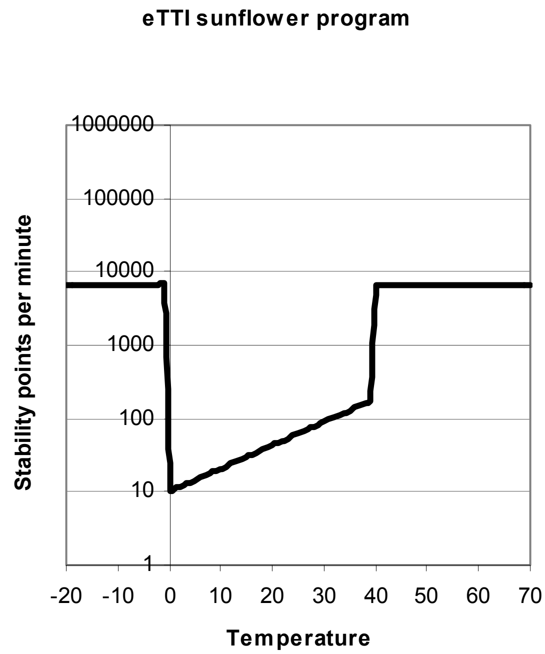
In this sunflower vase-life example; the respiration data from table 1, the maximum stability lifetime "F" of 390640, and the best fit stability lifetime equation (3), can be combined with equation (5) to produce a table of P(temp) values that covers the temperature range between the 0 ^{o}C and 20 ^{o}C experimental data points. This is shown on the right hand side of Table 1 (above).

Although the sunflower stability data between the 0 ^{o}C and 20 ^{o}C data points fit the exponential equation (3) well, in practice, the real sunflower vase-life function is "U" shaped. This is because cut-flowers are severely damaged by freezing. Sunflowers are also rapidly damaged at very high temperatures.

The LifeTrack unit is able to accurately model these boundary conditions as well. This is done by incorporating this additional temperature information into the unit's stability point lookup table. Here, temperatures below 0 ^{o}C, and temperatures above 30 ^{o}C, are given a very high number of stability points. As a result, if the sunflowers encounter these conditions, they will properly be designated as "expired". The complete set of P(temp) calculations, including these boundary conditions, is shown in Table 2.

Table 2: P(temp) calculations for sunflower vase-life between -20 to 70 °C

Temp °C	Vase-life min	P(temp)	Notes
-20	60	6511	Low boundary
			Low boundary
-1	60	6511	Low boundary
0	39064	10	
1	36314	11	
2	33757	12	
3	31381	12	
4	29172	13	
5	27118	14	
6	25209	15	
7	23434	17	
8	21784	18	
9	20251	19	
10	18825	21	
11	17500	22	
12	16268	24	
13	15123	26	
14	14058	28	
15	13068	30	
16	12148	32	
17	11293	35	
18	10498	37	
19	9759	40	
20	9072	43	
21	8433	46	
22	7840	50	
23	7288	54	
24	6775	58	
25	6298	62	
26	5854	67	
27	5442	72	
28	5059	77	
29	4703	83	
30	4372	89	
41	60	6511	High boundary
			High boundary
70	60	6511	High boundary

