BANDGAP REFERENCE CALCULATOR USER'S GUIDE

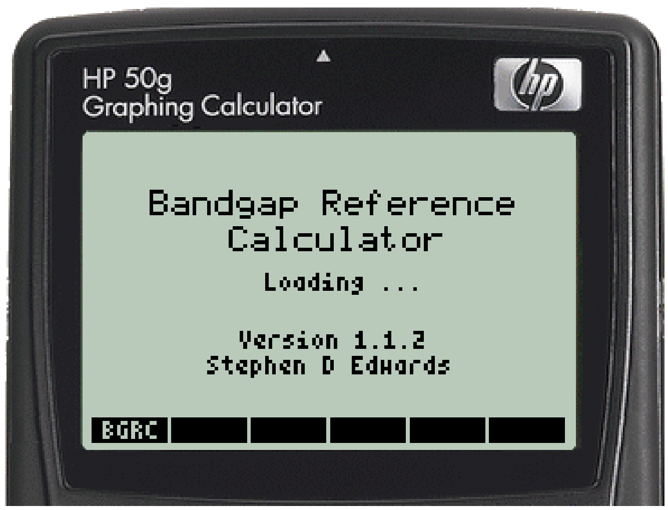

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TABLE OF CONTENTS

SECTION 1 - INTRODUCTION

Bandgap Reference Calculator (BGRC) is a program for the HP50g calculator that aids in the design and analysis of a two transistor Brokaw bandgap voltage reference circuit. BGRC calculates all circuit parameters and the output voltage as a function of junction temperature and circuit parameter. BGRC can also run on a PC using the free program HPUserEdit 5.4, found at www.hpcalc.org, or the calculator page at www.maximintegrated.com/design/tools/calculators/hp50g/.

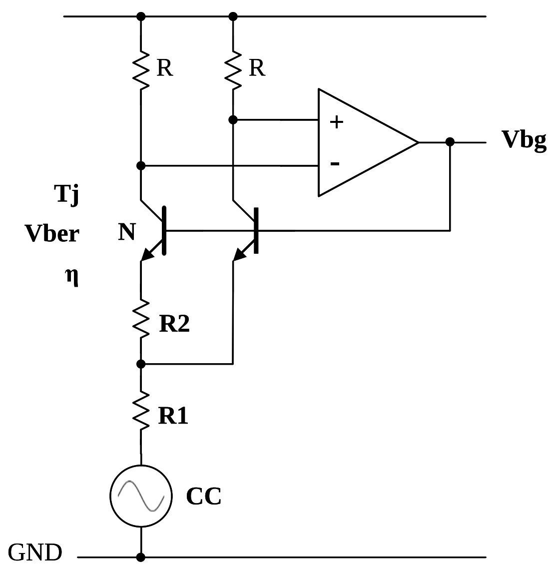


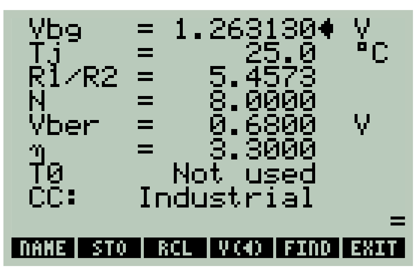
Figure 1 Brokaw Bandgap Reference Cell

In this guide all calculated parameters are shown in bold font.

BGRC can find any circuit parameter as a function of the others, making it useful for both design and analysis of bandgap reference circuit. Seven parameters can be entered or found,

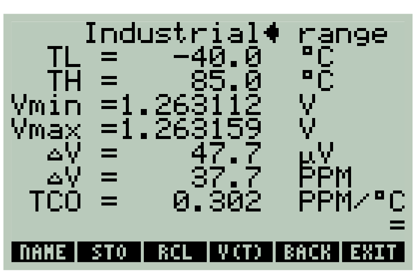
1. Output 'bandgap' voltage, **Vbg,** in volts
2. Junction temperature, **Tj,** in °C
3. Resistor Ratio, **R1/R2**
4. Transistors emitter area ratio, **N**
5. Base emitter voltage at 25°C, **Vber**, in volts
6. Process dependent parameter, **η**
7. Magic temperature, **T0**, in °C
8. Curvature Correction Select, **CC**

The initial screen displays these parameters with their default values,



BGRC can plot **Vbg** as a function of any other circuit parameter. This is useful for estimating the circuit's initial accuracy (IA) and average temperature coefficient (**TCO**).

When plotting **Vbg** as a function of **Tj**, the following list of parameters appear,



1. **Industrial range**, one of six standard temp ranges
2. **TL** and **TH** are the upper and lower plotting temperature limits
3. **Vmin** and **Vmax** are the minimum and maximum excursions of **Vbg** between **TL** and **TH**
4. **ΔV** is the maximum **Vbg** deviation between **TL** and **TH**
5. **TCO** is the average temp coefficient over **TL** and **TH**

Refer to Section 7 for an explanation of these parameters and how they are calculated.

SECTION 2 - INSTALLATION

BGRC can be installed on the HP50g calculator or a Windows PC.

Installing BGRC on the HP50g Calculator

BGRC may be installed in any one of three ways:

A. Best when installing one calculator:

   Copy the executable file BGRC.hp to the home directory or subdirectory of the HP50g calculator. Launch BGRC.hp.

B. Best when installing between two and six calculators:

   Copy the executable file BGRC.hp to the root directory of an SD card, and the much smaller file BGRC to the home directory or subdirectory of the HP50g calculator. Launch BGRC.

C. Best when installing six or more calculators:

   Install BGRC using the Calculator Launcher (CALC) utility found at www.maximintegrated.com/design/tools/calculators/hp50g/. to the CALC User's Guide for an explanation of this utility.

Refer to the HP50g Graphing Calculator User's Guide for instructions on how to copy files to the calculator.

Installing BGRC on a Windows PC

BGRC can be run on a Windows PC using the free program HPUserEdit 5.4. HPUserEdit is an IDE for the HP50g and contains a suitable emulator.

To install HPUserEdit:

Download and install HPUserEdit 5.4, found at www.hpcalc.org. Search for "HPUserEdit5". The default language is Spanish. However, other languages can be selected as follows,

1. Select 'Opciones' (Options)
2. Select 'Idiomas' (Language)
3. Select the preferred language (English is assumed in this document)

To run BGRC:

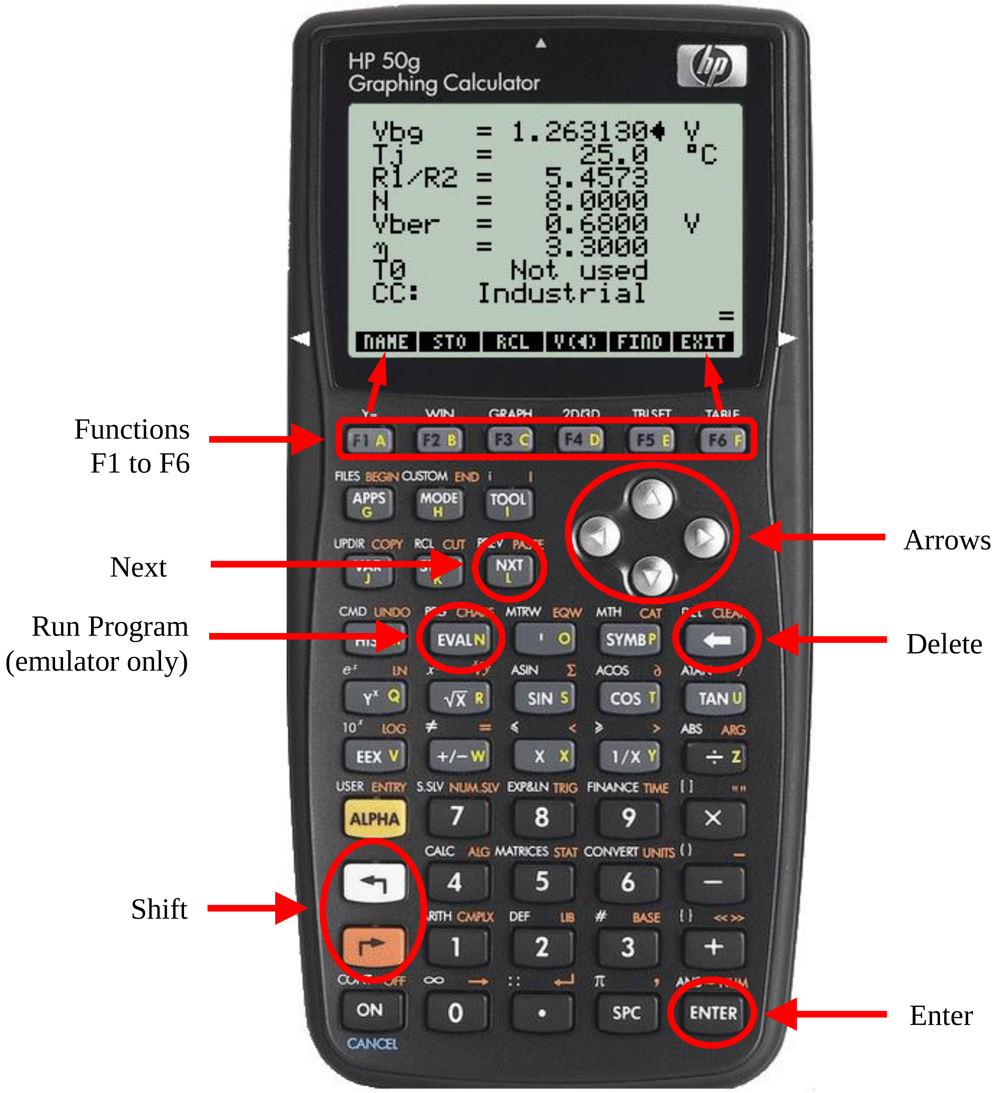
1. Launch HPUserEdit
2. Launch the HP50g emulator by selecting Emulator/Run_the_Emulator from the menu bar. A virtual HP50g appears.
3. Drag and drop BGRC.hp from an unzipped folder to the calculator screen, and click the EVAL key.

