THE UNIVERSITY OF ARIZONA
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Heat Units

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Introduction

Environmental temperatures impact the development of biological organisms that do not regulate their internal temperature, including crops and crop pests. Heat unit systems quantify the thermal environment of these organisms and are commonly used in phenology models—models that relate organism growth and development to local weather/climate conditions. This bulletin provides an overview of the heat unit concept and the two methods commonly used to compute heat units, then provides examples of how heat units can assist with the management of agricultural production systems in Arizona and concludes with a discussion on how to obtain local heat unit information.

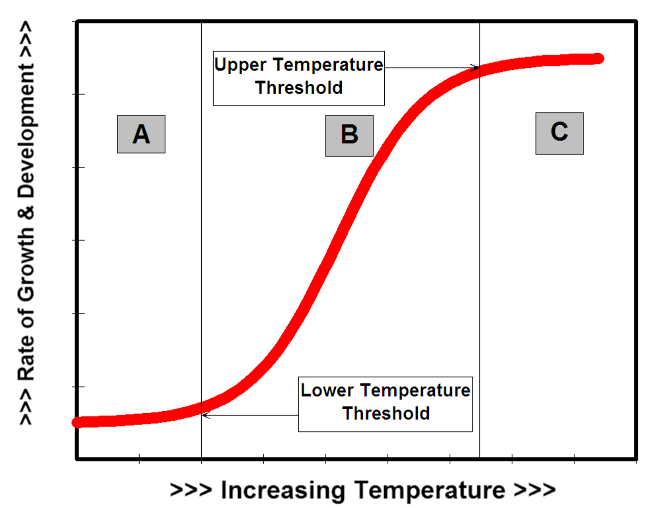

Figure 1. The relationship between organism growth and development and temperature often follows a sigmoid or S-shaped curve. Growth and development ceases when temperatures decline below the lower temperature threshold (A) or increase above the upper temperature threshold (C). Growth and development increases rapidly when temperatures fall between the lower and upper temperature thresholds (B).

What Are Heat Units?

The thermal environment impacts the development of most crops and crop pests. When the development of these organisms is related to temperature, the resulting relationship typically follows a sigmoid or S-shaped curve (Figure 1). This S-shaped curve has three distinct regions identified with the letters A, B and C in Figure 1. The portions of the curve that are nearly horizontal or flat (A & C in Figure 1) represent thermal environments that are either too cold or hot for the organism in question. The temperature where the curve flattens due to cool temperatures (A in Figure 1) is referred to as the lower temperature threshold for development. Similarly, the temperature where the curve flattens at high temperatures (C in Figure 1) represents the upper temperature threshold for development. Between the lower and upper temperature thresholds resides a range of temperatures wherein development increases with increasing temperature (B in Figure 1). Heat unit computation systems adjust local temperature data for the aforementioned upper and/or lower temperature thresholds and estimate the expected rate of growth and development (Figure 1). Heat units are typically reported in units of degree-days (DD).

How Are Heat Units Computed?

Temperature data must be available to compute heat units. A number of procedures have been developed to compute heat units with the two most common being the single sine curve and mean temperature methods (Zalom et al., 1983; Perry et al., 1986). Mean temperature methods are most widely used in humid regions where diurnal temperature fluctuations are relatively small during the growing season. The single sine curve approach is more common in semi-arid and arid regions that experience large diurnal fluctuations in temperature.

Sine Curve Heat Units

The single sine curve procedure reconstructs the daily temperature cycle by forcing a sine curve through the maximum and minimum temperatures for the day (Figure 2). The upper and lower temperature thresholds for the heat unit system are then superimposed on the temperature cycle. The temperature thresholds for the Arizona cotton heat unit system (upper = 86ºF; lower = 55ºF) are used in Figure 2. The area bounded by the sine curve and upper and lower temperature thresholds represents the temperature or heat that contributes to growth and development (grey area). Note that temperatures above the upper threshold and below the lower threshold do not contribute to growth and development and are excluded in the calculation procedure. Numerical integration is used to quantify the grey area in Figure 2 and generates a value of 15 DDF (DDF: degree-