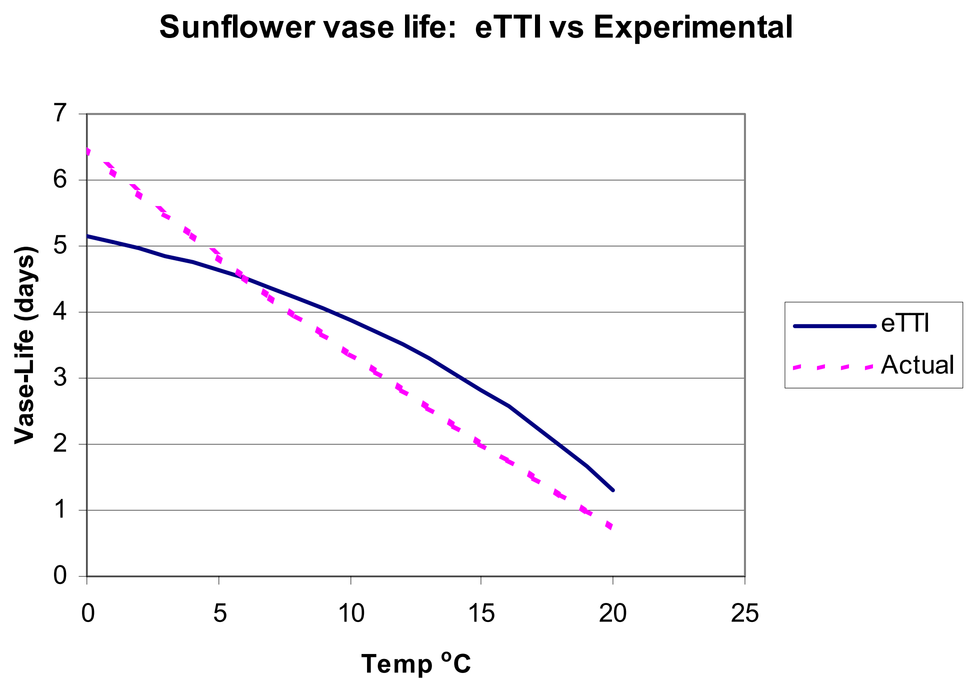


Graph of eTTI stability points per minute (log scale) showing "U" shaped boundary regions surrounding the central sunflower respiration vs vase-life region.

How accurate is it?

In general, the accuracy of the LifeTrack is a function of how detailed and realistic the stability model is.

Graph 1 below shows a comparison between the LifeTrack predicted sunflower vase-life, and the actual experimental data of Celikel and Reid.



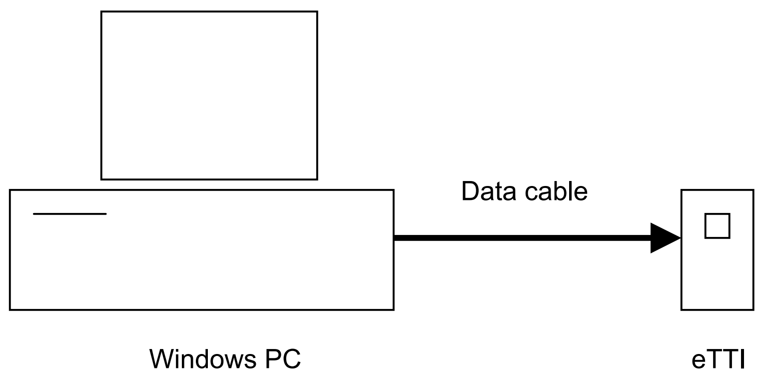
In this experiment, sunflowers were stored for 5 days at various temperatures between 0 and 15 °C. The sunflowers were then placed in a vase, at 20 °C, and the days of vase life remaining were observed. Note the relatively close correlation between the LifeTrack predicted remaining vase-life, and the experimental data.

Different agricultural items may have different stability characteristics. In some cases, alternative stability models may be more appropriate. Here, CliniSense, as part of the basic LifeTrack programming service, will strive to ensure that a sound and accurate stability model is used.

Programming the LifeTrack units: After the "F" and P(temp) data have been calculated, the process of producing a customized LifeTrack is extremely simple. The "F" value and table of P(temp) values are downloaded electronically into the LifeTrack through the LifeTrack unit's data input jack. The programmed LifeTrack is then ready to use.

To do this, the table of P(temp) values is loaded into a LifeTrack data download program, which runs on a standard personal computer (PC). The LifeTrack is then connected to the PC's serial port via an adapter cable, and the data transferred. After the data is downloaded, the program and LifeTrack unit automatically check the success of the download by comparing the data to a checksum. A schematic of this download process is shown in the figure below:

Use of a PC and data cable to customize a LifeTrack unit



Before use, the LifeTrack units are subjected to additional QC testing and verification. To facilitate this process, the LifeTrack has the ability to operate in various "QC test" modes that test the unit at accelerated speeds, and report temperature sensor calibration by telemetry. These QC test modes enable large numbers of LifeTrack units to be calibrated, programmed, and tested using a high-volume, automated, manufacturing process.

After programming and appropriate QC verification, a QC security sticker (containing appropriate labeling) may be placed over the unit's test button, data port, and reset button to keep unauthorized users from tampering with the unit.

To facilitate use in the processing environment, the LifeTrack can be programmed with a variable "start of testing delay" value between 0 and 1440 minutes (1 day). This allows the grower time to initialize, handle, and package the LifeTrack unit before monitoring begins.