The splash screen shown on page 1 of this guide is displayed when the calculator is loading. It appears momentarily, and may not be visible when run on a PC.

BGRC creates a file named 'CalcDB' in the calculator's home directory the first time it is run. 'CalcDB' holds the parametric values used by BGRC when launched, and is used by the STO and RCL commands to store and recall the parameters.

SECTION 3 - KEYBOARD

The following diagram shows the location of all keys used by BGRC:



When using the emulator, the calculator keys map to the PC keyboard as follows:

Calculator Keys	►	PC Keyboard Keys
Yellow Letters	►	Letters
Numbers	►	Numbers
Enter and Delete	►	Enter and Delete
Arrows	►	Arrows
Left Shift	►	Shift
Right Shift	►	Control

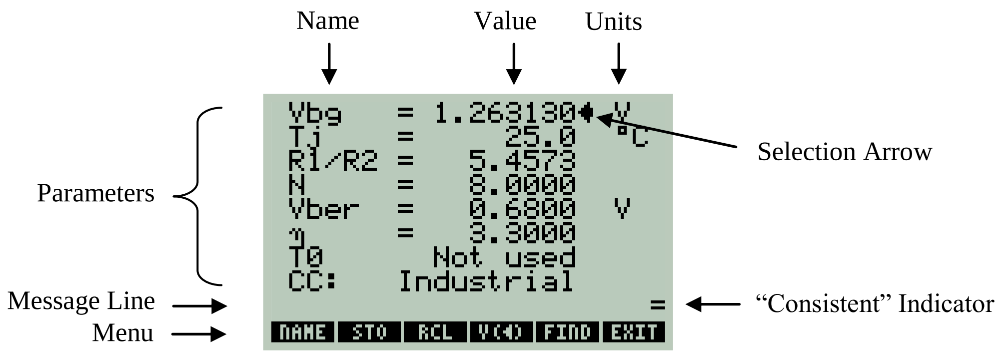
Section 4 - Commands

BGRC has four sets of commands:

- Main Menu Commands
- Extended Menu Commands
- Plot Commands

Main Menu Commands for Circuit Parameters

After launching BGRC the first time, the following screen appears, listing eight circuit parameters.

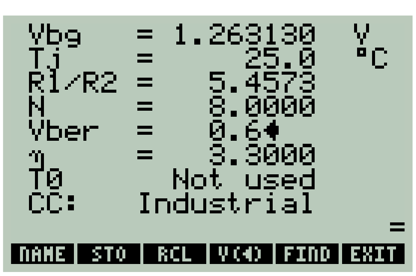


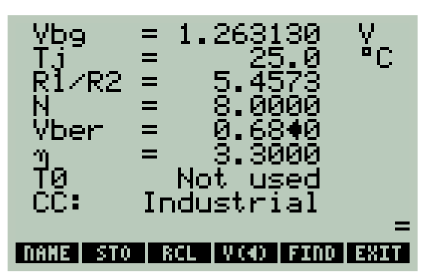
The ▼ and ▲ keys move the Selection Arrow up or down to select a parameter.
The ◂ (insert) or ◆ (delete) keys enter or edit a parameter. Press ENTER when finished.

F1 (NAME) displays a description of the selected parameter in the message line
↰ F1 (NAME) displays the full precision of the selected parameter in the message line
F2 (STO) stores all parameters
F3 (RCL) recalls all stored parameters
F4 (V(◂)) plots **Vbg** with respect to the selected parameter
F5 (FIND) finds the selected parameter
F6 (EXIT) or ON (Cancel) exits the program
↰ F6 (EXIT) launches previous run calculator (for physical calculators only - requires CALC)
↱ ON turns off the calculator

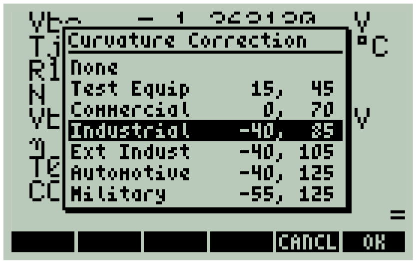
Enter or edit a parameter value using the ◆ or ◂ key as shown. Press ENTER when finished.

Delete key (◆), Insert key (◂),





Attempting to edit **CC** will display the following menu,

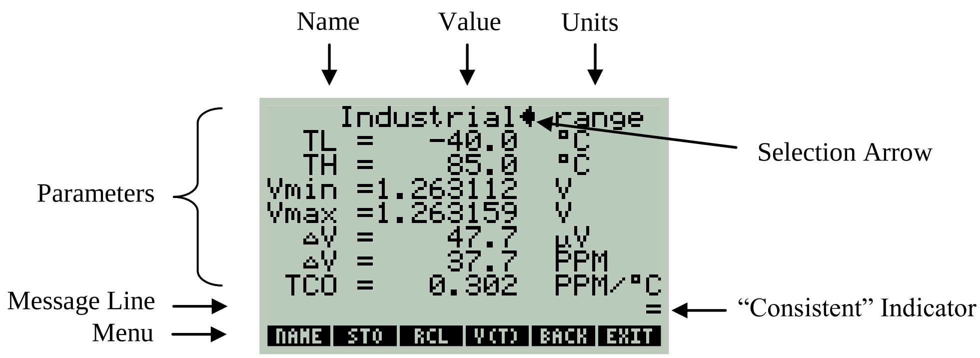


Use the up ( ) or down ( ) arrow keys to select an optional curvature correction level optimized for one of the standard temperature ranges shown.

The equal sign (=), in the lower right hand corner of the display, indicates that all the parameters are consistent with each other. That is to say, **Vbg** result from the displayed values of **Tj**, **R1/R2**, **N**, **Vber**, **η**, and **T0**. The parameters are always consistent immediately following a F5 ( ) command, and the "=" will appear. Any entry of a parameter value will display the "≠" sign, indicating that the parameters may no longer be consistent.

Main Menu Commands for Vbg(T) Parameters

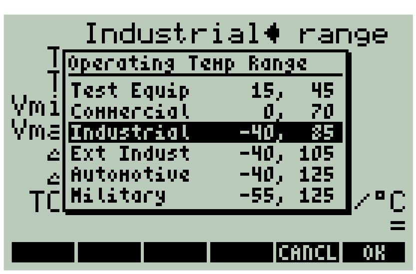
When **Tj** is selected, pressing F4 ( ) displays the following screen. Eight parameters are listed. All parameters relate to the plot of Vbg(T).



Two new commands appear on this display.

F4 ( ) plots **Vbg** with respect to **Tj**.
F5 ( ) returns to the list of circuit parameters

The **range** parameter selects the operating temperature range use to plot Vbg(T). Attempting to edit the **range** parameter will display the following menu of standard operating ranges.

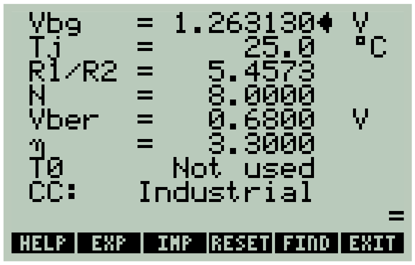


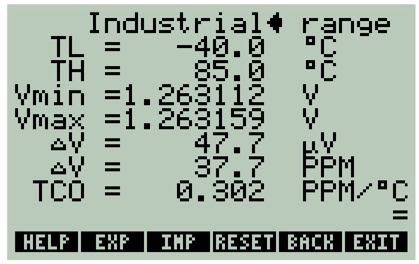
Use the up ( ) or down ( ) arrow keys to select a standard operating temperature range for plotting.

All other commands operate as described in the previous section.

Extended Menu Commands

Press the NXT key to display the Extended Menu showing four additional commands. Press NXT again to return to the Main Menu.



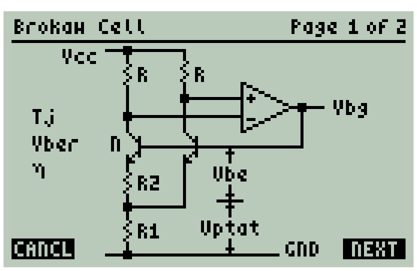


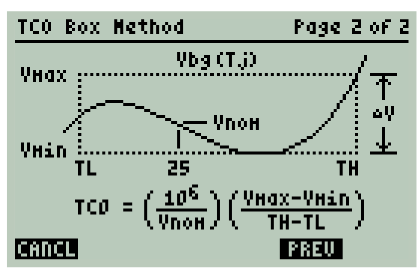
← Extended Menu

F1 (HELP) displays the Brokaw Cell circuit and the definition of the TCO Box Method
F2 (EXP) exports the selected parameter to the stack upon exiting.
F3 (IMP) imports the number on level 1of the stack, when BGRC was launched, to the selected parameter.
F4 (RESET) restores all default parameter values. Parameters are not stored until STO is executed.

Help Commands

Press F1 (HELP) to display the help screen, and F5 (PREV) and F6 (NEXT) to view pages 1 and 2 shown below. Press F1 (CANCL) to return to the parameter display.





The Main Menu reappears after executing an extended menu command.

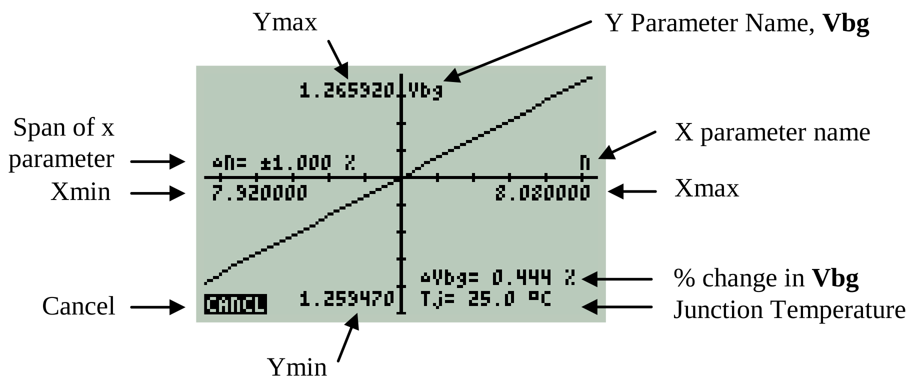
Plot Commands

F4 ( ) plots **Vbg** with respect to the selected parameter. First move the selection arrow to the desired parameter, then press the key.