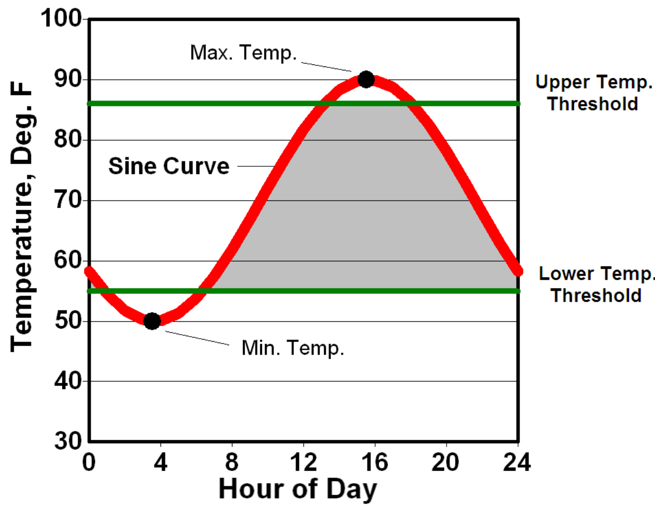

Figure 2. Graphical depiction of heat unit computation using the single sine curve procedure. A sine curve is fit through the daily maximum and minimum temperatures to recreate the daily temperature cycle. The upper and lower temperature thresholds for growth and development are then superimposed on the figure. Mathematical integration is then used to measure the area bounded by the sine cure and the two temperature thresholds (grey area).

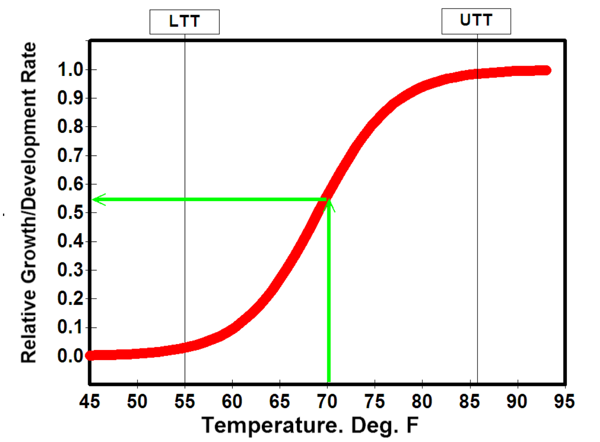

Figure 3. Graphical representation of a 15 DDF heat unit value for cotton in Arizona. Thermal conditions after adjusting for temperatures above and below the upper and lower temperature thresholds (abbreviated UTT and LTT) contribute to a growth/development rate equivalent to 15°F above the LTT.

days based on Fahrenheit temperature scale). A heat unit value of 15 DDF simply means that thermal conditions on that date support a development rate equivalent to 15°F above the lower temperature threshold for the organism in question. A good way to visualize the meaning of a heat unit value is to return to the S-shaped curve relating growth and/or development to temperature. In this case with a heat unit value of 15 DDF one simply extends a vertical line from the x-axis at 15 degrees above the lower temperature threshold until the line intersects the S-shaped curve to obtain the relative rate of growth and development (Figure 3).

Figures 4 and 5 provide two additional graphical examples of the single sine curve computation procedure. Figure 4 represents an early spring day where nighttime temperatures (35°F) are well below the lower threshold and daytime temperatures (75°F) reside between the two thresholds. Heat unit accumulation on this cool day totals just 6 DDF. Figure 5 represents a typical mid-summer day where the minimum temperature (68°F) falls between the two temperature thresholds and the maximum temperature (108°F) is well above the upper temperature threshold. Heat unit accumulation in this case totals 26 DDF.

Mean Temperature Heat Units

A number of mean temperature procedures are also used to compute heat units. The computation procedure is generally simpler than that of the sine curve approach. Two mean temperature procedures have been employed in Arizona to predict the development of small grains. One system adjusts the maximum and minimum temperatures if they fall outside the range of the upper and lower temperature thresholds (95°F and 32°F) before computing the mean temperature (Bauer et al., 1984). For this procedure, maximum

