AN1333

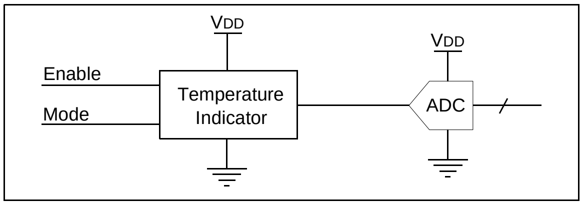
Use and Calibration of the Internal Temperature Indicator

Author: *Jonathan Dillon*
Microchip Technology Inc.

INTRODUCTION

Many PIC16 family devices include an internal temperature indicator. These devices include the PIC16F72X device family, PIC16F1XXX device family, and the PIC12F1XXX device family. The temperature indicator is internally connected to the input multiplexer of the ADC (Figure 1). Refer to the specific device data sheet for more details.

FIGURE 1: TEMPERATURE INDICATOR



These devices incorporate an internal circuit which produces a variable output voltage with temperature using internal transistor junction threshold voltages. The indicator can be used to measure the device temperature between -40°C and +85°C. The circuit must be calibrated by the user to provide accurate results.

USING THE TEMPERATURE INDICATOR

The control bits for enabling the temperature indicator and selecting its mode of operation should be detailed in the device's data sheet in the temperature indicator chapter.

The indicator uses the temperature coefficient of a transistor junction threshold voltage (V_t) to produce a voltage which is temperature dependent. The High-Range mode increases the number of junctions which gives a greater response to temperature changes. The Low-Range mode uses fewer junctions, which allows use of the temperature indicating circuit over a wider device operating voltage range (see Figure 3).

The variation in V_t with temperature, measured on a single sample device, was found to be:

EQUATION 1:

$$V_t = 0.659 - (Temperature \quad °C + 40) * (0.00132)$$

FIGURE 2: DIODE FORWARD VOLTAGE VS. TEMPERATURE FOR A SAMPLE PIC16F1937 DEVICE

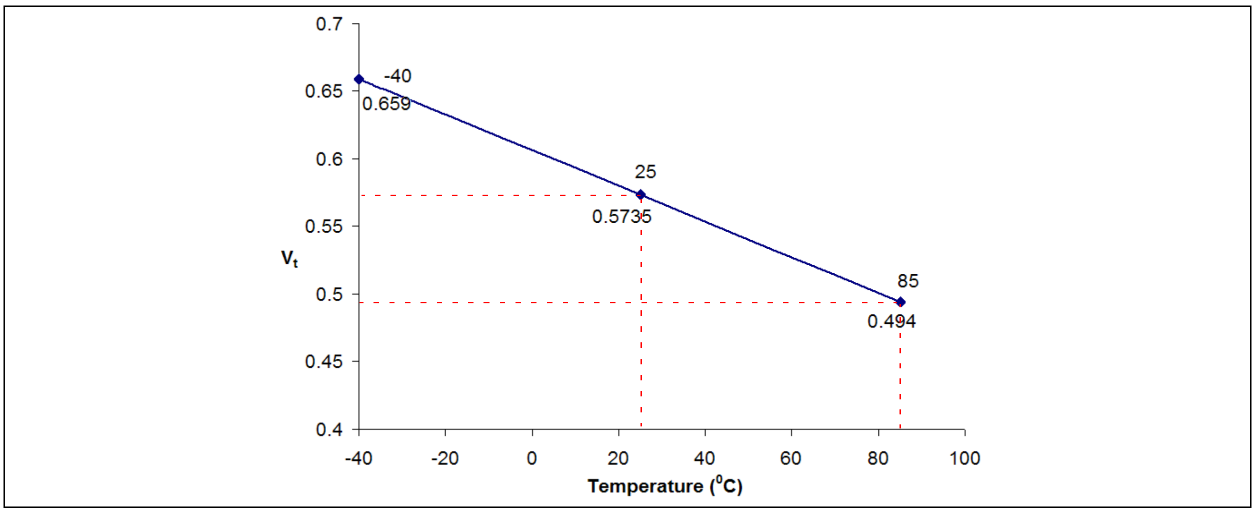
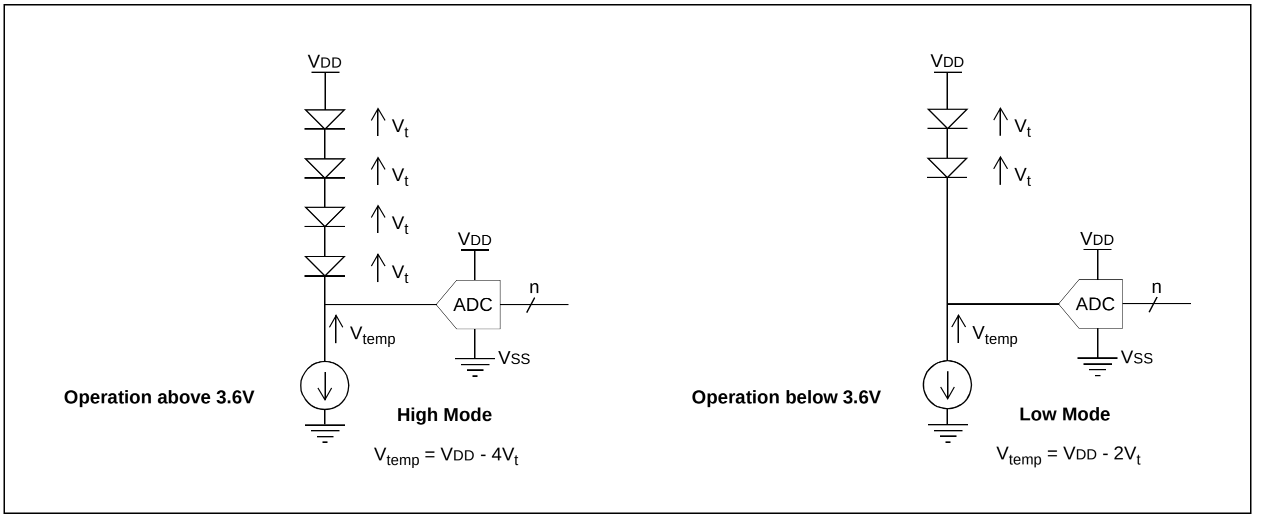