There are two types of plots, each with different commands.

1. The first type of plot appears when Vbg(**R1/R2**). Vbg(**N**), Vbg(**Vber**), or Vbg(**η**) are plotted.

   The key elements of this type of plot display are show below. Vbg(**N**) is used as an example.

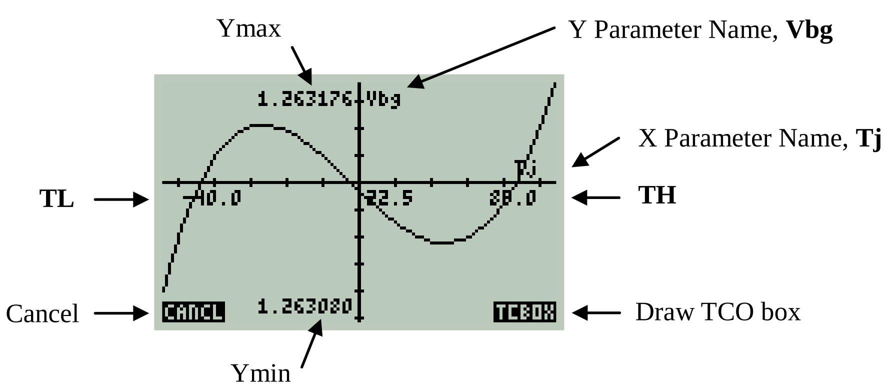


   The following commands are active when this type of plot is displayed:

	▲	Zoom out by 2x
↰	▲	Zoom out by 10x
	▼	Zoom in by 2x
↰	▼	Zoom in by 10x
F1	(CANCL)	Return to the Vbg(T) parameter list

2. The second type of plot appears when Vbg(**Tj**) is plotted, and the F4 ( ) command is executed from the Vbg(T) main menu.

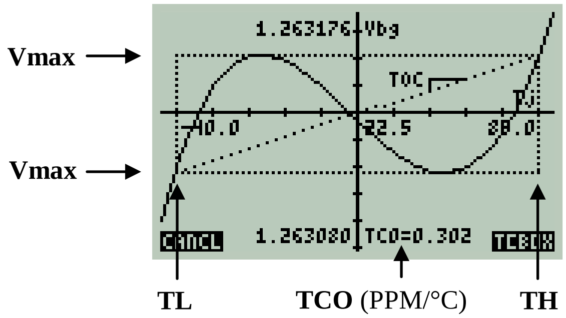
   The key elements of this type of plot display are show below:



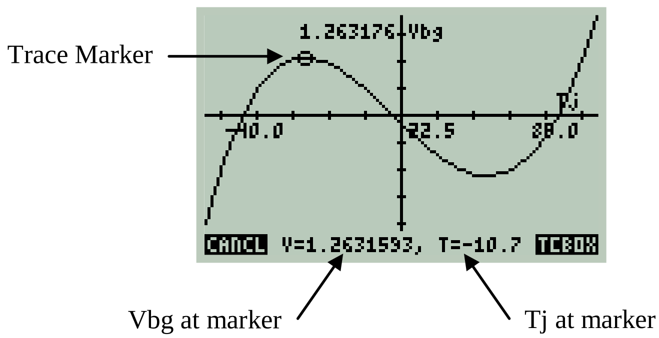
   The x-axis span is set by parameters **TL** and **TH** in the Vbg(T) menu.

F6 (TCBOX) Draws or removes the TCO box

The elements of the TCO Box appears are shown below,



The left and right arrow keys (and) will display a trace that can be moved along the curve displaying the **Vbg** and **Tj** values.



Move the trace marker left by 1°C

Move the trace marker left by 5°C

Move the trace marker left to the nearest **TL**, **TH**, Peak, or 25°C temperature

Move the trace marker right by 1°C

Move the trace marker right by 5°C

Move the trace marker right to the nearest **TL**, **TH**, Peak, or 25°C temperature

Finally,

F1 (CANCL) Return to the parameter display

SECTION 5 - MESSAGES

The calculator displays five types of messages on the message line:

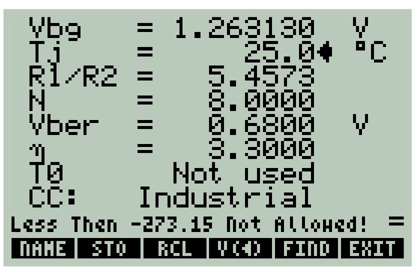
1. Name Messages

Name messages describe the selected parameter when NAME is active.

2. Busy Messages

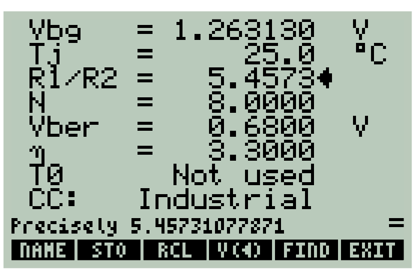
Busy messages explain what the program its doing.

3. Error Messages



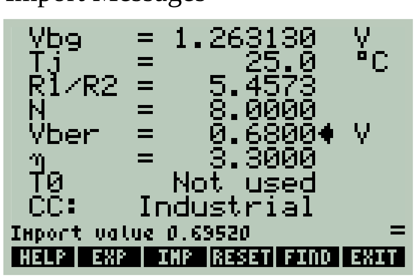
Error messages warn of an illegal entry.

4. Full Precision Messages



Full Precision messages show the full precision of the selected parameter, when ↰ NAME is active.

5. Import Messages



Import messages show the value to be imported.

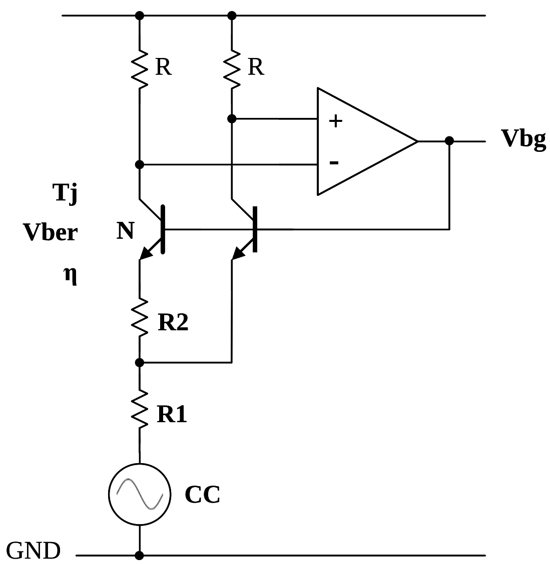
SECTION 6 - EXAMPLES

The following example is used to demonstrate how to use the BGRC calculator. Enter (◄ , ⬅), Find, (FIND, F5), and Plot (V(◄), F4) command will be demonstrated.

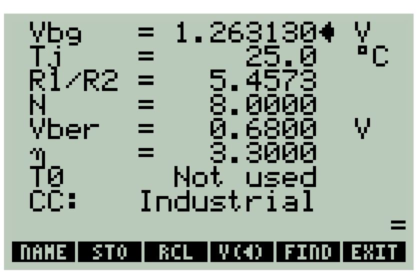
Design three Brokaw bandgap reference circuits with different temperature drifts (TCO) optimized as follow:

1. Lowest drift at or near room temperature without curvature correction
2. Lowest average drift over the commercial temperature range without curvature correction
3. Lowest possible drift over the commercial temperature range using curvature correction

The Brokaw bandgap reference circuit, with the BGRC parameters is shown below.



1. Design a Brokaw cell having the lowest drift *at or near room temperature* (without curvature correction)



Step 1:

Launch BGRC. A list of bandgap circuit parameters appear, with their default values

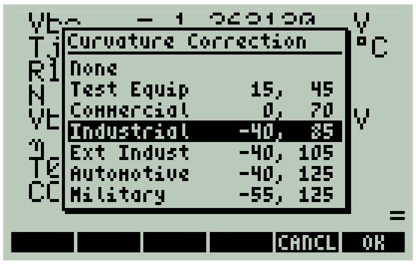
Begin by entering the circuit parameters:

Vber and **η** are semiconductor process parameter. **Vber** is *Vbe* at 25°C, and **η** is a constant that describes the exponential behavior of the transistors' saturation (I_S) and collector (I_C) currents over temperature. These are typical values and will be used in this example. **N** is the ratio of the emitter area of the left to right-hand transistors. An **N** of eight is a practical transistor ratio and will be used here.

BGRC enables curvature correction (CC) by default. Disable it.

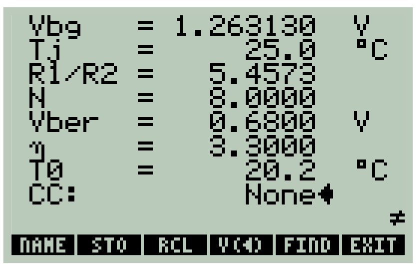
Step 2:

Use the down arrow key ( ) to select **CC.** Edit **CC** by pressing the Insert ( ) or Delete ( ) key.



Step 3:

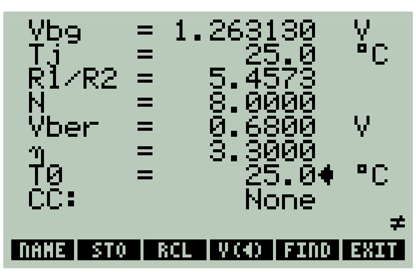
The curvature correction menu appears. Disable curvature correction by selecting "None" using the up arrow key ( ) and pressing 'OK' (F6).



Note that the consistency indicator has changed from "=" to "≠" indicating that all the parameters are now no longer consistent.

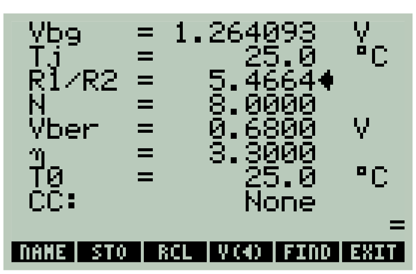
The shape of the Vbg vs T curve of a non-curvature corrected bandgap voltage is approximately a downward opening parabola. **T0** defines the peak of the parabola where dVbg(T)/dT is zero. **T0** is sometimes called the "Magic Temperature", and the voltage at **T0**, called the "Magic Voltage".