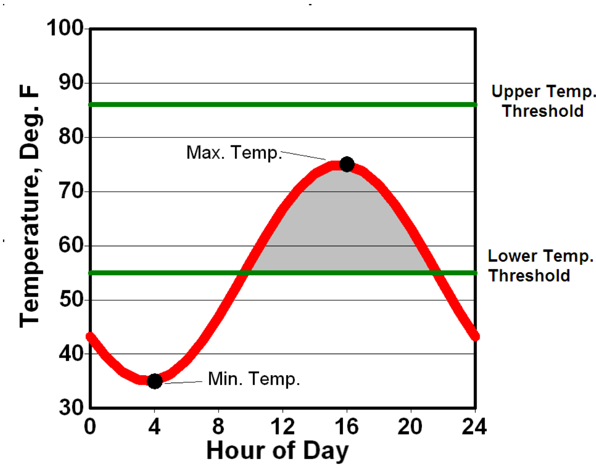

Figure 4. Graphical depiction of heat unit accumulation (grey area) on a cool spring day where the maximum and minimum temperatures were 75°F and 35°F, respectively.

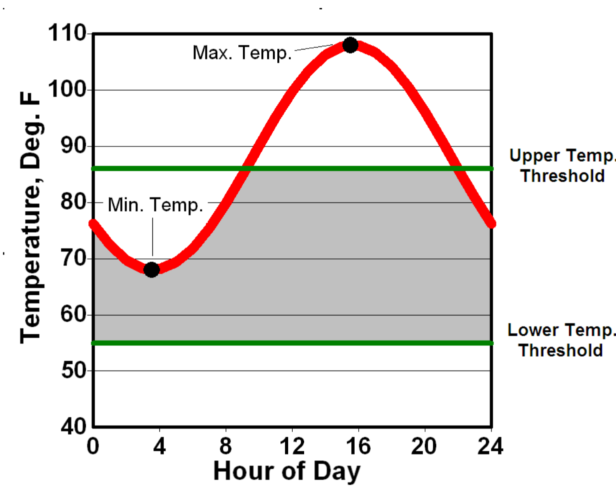

Figure 5. Graphical depiction of heat unit accumulation (grey area) on a hot summer day where the maximum and minimum temperatures were 108°F and 68°F, respectively.

temperatures in excess of 95°F are set to 95°F and minimum temperatures below 32°F are set to 32°F. The daily heat unit value is then obtained by subtracting 32°F from the adjusted mean temperature. For a typical mid-winter day with maximum and minimum temperatures of 69°F and 35°F, respectively, the computation procedure is very simple:

Maximum Temperature Remains = 69°F

Minimum Temperature Remains = 35°F

Mean Temperature = (69°F + °35°F)/2 = 52°F

Small Grains Heat Unit Value = 52°F - 32°F = 20 DDF

For a hot late spring day with a maximum temperature of 99°F and a minimum temperature of 65°F the computation proceeds as follows:

Maximum Temperature Adjusted To = 95°F

Minimum Temperature Remains = 65°F

Mean Temperature = (95°F + 65°F)/2 = 80°F

Small Grains Heat Unit Value = 80°F - 32°F = 48 DDF

The second computation procedure for small grains applies upper (78.8°F) and lower (32°F) temperature thresholds after the mean temperature is computed from the daily extremes (Ottman, 2008). If the mean temperature falls between the upper and lower thresholds, the resulting heat unit value is computed by subtracting 32°F from the mean. If the mean exceeds the thermal limit of 78.8°F, the heat unit value is set to the maximum possible value of 46.8 DDF which is computed by subtracting the lower thermal limit (32°F) from the upper thermal limit (78.8°F). The daily heat unit value is set to 0 when the mean temperature falls below 32°F. For the two sets of maximum and minimum temperatures used above (69°F/35°F & 99°F/65°F), the computations would proceed in the following manner:

Maximum = 69°F and Minimum = 35°F

Mean Temperature = (69°F + °35°F)/2 = 52°F

Small Grains Heat Unit Value = 52°F - 32°F = 20 DDF

Maximum = 99°F and Minimum = 65°F

Mean Temperature = (99°F + 65°F)/2 = 82°F

Mean Temperature Adjusted To = 78.8°F

Small Grains Heat Unit Value = 78.8°F - 32°F = 46.8 DDF

The two methods produce similar heat unit totals during most days; differences develop during cold weather (minimum temperatures below 32°F) and during hot days in late spring (maximum temperatures above 95°F).