FIGURE 3:



The ouptut equations for the two modes of operation:

- Low range
  $V_{temp} = V_{DD} - 2*V_t$
- High range
  $V_{temp} = V_{DD} - 4*V_t$

Where:

V_{temp} is the analog voltage output by the indicator

V_{DD} is the positive voltage supplied to the device

V_t is the threshold voltage for the transistors which is dependent on the device fabrication process

Using Equation 1 with the operational modes of the indicator we have Equation 3.

Note:	Care needs to be taken in selecting a mode, since V_t may be as high as 0.75V at low temperatures, while the minimum V_{DD} of some devices can be as low as 1.8V. For low-voltage operation, the low range is necessary, as V_{temp} can only be a positive voltage. High mode is the preferred mode of operation when the supply voltage allows its use due to its greater temperature response increasing the temperature resolution.

The voltage, V_{temp}, is measured using the internal analog to digital converter and is internally connected to the analog channel select MUX. Refer to the ADC chapter of the device data sheet to determine the input channel.

The mode selection and temperature indicator enable are documented in the temperature indicator chapter of the data sheet.

When selecting the temperature indicator of the channel select MUX sufficient time must be allowed for the ADC to acquire the voltage before conversion is started.

The analog to digital converter's transfer function can be found in Equation 2. The conversion result is dependent on the supply voltage to the analog to digital converter's voltage reference and, for this document, the positive reference is the supply voltage, while the negative reference is the ground.

EQUATION 2:

$$ADC_{Result} = \frac{V_{temp}}{VDD} * (2^n - 1)$$

Where:

n = number of bits of ADC resolution (8 or 10 bits)

During operation, the supply voltage can be determined by performing an analog to digital conversion of the fixed voltage reference. However, if V_{DD} is regulated or an external reference is connected to the ADC, the calculations can be simplified, since it can be assumed to be constant.

EQUATION 3: V_{TEMP} VOLTAGE FROM SERIES OF DIODES AS GIVEN IN Equation 1

$$V_{temp} = VDD - mode * [0.659 - ((Temperature \quad °C + 40) * 0.0132)]$$

Where:

High-Range mode = 4

Low-Range mode = 2

Combining Equation 2 and Equation 3 to relate the ADC conversion of the temperature indicator circuit's output voltage to the temperature:

EQUATION 4: RE-ARRANGING TO CALCULATE TEMPERATURE:

$$ADC_{Result} = \frac{VDD - mode * [0.659 - ((Temperature \quad °C + 40) * 0.0132)]}{VDD} * (2^n - 1)$$

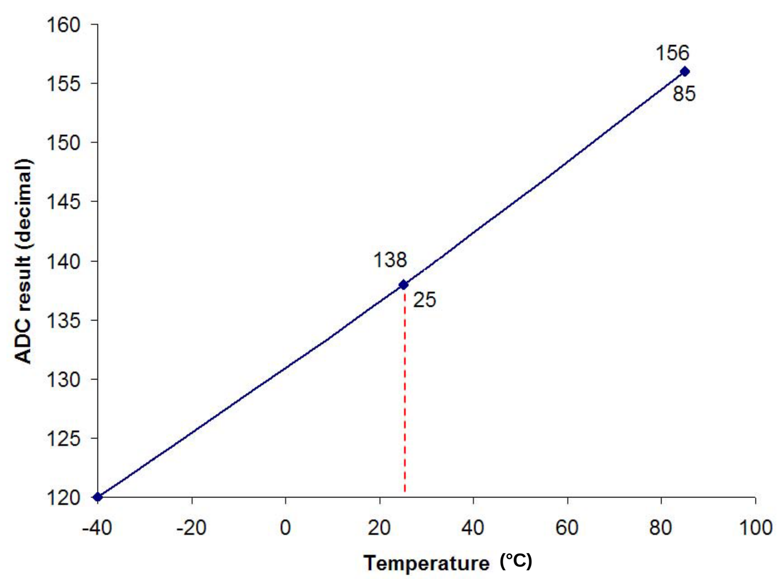
EQUATION 5:

$$Temperature \quad °C = \frac{0.659 - \frac{VDD}{mode}\left(1 - \frac{ADC_{Result}}{(2^n - 1)}\right)}{0.00132} - 40$$