Setting **T0** to room temperature (25°C) will yield the lowest drift at or near room temperature. But, what is the average TCO over 0 to 70°C?



Step 4:

Select **T0** using the up arrow key ( ) and enter 25 °C into **T0**.

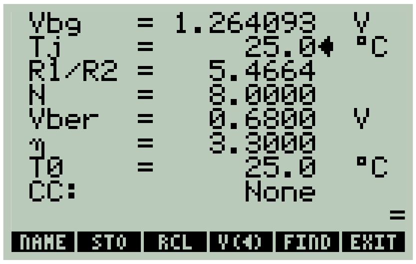


Step 5:

Trim the circuit for the new **T0** by selecting **R1/R2** using the up arrow key ( ) and pressing the F5 (FIND) menu key. Note that the consistency indicator has changed from "≠" to "=" indicating that all the parameters are now consistent.

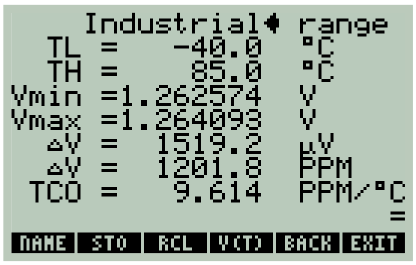
Because **Tj** is set to the magic temperature of **T0**, **Vbg** shows that the magic voltage is 1.264093V.

Next, find the average temperature coefficient (**TCO**) over 0 to 70°C.

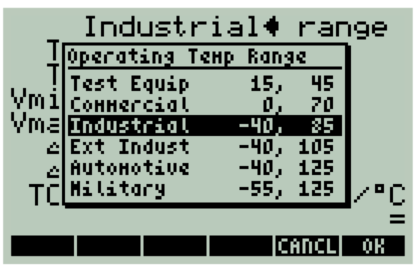


Step 6:

Find the average **TCO** by moving the selection arrow up to **Tj** and pressing the plot menu key, F4 (V(T)).

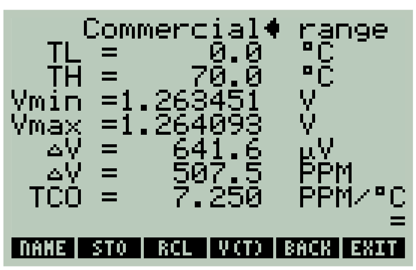


The Vbg(T) parameter list appears as shown. The industrial temperature range is set by default.



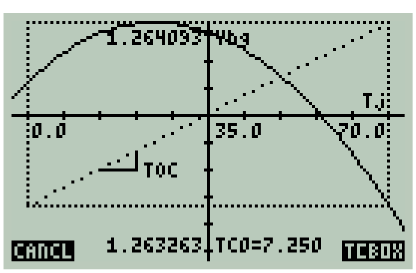
Step7:

Change the operating temperature range by pressing the Insert (◄) or delete (◄) key. The Operating Temperature Range menu appears. Select "Commercial" using the up arrow key (▲). Press 'OK' (F6).



The commercial temperature range values (**TL**=0°C and **TH**=70°C) are automatically entered and **TCO** calculated.

TCO will be 7.25 ppm/°C when **T0** = 25°C.

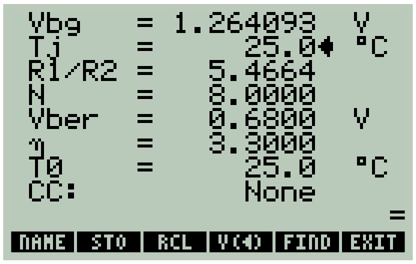


Step 8:

TCO and **T0** can be seen graphically by plotting Vbg(T). Plot Vbg(T) by pressing (F4). Press F6 (TCBOX) to plot the TCO box.

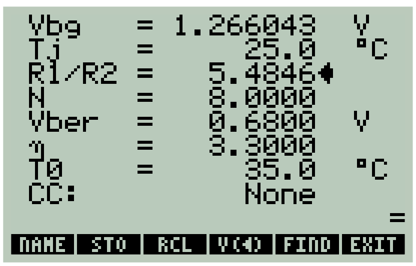
2. Design a Brokaw cell having the *lowest average drift* over the commercial temperature range without curvature correction.

   It can be seen from this plot that **TCO** will be minimized if **T0** is placed half way between **TL** and **TH**. For the commercial temperature range of 0 to 70°C, **T0** would be 35°C. The following steps show how to enter **T0** and find **TCO**.



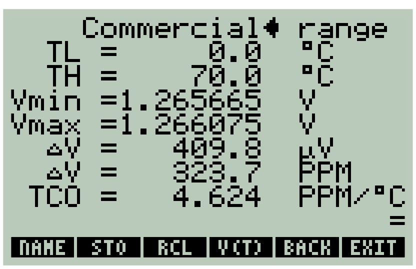
Step 1:

Return to the main parameter page by first exiting the plot and returning to the Vbg(T) parameter page by pressing F1 (CANCL), and then going to the Main parameter page by pressing F5 (BACK).



Step 2:

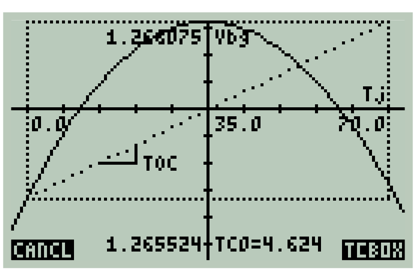
Enter 35°C in **T0** and trim the circuit for the new **T0** by selecting **R1/R2** and pressing the F5 (FIND) menu key.



Step 3:

Find the average **TCO** my moving the selection arrow up to **Tj** and press the plot menu key, F4 (VIEW). The Vbg(T) parameter list appears as shown. The commercial temperature range (**TL**=0°C and **TH**= 70°C) was previously entered and **TCO** calculated.

TCO reduces to 4.62 ppm/°C when **T0** = 35°C.

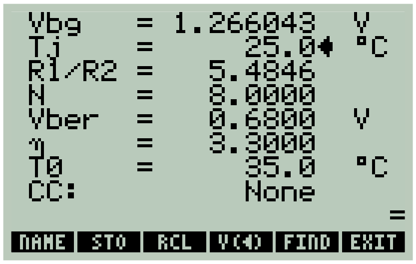


Step 4:

Vbg(T), TCO and **T0** can be seen graphically by plotting Vbg(T). Plot Vbg(T) by pressing (F4). Press F6 (TCBOX) to plot the TCO box.

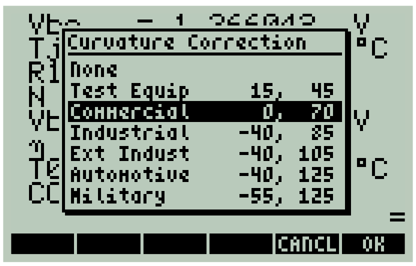
Setting **T0** midway between 0 and 70°C yields nearly the lowest **TCO** for this operating temperature range.

3. Design a Brokaw cell having the *lowest possible average drift* over the commercial temperature range *using curvature correction*



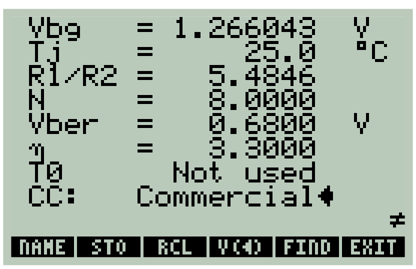
Step 1:

Return again to the main parameter page by first exiting the plot and returning to the Vbg(T) parameter page by pressing F1 (CANCL), and then going to the main parameter page by pressing F5 (BACK).



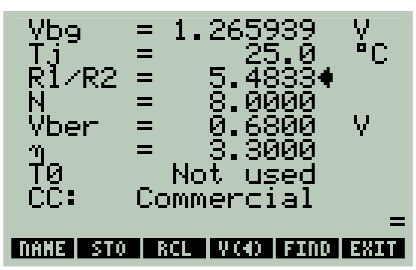
Step 2:

Use the down arrow key ( ) to select **CC**. Edit **CC** by pressing the Insert ( ) or Delete ( ) key. The curvature correction menu appears. Select “Commercial” curvature correction using the up arrow key ( ). Press ‘OK’ (F6).



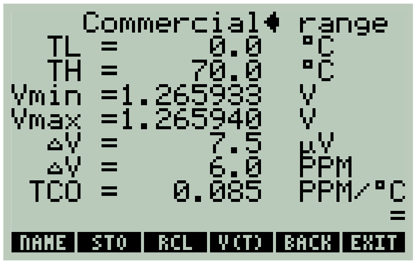
Step 3:

“Commercial” curvature correction is selected. The consistency indicator changes from “=” to “≠” indicating that all the parameters are now no longer consistent.



Step 4:

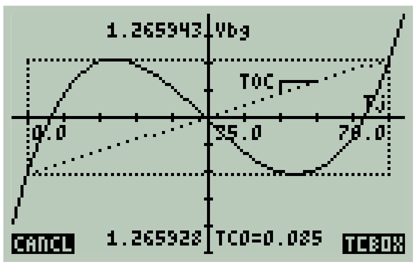
Trim R1/R2 for the commercial temperature range by selecting **R1/R2** and pressing the F5 (FIND) menu key. The consistency indicator changes from “≠” to “=” indicating that all the parameters are now consistent.



Step 5:

Find the average **TCO** my moving the selection arrow up to **Tj** and press the plot menu key, F4 (V(T)). The Vbg(T) parameter list appears as shown. The commercial temperature range (**TL**=0°C and **TH**= 70°C) was previously selected and **TCO** calculated.

TCO is dramatically reduced to 0.085ppm/°C



Step 6:

The change in **Vbg(T)** and **TCO** can be seen graphically by plotting Vbg(T). Plot Vbg(T) by pressing (F4). Press F6 (TCBOX) to plot the TCO box.