Another heat unit system based on mean temperatures is the Degree-Day 60 (DD60) system commonly used in humid regions to project cotton growth and development (Ritchie, et al., 2004). With the DD60 system, one simply takes the average of the maximum and minimum temperatures for the day and subtracts a lower temperature threshold of 60°F. When the mean temperature is less than 60°F the daily heat unit value is set to 0 DDF. For a summer day with maximum and minimum temperatures of 103°F and 77°F, respectively, the computation would proceed as follows:

Daily Mean Temperature = (103°F + 77°F)/2 = 90°F

DD60 Heat Unit Value = 90°F - 60°F = 30 DDF

The heat unit system most often applied to corn adjusts the daily temperature extremes for the upper and lower temperature thresholds before computing the mean temperature (Wisner, 1972). In this system, maximum temperatures that exceed 86°F are set equal to 86°F and minimum temperature that fall below 50°F are set to 50°F. Once these modifications are made to the daily temperature extremes, one simply computes the mean of the modified temperatures and subtracts the lower temperature threshold of 50°F to determine the daily accumulation of heat units. For the situation where the maximum and minimum temperatures were 93°F and 77°F, respectively, the calculation proceeds as follows:

Maximum Temperature Adjusted To = 86°F

Minimum Temperature Remains = 77°F

Mean Temperature = (86°F + 77°F)/2 = 81.5°F

Corn Heat Unit Value = 81.5°F - 50°F = 31.5 DDF

For a typical early spring temperature regime of 76°F and 48°F, the corn heat unit computation would be completed as follows:

Maximum Temperature Remains = 76°F

Minimum Temperature Adjusted To = 50°F

Mean Temperature = (76°F + 50°F)/2 = 63°F

Corn Heat Unit Value = 63°F - 50°F = 13 DDF

Use of Heat Units: Some Arizona Examples

The University of Arizona has used the single sine curve computation procedure with upper and lower temperature thresholds 86ºF and 55ºF to estimate the development of cotton and pink bollworm (PBW) for more than 30 years (Dennis and Briggs, 1968; Huber, 1981; Silvertooth et al. 1992; Silvertooth, 2001). To estimate crop development, the accumulation of heat units begins when the seed comes in contact with soil moisture which is the planting date for cotton planted into moisture (pre-irrigated soil) or the watering date for dry planted cotton. The number of heat units required after planting (HUAP) for cotton to reach important developmental stages is provided in graphic form in Figure 6 and serves as the basis for the Cotton Development Advisories generated each week by the Arizona Meteorological Network (**http://ag.arizona.edu/azmet/cotton.htm.**). The same heat unit system has been used to estimate spring emergence of PBW moths in Arizona (Huber, 1981; Huber 1982; Brown et al.,

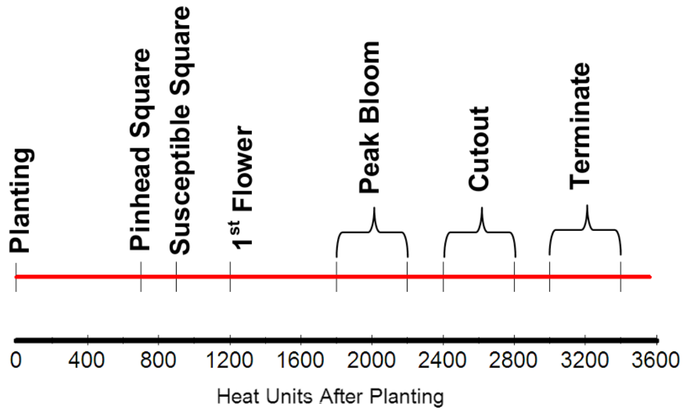

Figure 6. Developmental timeline for Upland cotton based on heat units (sine curve computation, temperature thresholds: 86°F/55°F) accumulated after planting.