With curvature correction, **TCO** is reduced to the lowest possible value of 0.085ppm/°C.

In summary, it was shown that

1) Trimming for zero TCO at 25°C yields the lowest drift at or near room temperature, but will have a relatively high average TCO of 7.25 ppm/°C over 0 to 70°C.
2) Trimming for zero TCO at mid span (35°C) yields the lowest average TCO for a non-curvature corrected bandgap circuit of 4.62 ppm/°C over 0 to 70°C.
3) Applying curvature correction for the commercial temperature range, yielding the lowest possible TCO for any curvature corrected bandgap circuit of 0.085ppm/°C over 0 to 70°C.

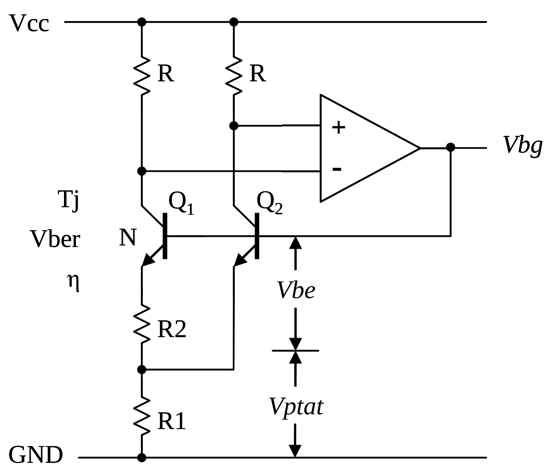
SECTION 7 - BACKGROUND

There is a universal need for a stable reference voltage in electronic circuits. They are found in almost every modern electronic product – either as a discrete device or as part of an integrated circuit. The defining characteristic of a voltage reference is that its output voltage has negligible change over temperature, time, transient loads, and supply voltage. This section focuses on how the output voltage changes with temperature.

The bandgap reference is the most common type of reference in use today. The Brokaw bandgap reference, discussed here, is popular for its simplicity, ability to operate at low supply voltages, and ease of scaling the output voltage above and below the bandgap voltage. The accuracy of a reference often determines the performance of a product. Therefore, it is important for circuit designers to understand the behavior and accuracy limits of a bandgap reference.

Bandgap Basics

Bandgap voltage references take their name from the fact that, as will be shown, their output voltage nearly equals the bandgap voltage of silicon at 0°K. The Brokaw bandgap reference circuit used by BGRC is shown below.



In this circuit,

- Resistors (R, R1, and R2) and the OpAmp are ideal
- Transistors (Q_1 and Q_2) use real models
- Vber = 0.68V
- η=3.3
- N=8
- Tj is 25°C
- *Vbg* is the output bandgap voltage
- *Vbe* is the base-emitter voltage
- *Vptat* is a voltage proportional to absolute temperature

Description of Operation

Vber and η are semiconductor process parameters. Vber is *Vbe* at 25°C. η is a constant that describes the exponential behavior of the transistors' saturation (I_S) and collector (I_C) currents over temperature. N is the ratio of the transistors emitter areas.

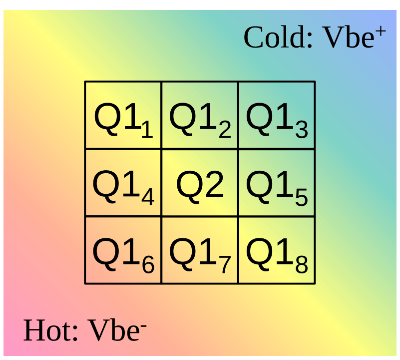
As can be seen in the schematic, the output voltage of the bandgap references (*Vbg*) is the forward voltage drop of a transistor's base-emitter diode (*Vbe*) plus correction term (*Vptat*).

$$Vbg = Vbe + Vptat \quad \text{(Equation 1)}$$

Vbe has a negative temperature coefficient (tempco) and *Vptat* a positive tempco. With proper trimming of R1 and R2, the output voltage, *Vbg*, can be made to have a nearly zero tempco.

Vptat is created by using the opamp to force equal currents through the two bipolar transistors which have different emitter areas. Q1 has N times greater emitter area then Q2 and therefore requires a smaller base–emitter voltage. The difference between these two negative tempco base-emitter voltages is a positive tempco voltage. This positive tempco voltage appears across R2 producing a positive tempco current that goes to ground through R1. Finally, this positive tempco current produces the positive tempco voltage, *Vptat.*

N of 8 is a commonly used ratio of emitter areas, because this allows an 8x transistor to be constructed using 8 identical transistors place symmetrically around an identical single transistor, as follows.



This arrangement minimizes the sensitivity of the eight Q1s to thermal and stress gradients across the die, and on average keeps the specifications of Q1 and Q2 the same. This, in turn, helps keep N constant over changes in temperature and package stress.

Each term in Equation 1, *Vbe, Vptat, and Vbg*, will be examined more closely. Various trimming methods will be discussed that yield progressively smaller voltage drifts over temperature.

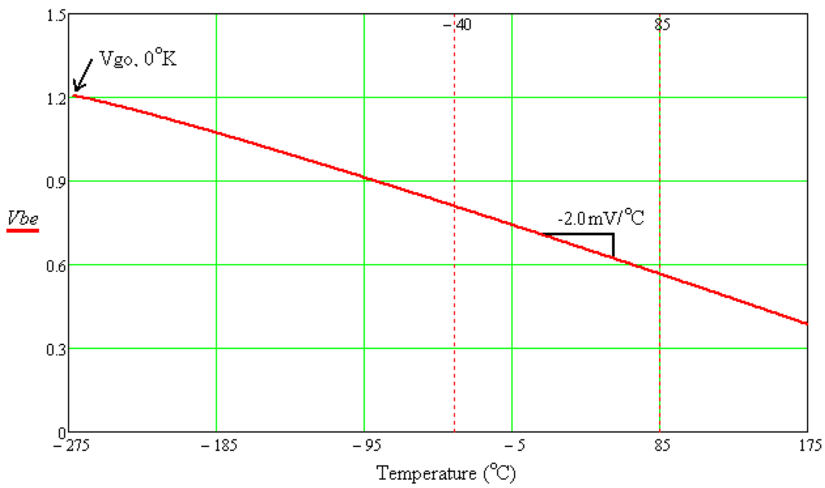
Vbe vs Temperature

Vbe is the forward voltage drop across the base emitter junction of transistor Q_2. The equation describing this voltage is,

$$Vbe = Vgo + \left(\frac{T}{Tr}\right)(Vgo - Vber) - (\eta - 1)\frac{kT}{q}\ln\left(\frac{T}{Tr}\right) \quad \text{(Equation 2)}$$

T is the base-emitter junction temperature. All temperatures are in °K.

Plotting *Vbe* from absolute zero to +175°C,



Markers for the industrial temperature range (-40°C and +85°C) are include in the graph as a reminder of where bandgap references commonly operate.

Vbe is 1.205V at absolute zero and decreases with temperature at a rate of approximately -2.0mV/°C at room temperature. *Vbe* is said to have a drift that is "complementary to absolute temperature"

The maximum deviation of *Vbe* (in PPM) over a temperature range is defined as

$$\Delta V = 1000000\left[\frac{V\max - V\min}{V0}\right],$$

Where *V0* is the voltage at 25°C.

Vbe changes by 360,000 PPM over the industrial temperature range – This is over one third of its voltage at 25°C!

<u>Key Points:</u>

- The forward voltage drop of a silicon diode has very large negative temperature coefficient.
- *Vbe* varies by 360,000 PPM over the industrial temperature range!

Vptat vs Temperature

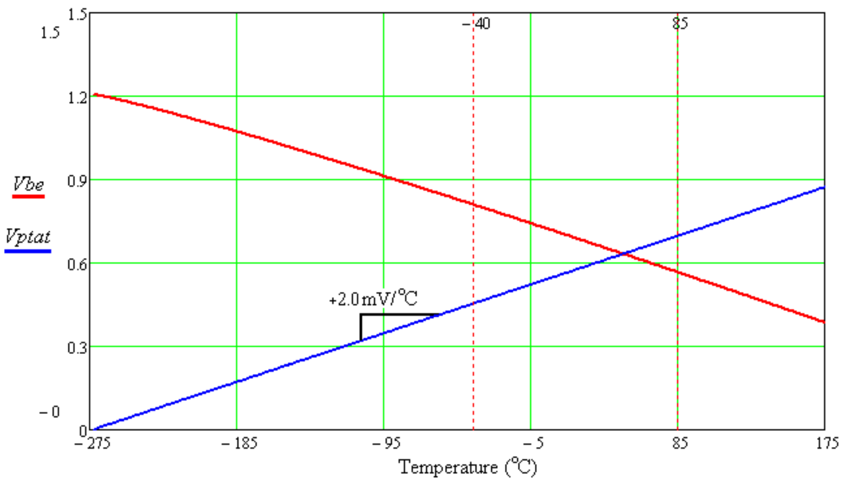
The Brokaw cell produces a voltage that is proportional to absolute temperature (*Vptat*). The equation for *Vptat* is,

$$Vptat = 2\left(\frac{R1}{R2}\right)\frac{kT}{q}\ln(N) \qquad \text{(Equation 3)}$$

T is the base-emitter junction temperature in °K.