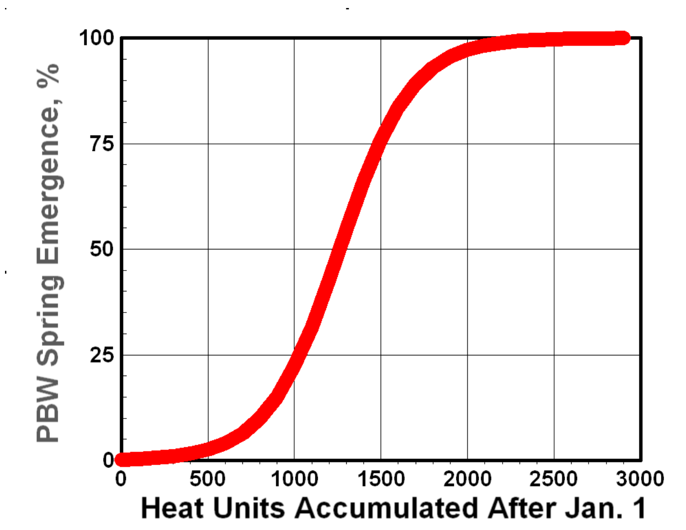

Figure 7. Spring emergence of pink bollworm (PBW) moths plotted as a function of heat unit accumulation (sine curve computation, temperature thresholds: 86°F/55°F) after January 1.

1990). In this case the accumulation of heat units begins on January 1 of each year. Spring emergence typically begins when heat unit accumulation totals 500 DDF, reaches the 50% emergence level at 1180 DDF and ends when heat unit accumulation totals approximately 2250 DDF (Figure 7).

The bi-weekly Small Grain Advisory (**http://extension.arizona.edu/programs/forage-and-grain-crops**) provides timely information on crop development, suggested management operations and water use (Figure 8). The Advisory makes use of heat units computed using the sine curve method (Thresholds: 86°F and 45°F) to estimate crop development and crop coefficients (for estimating water use) during the growing season (Ottman, 2004).

Heat units can also be used to estimate the development of horticultural crops. The development of chile peppers (Figure 9) and melons can be predicted using the accumulation of heat units computed using the sine curve procedure with upper and lower thresholds of 86°F and 55°F, respectively (Silvertooth et al., 2010; Soto-Ortiz and Silvertooth, 2008).

The development of planting and harvest schedules for horticultural crops represents another area where heat units have been successfully employed. Seed companies often provide information on the number of heat units required for a given variety to attain harvest maturity. Given this heat unit requirement and some information on typical seasonal patterns of heat unit accumulation, planting schedules can be developed that allow for orderly harvests over a targeted period. An example of a planting schedule for sweet corn is provided in Figure 10. Because each season's weather differs from the long term average, planting schedules only approximate harvest dates. However, by monitoring in-season heat unit accumulation for each planting date, growers can project the actual harvest date with considerable accuracy several weeks ahead. Such late season projections can assist in scheduling harvest, packing and shipping crews.

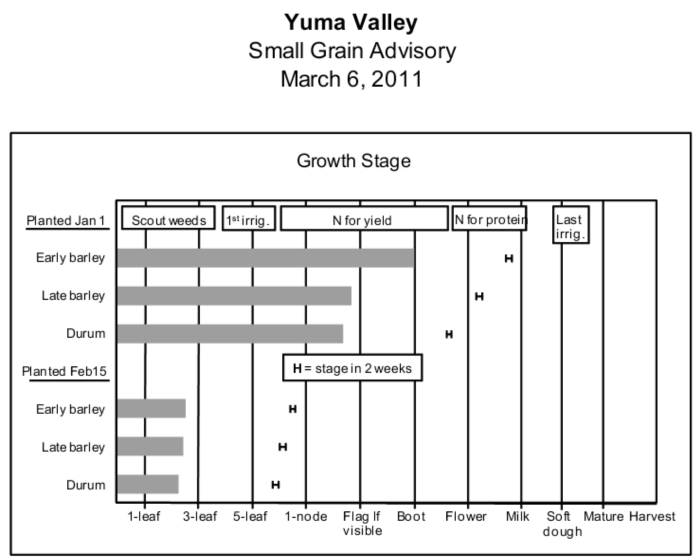

Figure 8. The bi-weekly Small Grain Advisory provides timely information on crop development, suggested management operations and water use. Heat units are used to estimate crop development and water use during the growing season.

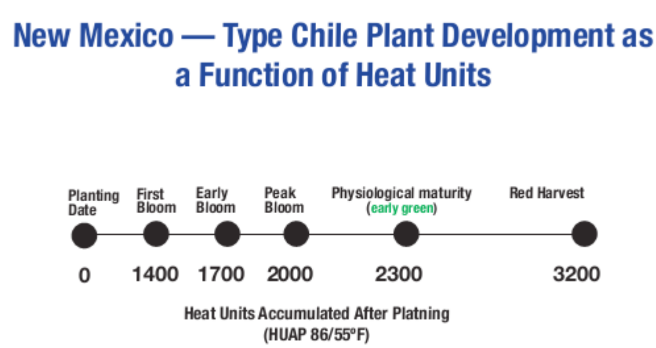

Figure 9. Developmental timeline for New Mexico-Type Chile based on heat units (sine curve computation, temperature thresholds: 86°F/55°F) accumulated after planting.

SWEET CORN PLANTING SCHEDULE

Location: Maricopa
Variety: Supersweet Jubilee
Heat Unit Requirement: 1750 DDF

Planting Date	Desired Harvest Date
Feb. 22	June 1
Mar. 14	June 8
Mar. 30	June 15
Apr. 13	June 22

Figure 10. Planting schedule for sweet corn at Maricopa, AZ. The objective of the schedule is to select planting dates that will produce harvest dates separated by one week. The schedule is developed using long term average values of heat unit accumulation available from the Arizona Meteorological Network.

How To Obtain Local Information on Heat Units

The University of Arizona operates a near-real time weather information system known as the Arizona Meteorological Network (AZMET). AZMET presently operates 27 automated weather stations across southern and central Arizona (Figure 11) that provide temperature data that can be used for the computation of heat units. AZMET produces a daily heat unit report for all stations in the network (Figure 12). The report provides daily and year-to-date totals of heat unit accumulation computed using the single sine curve procedure for three sets of temperatures thresholds: 86°F/55°F, 86°F/50°F, and 86°F/45°F. Heat units computed using 86°F/55°F thresholds are used to estimate the growth and development of cotton, pink bollworm, chile and melons. Heat units based on 86°F/50°F have been used for models related to corn and melons while heat units based on the 86°F/45°F thresholds have been used for small grains and the Egyptian Alfalfa Weevil (Knowles, 1998). All AZMET data are available free of charge via the internet at **http://ag.arizona.edu/azmet/az-docs.htm**.

In areas not served by AZMET, heat unit information can be developed provided there is a local source of temperature data. A likely source of temperature data is the local National Oceanic and Atmospheric Administration (NOAA) volunteer observer. Most areas have NOAA volunteers and it may be possible to obtain an observer's temperature data on a regular basis.

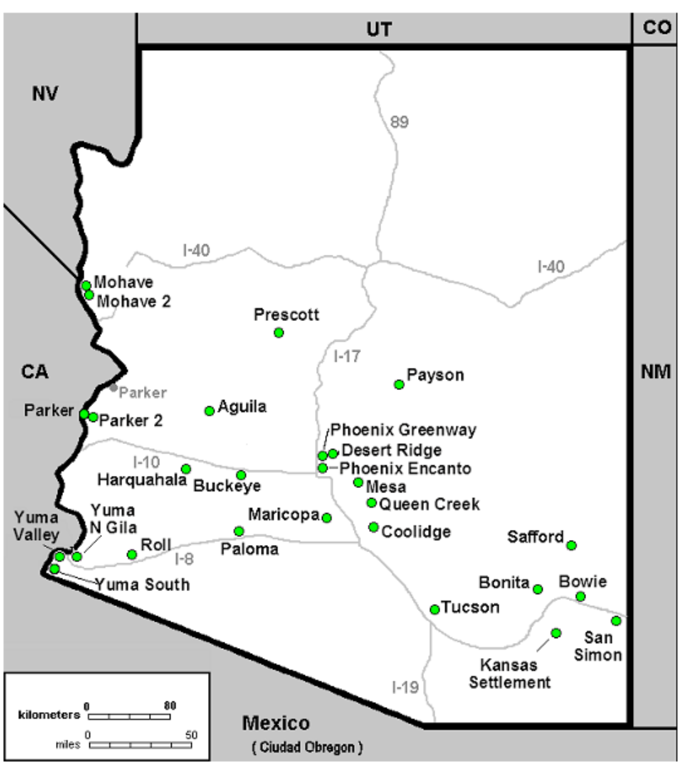

Figure 11. The Arizona Meteorological Network (AZMET) operates a network of 27 automated weather stations that provide temperature and heat unit information on a daily basis. Map current as of October 2012.