The magnitude of the drift is proportional to R1/R2. N is usually fixed. The ratio of R1 to R2 can be trimmed such that the drift of *Vptat* is equal and opposite to the drift of *Vbe.*

Adding *Vptat* to the plot,



In our circuit, when R1/R2 is trimmed to ≈ 5.466, the drift of *Vptat* is equal and opposite the drift of *Vbe.*

<u>Key Points:</u>

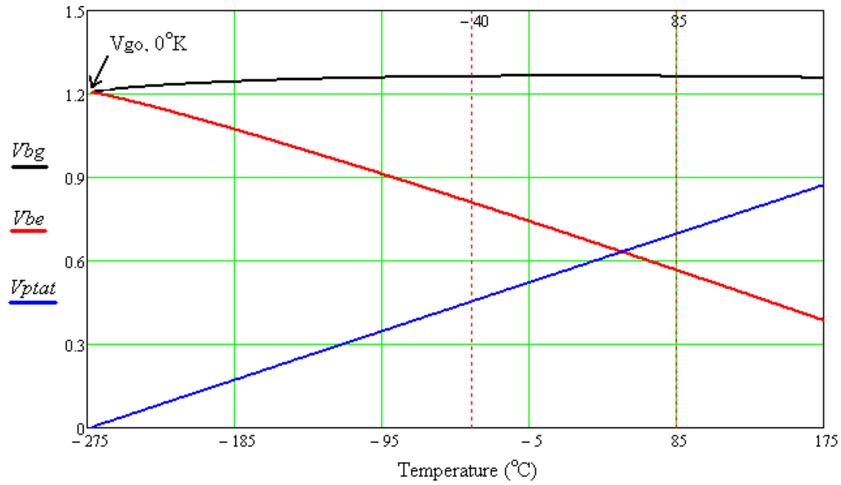
- *Vptat* has a constant positive temperature coefficient.
- The magnitude of the temperature coefficient can be made to be equal and opposite to the negative temperature coefficient of *Vbe.*

Vbg vs Temperature

Finally, $Vbg = Vbe + Vptat$. Adding equations 2 and 3,

$$Vbg = Vgo + \left(\frac{T}{Tr}\right)(Vgo - Vber) - (\eta - 1)\frac{kT}{q}\ln\left(\frac{T}{Tr}\right) + 2\left(\frac{R1}{R2}\right)\frac{kT}{q}\ln(N) \quad \text{(Equation 4)}$$

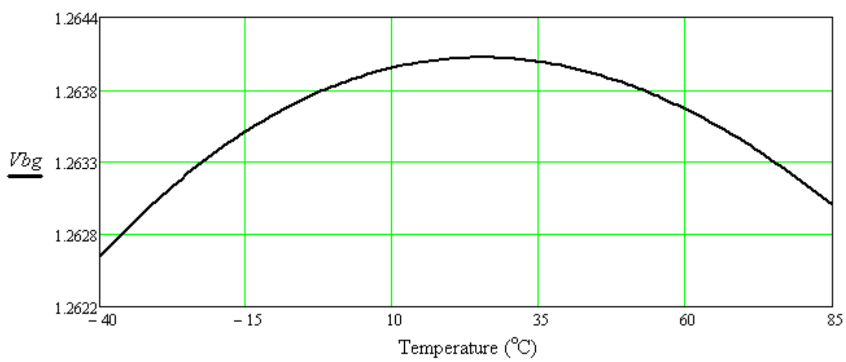
Adding *Vbg* to the plot,



R1/R2=5.466346

This curve shows how the Bandgap Voltage Reference got its name. It can be seen that *Vbg* is approximately equal to the bandgap voltage at 0°K (*Vgo*) of 1.205V because the terms in Equation 2 that cause *Vbe* to change with temperature have been canceled out by *Vptat.*

Plotting *Vbg* at a smaller scale shows a slightly "parabolic" shape.



In this instance,
Vbg peaks at 25°C.

<u>Key Point:</u>

- Adding the positive tempco of *Vptat* to the negative tempco of *Vbe*, yields an output voltage (*Vbg*) that has a nearly zero temperature coefficient.
- *Vbg* has a nearly parabolic shape.

Trimming R1/R2 for Zero Drift at a Specified Temperature

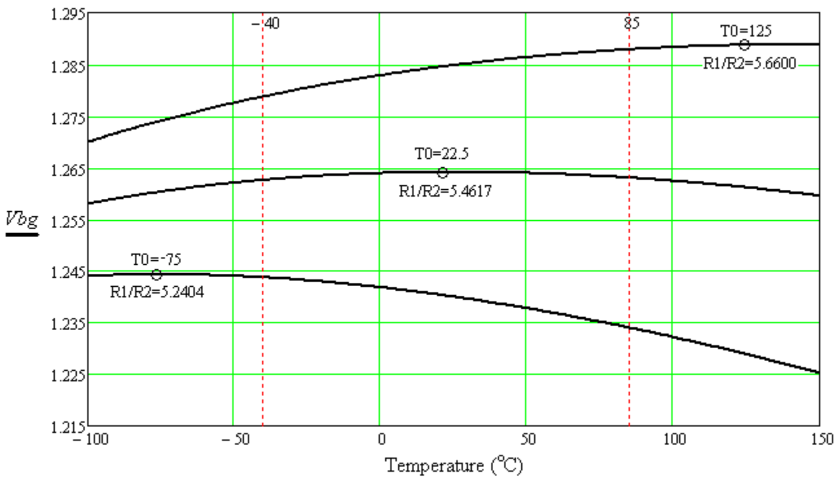
The location of the peak voltage of *Vbg* is a function of the ratio of R1 to R2. This relationship can be derived by first recognizing that *Vbg* peaks at T0, where $\frac{dVbg(T)}{dT} = 0$. Solving this equation for T, substituting T with T0, and solving for R1/R2, yields the resistor ratio that will places the peak of Vbg(T) at any specified T0. This equation is,

$$\frac{R1}{R2} = \frac{\frac{q}{kTr}(Vgo - Vber) + (\eta - 1)\ln\left(\frac{T0}{Tr} + 1\right)}{2\ln(N)} \qquad \text{(Equation 5)}$$

All temperatures are in °K.

T0, where $\frac{dVbg(T)}{dT} = 0$, is called the "Magic Temperature" and *Vbg* at *T0* the "Magic Voltage".

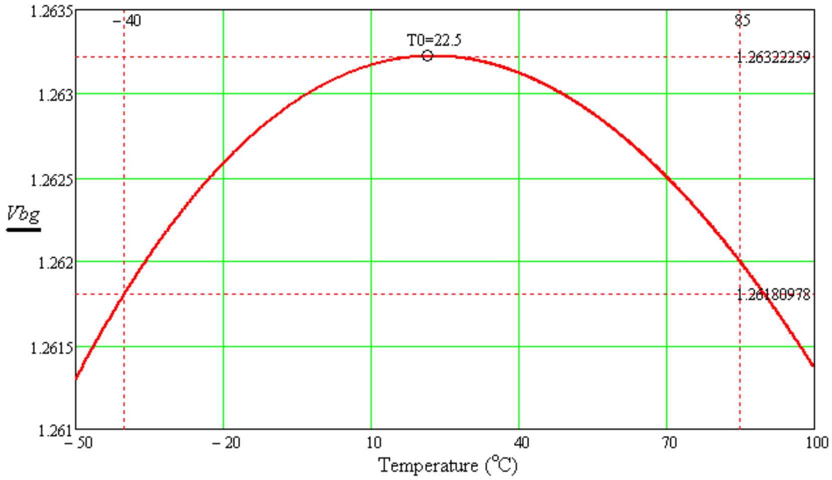
This relationship is illustrated by plotting three *Vbg* curves with different trims and peak temperatures.



Observe that increasing R1/R2 effectively rotates *Vbg* counter-clockwise around *Vbg(0°K).* Due to the parabolic shape of *Vbg*, as the curve rotates T0 increases.

A small change in voltage over a range of temperatures can be obtained by placing T0 halfway within the range. This method is commonly used by manufactures to trim references for different standard temperature ranges.

Plotting Vbg.



When T0 is placed halfway within the industrial temperature range, the change in *Vbg* can be reduced to 1,118 PPM.

<u>Key Points:</u>

- The peak of *Vbg* can be place at any temperature by trimming the ratio of R1 to R2.
- Placing T0 midway within the operating temperature range will produce a small change in *Vbg* over the range.
- Using this trim method, *Vbg* varies 1,118 PPM over the industrial temperature range.

Trimming R1/R2 for the Smallest Change in Vbg Over a Temperature Range

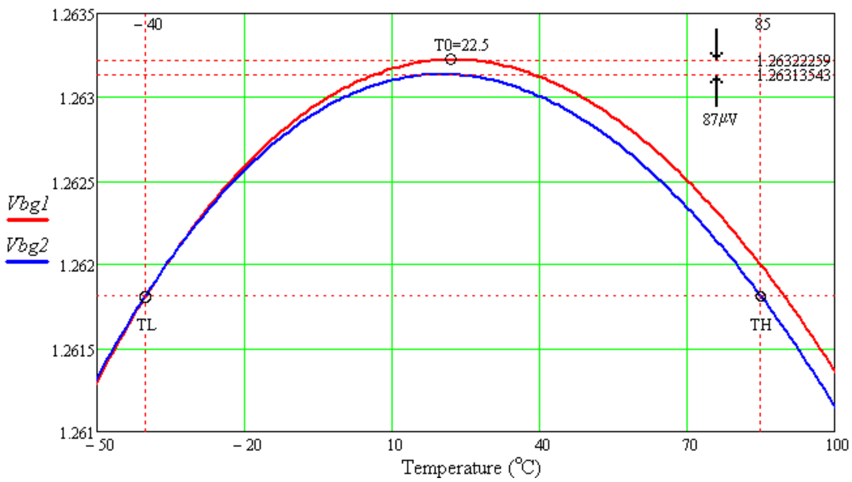
Placing the peak of *Vbg* midway between TL and TH does not produce the lowest possible deviation over temperature because *Vbg* is not perfectly symmetrical around T0.

The smallest deviation in *Vbg* between TL and TH occurs when *Vbg(TL) = Vbg(TH).* When,

$$\frac{R1}{R2} = \frac{\frac{q}{kTr}\left(Vgo - Vber\right) + \left(\eta - 1\right)\left[\left(\frac{TL}{TH - TL}\right)\ln\left(\frac{TL}{Tr}\right) - \left(\frac{TH}{TH - TL}\right)\ln\left(\frac{TH}{Tr}\right)\right]}{2\ln(N)} \qquad \text{(Equation 6)}$$

All temperatures are in °K.

An example of the reduction in voltage variation gained by using this improved trimming method is shown below.



Vbg1 results from using Equation 5 to set the peak voltage half way between TL and TH. Vbg2 results from using Equation 6 to set *Vbg(TL) = Vbg(TH).* To highlight the improvement in voltage deviation the plot of *Vbg1* has been shifted down to match *Vbg2's* voltage at TL. It can be seen that *Vbg2* has an 87µV smaller maximum deviation then *Vbg1*.