Maricopa : 2012 Heat Units

				85/55		86/50		86/45	
DOY	Date	Max	Min	HU	CUM	HU	CUM	HU	CUM
1	Jan 1	79	34	7.9	8	10.7	11	13.8	14
2	Jan 2	78	39	8.1	16	11.2	22	14.7	29
3	Jan 3	71	39	5.1	21	7.9	30	11.1	40
4	Jan 4	77	35	6.9	28	9.7	39	12.8	52
5	Jan 5	74	36	5.8	34	8.5	48	11.6	64
6	Jan 6	70	33	4.1	38	6.6	55	9.5	74
7	Jan 7	71	32	4.6	43	6.9	61	9.8	83

DOY = Day Of Year (1 to 365)
Max = Maximum Air Temperature
Min = Minimum Air Temperature
HU = Daily Heat Units
CUM = Accumulated Heat Units : Since Jan 1, 2012

Temperature & Heat Units are in Fahrenheit Units
Heat Units calculated by Single Sine Method

Figure 12. Example of an AZMET Heat Unit Report. The report provides daily temperature extremes and daily and year-to-date totals of heat unit accumulation computed using the single sine curve method for three sets of temperature thresholds: 86ºF/55ºF, 86ºF/50ºF and 86ºF/45ºF.

Figure 13. The Stevenson Screen (left) and the 12-plate Gill shield (right) are used to protect temperature sensors from radiation and precipitation. The temperature sensor should be installed at 5' (1.5m) above the surface.

When no local temperature data are available, it will be necessary to set up some form of temperature monitoring equipment. Temperature is relatively easy to monitor and one can obtain useful data with equipment ranging from simple maximum and minimum thermometers that can be read manually to more complex electronic sensors that can be downloaded directly to a personal computer. Temperature sensors must be sheltered from direct sunlight and thus should be installed in some form of radiation shield. Effective radiation shields include the standard white wooden box with louvered sides known as the Stevenson Screen and the smaller plastic shields used to protect electronic sensors (Figure 13). Locate the shelter adjacent to the production area of interest. Avoid locations where wind flow is impeded (e.g., near walls, trees or buildings) or where the upwind surface is not representative of an agricultural field (e.g., hot parking lots). Mount the shelter such that the enclosed thermometer resides 5 feet (1.5 m) above the ground. Shelters housing manual read thermometers should be oriented such that the shelter door opens to the north to minimize radiation errors during measurement periods.

The best means of converting local temperature data into heat units is through the use of spreadsheet software. The mathematics required to compute HUs using mean temperature procedures can be easily entered into spreadsheets. An Excel based software program is now available for applications requiring heat units computed using the sine curve procedure (Brown, 2010). The program, referred to as the Arizona Heat Unit Program (AHUP) computes daily and cumulative values of heat unit accumulation from user entered temperature data. The program will work on any set of thermal limits and produces an output table (Figure 14) that can be stored as a worksheet or directed to a printer to produce hardcopy output. AHUP can be downloaded from the AZMET website at **http://ag.arizona.edu/azmet.**

Heat Unit System		
	Temperature	Units (C or F)
Upper Threshold	86	F
Lower Threshold	55	F

Press ctrl z to clear old dates & data				Heat Units Deg-F-Days		Heat Units Deg-C-Days	
Date	Max Temp	Min Temp	Status	Daily	Accumulated	Daily	Accumulated
1-Jul	96	65	OK	23.0	23.0	12.8	12.8
2-Jul	100	72	OK	26.6	49.6	14.8	27.5
3-Jul	105	67	OK	25.0	74.5	13.9	41.4
4-Jul	103	76	OK	28.3	102.9	15.7	57.1
5-Jul	105	80	OK	29.7	132.6	16.5	73.6
6-Jul	107	77	OK	28.8	161.4	16.0	89.7
7-Jul	110	79	OK	29.5	190.9	16.4	106.1

Figure 14. Output from the Arizona Heat Unit Program, an Excel-based software package that computes sine curve heat units from user entered temperature data.

Precautions When Using Heat Units

Several methods of calculating heat units have been developed and are presently used worldwide in phenology models. While the sine curve and mean temperatures methods described in this bulletin are the two most common computation procedures, other methods such as the triangular and double sine curve procedures have found utility in some areas (Zalom et al., 1983). Before using any heat unit based model, it is very important to understand the computation procedure and compute heat units properly. If questions arise about the model or method of heat unit calculation, contact the Extension Biometeorology Program.

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