With this improved trimming method, the drift of *Vbg* reduces to 1,050 PPM over the industrial temperature range.

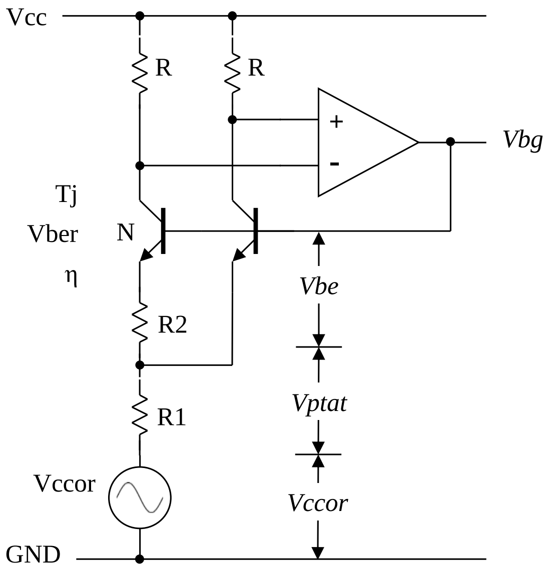
<u>Key Points:</u>

- The smallest deviation in *Vbg* between TL and TH occurs when *Vbg(TL) = Vbg(TH).*
- Using this trim method, *Vbg* varies 1,050 PPM over the industrial temperature range.

Curvature Correction

"Curvature Correction" is the process of adding a small parabolic voltage to *Vbg* in such a way that the parabolic component of the curvature is removed – further reducing the temperature coefficient of *Vbg*.

The addition of a curvature correction voltage, *Vccor*, is shown in the following schematic.



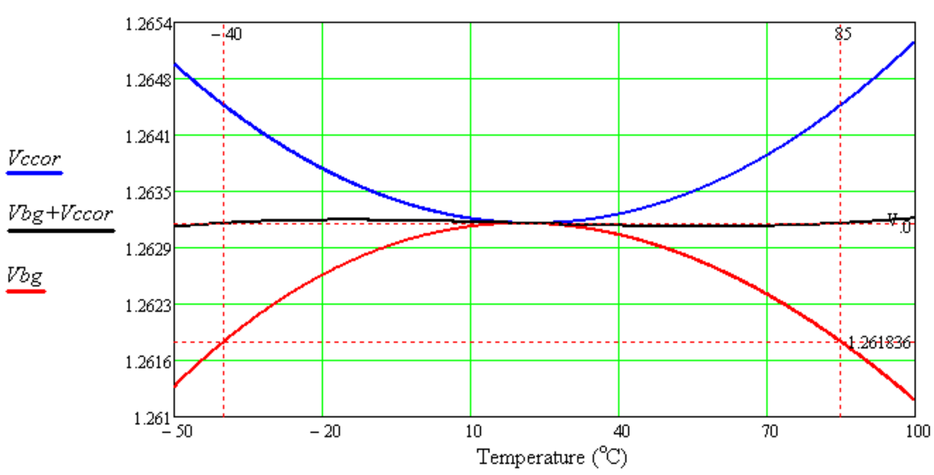
The output voltage of a curvature corrected bandgap reference (*Vbg*) is the forward voltage drop of a transistor's base-emitter diode (*Vbe*), a linear correction term (*Vptat*), and the curvature correction voltage (*Vcoor*).

Vccor is modeled as an ideal signal source having zero output impedance. In practice, *Vccor* may be introduced in other places in the circuit.

$$Vbg = Vbe + Vptat + Vccor \qquad \text{(Equation 7)}$$

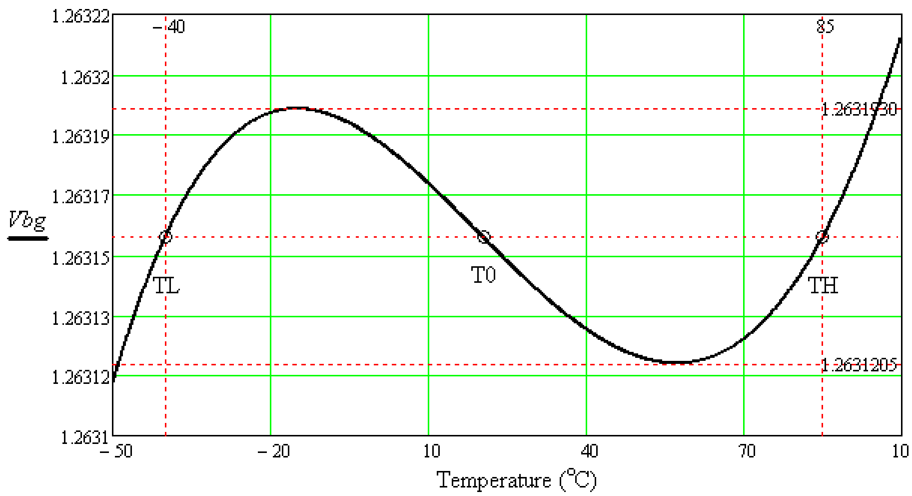
The curvature correction voltage, *Vccor*, is parabolic over temperature, where *Vccor(TL)=Vccor(TH)*=0V and *Vccor(T0)=–Vbg(T0),*

Vccor is shown in blue below.



Vccor has been shifted up on the plot by *Vbg(T0)* volts to facilitate comparison with the non curvature corrected *Vbg.* As can be seen, the change in voltage over temperature of *Vbg+Vccor* (black line) has been greatly reduced, but is not perfectly flat.

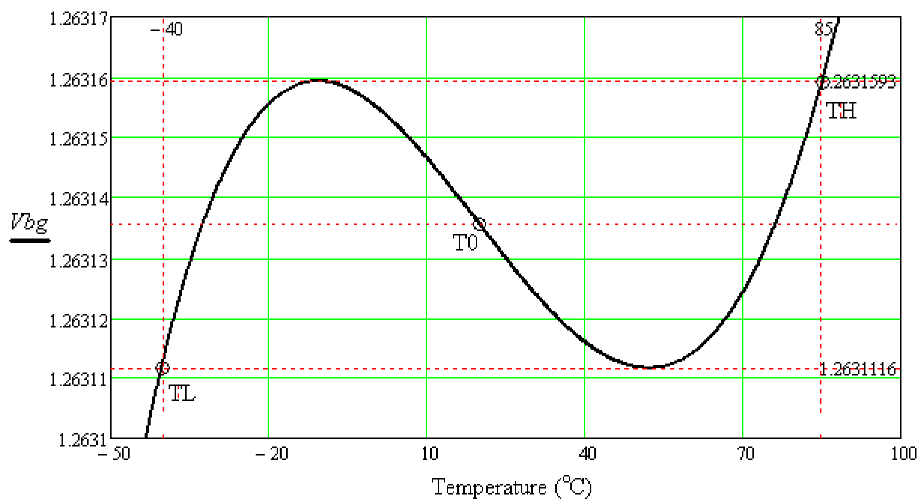
Plotting the curvature corrected *Vbg* at a smaller scale reveals its shape.



With curvature correction, *Vbg* changes only 57.4 PPM over the industrial temperature range.

Finally, a further reduction in drift can be obtained by using a curvature correction voltage where *Vbg(TL)* equals the local minimum voltage and *Vbg(TH)* equals the local maximum voltage.

Plotting *Vbg* using this improved *Vccor*, shows the improvement.



Vbg changes 37.7 PPM over the industrial temperature range.

Warning:
This is the theoretically lowest possible drift obtainable using bandgap reference. Due to process variations and package stresses, the drift of a real reference will be higher. The best bandgap references available today have drifts in the low hundreds of PPM.

<u>Key Points:</u>

- Removing the parabolic component of *Vbg* dramatically reduces drift.
- Using curvature correction, *Vbg* varies only 37.7 PPM over the industrial temperature range.
- The best bandgap references have a drift in the hundreds of PPM

TCO Box Method

Up to this point, drift in *Vbg* has been measured in PPM, defined by the formula,

$$1000000\left[\frac{V\max - V\min}{V0}\right]$$

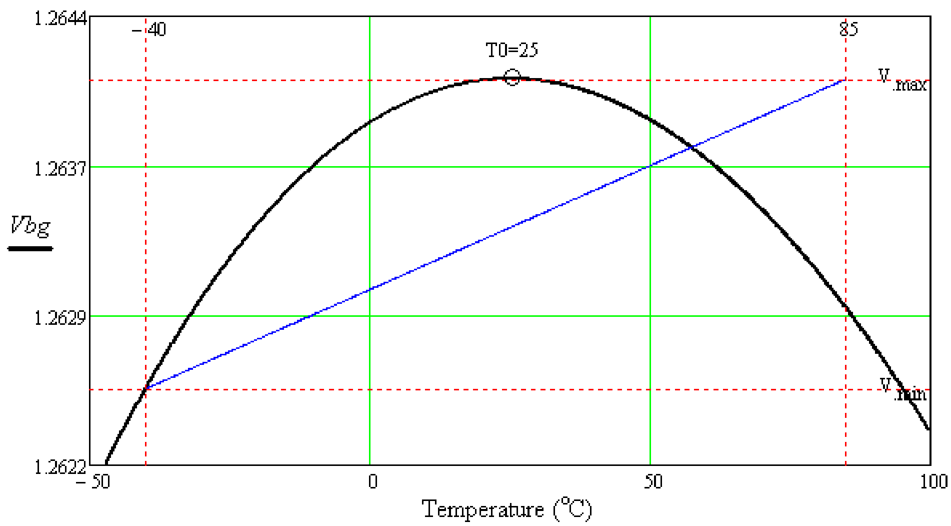
Where, *V0* is the voltage at 25°C.

However, it is standard practice to a specify drift as a temperature coefficient measured in PPM/°C. The formula is,

$$TCO = \frac{1000000\left[\frac{V\max - V\min}{V0}\right]}{TH - TL}$$

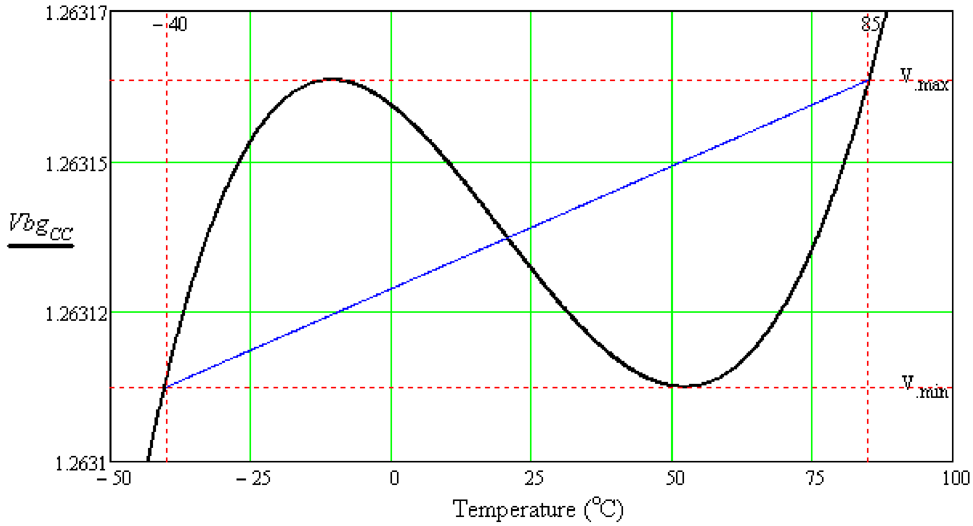
This is called the "Box Method", so named because the lines defining Vmax, Vmin, TL and TH form a box which bound *Vbg* over temperature. It is sometimes described as the average temperature coefficient. *TCO* is always a positive number, regardless of whether *Vbg* is increasing or decreasing.

For example, the TCO box for a non curvature corrected bandgap reference is shown below,



TCO is the slope of the blue line. TCO is 1200 PPM/°C. In this example, *Vbg* will only drift lower from room temperature, even though TCO is positive.

Another example for a curvature corrected bandgap reference is shown,



Again, TCO is the slope of the blue line. TCO is 0.30 PPM/°C. In this case, *Vbg* can drift higher or lower over temperature. Again, TCO is a positive constant.

Warning:
Defining the temperature coefficient using the box method can be deceiving. Although it is called a "coefficient" it does *not* describe a linear change in voltage with temperature, as the name implies, and therefore *cannot* be used to predict Vbg at any specific temperature. TCO is only useful as a relative comparison of the minimum and maximum drifts between different bandgap voltage references.

For example reducing the temperature range from -40 to 85°C to -25 to 75°C does not does not reduce drift because the peaks are still within the operating temperature range. Always examine the voltage vs. temperature curve to determine its suitability for any particular application.

<u>Key Points:</u>

- The box method is the industry standard method of specifying drift
- Be careful, reducing the operating temperature range may not reduce the voltage drift. Always examine the data sheet's output voltage vs. temperature curve.

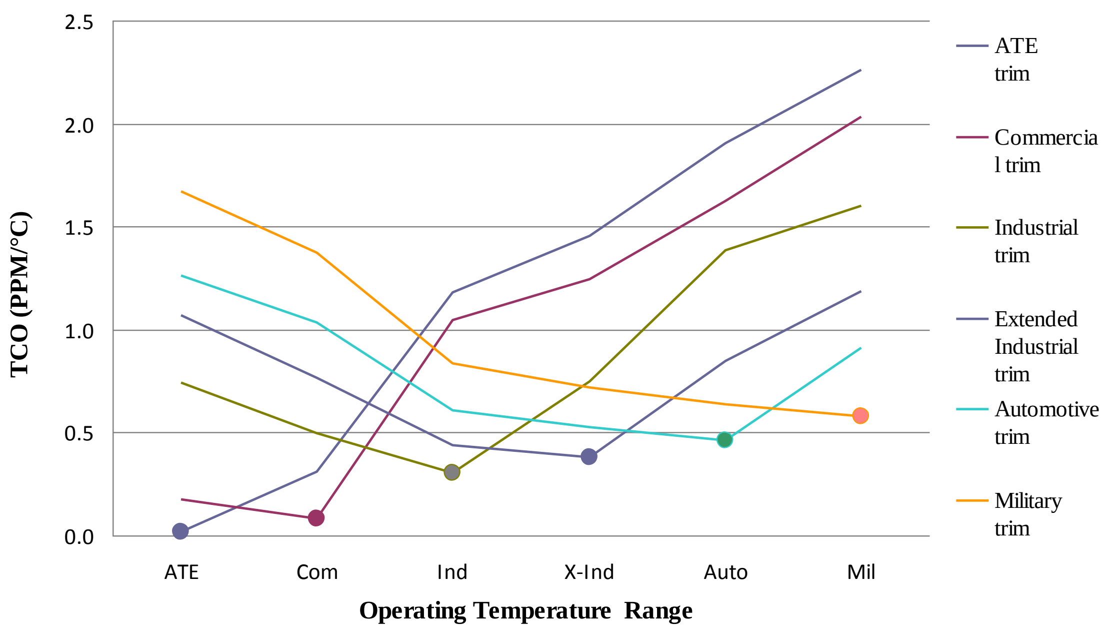
Summary

The progressive improvement in drift of each trimming method, over the industrial temperature range of TL=-40°C and TH=+85°C, is shown below.

Trimming Method	Min/Max Drift (PPM)	Average Tempco (PPM/°C)	Comments
Vbe(T) without correction	360,000.0	2,880.00	Included for comparison only
Linear correction only where, *dVbg/dT=0* at 25°C	1,200.0	9.60	Low drift at or near room temperature
Linear correction only where, *dVbg/dT=0* at midrange	1,118.0	8.94	Improved drift over the temperature range
Linear correction only where, *Vbg(TL)=Vbg(TH)*	1,050.0	8.40	Lowest drift without curvature correction
Curvature correction where, *Vbg(TL)=Vbg(TH)=Vbg(T0)*	57.4	0.46	Low drift using parabolic curvature correction
Curvature correction where, *Vbg(TL)=Vbg(local min)* and *Vbg(TH)=Vbg(local max)*	37.7	0.30	Lowest possible drift using parabolic curvature correction

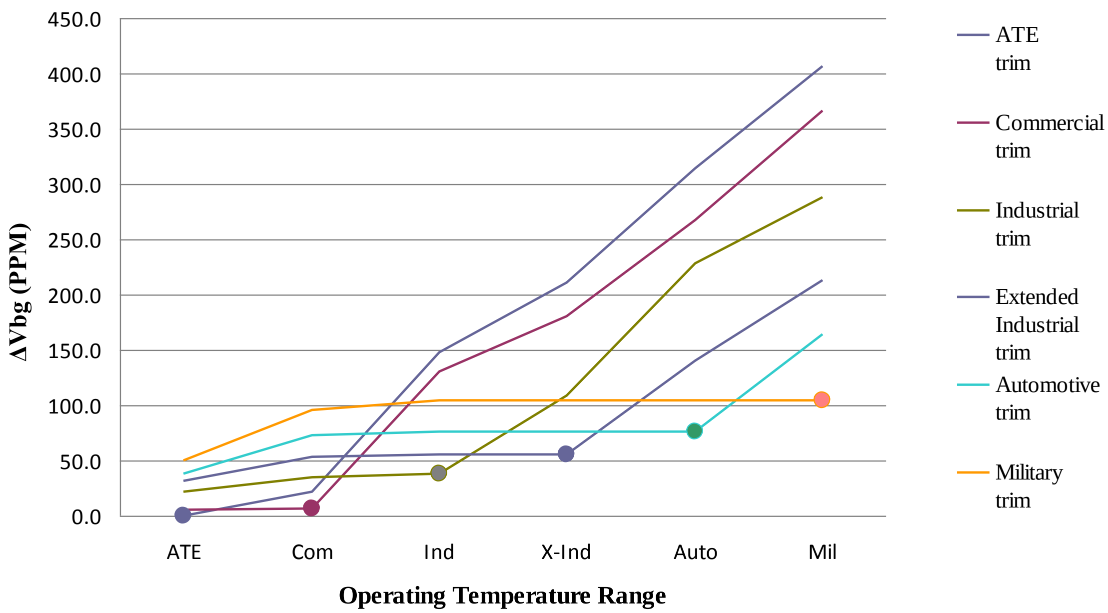
The following two graphs show the results of six bandgap references operated over six standard temperature ranges. The references are curvature corrected and each is trimmed for one of the six standard temperature ranges.

Plotting TCO vs Temperature Range for circuits trimmed for each of the operating range.



It is seen that minimum TCO *always* occurs when operated over the temperature range for which it was trimmed.

Plotting PPM vs Temperature Range reveals that a larger TCO doesn't necessarily mean a larger voltage drift.



Comparing the two previous graphs is can be seen that although TCO increases with smaller temperature ranges, the variation in *Vbg* remains nearly constant.

<u>Key Points:</u>

1. Operating over a smaller temperature range for which a device was trimmed may not decrease the change in *Vbg*.
2. Operating over a larger temperature range, for which a device was trimmed, increases TCO because ΔVbg does increase.
3. The temperature coefficient (TCO) specification for a bandgap reference is useful only for estimating the minimum and maximum variation of *Vbg* over the specified operating temperature range. TCO cannot be used to predict *Vbg* at a particular operating temperature.

SECTION 8 - REFERENCES

[1] A. P. Brokaw, “A Simple Three-Terminal IC Bandgap Reference”, IEEE Journal of Solid-State Circuits, volume SC-9, pp. 388-393, December, 1974.

[2] Yannis P. Tsividis, “Accurate Analysis of Temperature Effects in IC-V_{BE} Characteristics with Application to Bandgap Reference Sources”, IEEE Journal of Solid-State Circuits, Vol. SC-15, No. 6, pp.1076-1084, December, 1980.

[3] P. R. Gray and R. G. Meyer, Analysis and Design of Analog Integrated Circuits. New York: Wiley, 1977.

SECTION 9 - TOOLS, MODELS, AND SOFTWARE NOTICE