As the temperature varies, the ADC result of conversion of the temperature indicator channel will change linearly as seen in Figure 4, provided the supply voltage does not change.

Depending on the application, the Analog-to-Digital Converter result can be either compared directly against specific trip points, or used to determine the actual temperature by calculation, a look-up table or a combination of both.

FIGURE 4: ADC RESULT (DECIMAL) VS. TEMPERATURE (REGULATED SUPPLY VOLTAGE)



CALIBRATION

The temperature indicator requires calibration to achieve greater accuracy due to variations in offset and in slope between devices. The indicator is dependent on the device's transistor voltage threshold, V_t, which will vary within production allowances.

Calibration of the temperature indicator can be performed during production of the target application by two methods:

SINGLE-POINT CALIBRATION

Calibration is performed at a single temperature and the variation of slope is assumed to be relatively stable between devices. This method calibrates purely for the offset, which typically has greater variation between devices.

TWO-POINT CALIBRATION

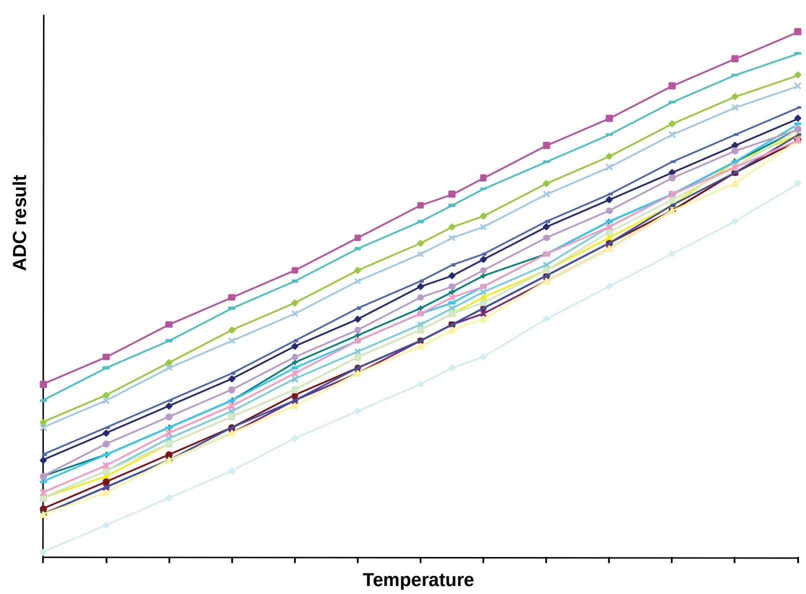
Calibration is performed at two temperatures from which we can determine the offset and slope. As a result, this method is more accurate, but requires two distinctively different temperatures.

For both of the above methods, the temperatures can be either forced (held to a specific value) or measured at calibration time via an external measurement. Forced temperatures simplify the calculations required during calibration, but are more difficult from a production view point and time may be required to allow the device to reach temperature. Errors in the forced temperature or measured temperature will result in reduced temperature accuracy at all temperatures.

The degree of calibration required is dependent on the application, where some applications do not require precise temperature, thus single-point calibration is suitable and faster to perform. It also avoids requiring equipment to vary temperature. For more accurate temperature measurements, the two-point calibration method is recommended.

Note:	The voltage from the temperature indicator is dependent on the supply voltage to the device, which makes calibration easiest when the voltage is regulated. For unregulated supplies the voltage must also be calculated from an A/D conversion of the internal fixed voltage reference. The techniques of using a fixed voltage reference to determine VDD can be found in application note AN1072, "*Measuring VDD Using the 0.6V Reference.*"

FIGURE 5: TEMPERATURE DATA FROM 12 SAMPLE DEVICES



SINGLE-POINT CALIBRATION

Testing of a limited number of sample devices as seen in Figure 5 shows a relatively constant response in V_{temp} with changes in temperature, however, there is a greater variation in offsets between devices. Single-point calibration corrects for this variation in offset, but does not allow for the variation in temperature response slope between devices.

For this calibration, we need to have an ideal ADC result value for either our forced temperature or otherwise at the measured temperature. The change in V_t by temperature varies between devices and, as a result, single-point calibration may only be accurate at the calibration temperature, and error will increase as it moves further from the calibration temperature (see Figure 6). The bow tie shape of the plotted ADC results due to the possible variation in temperature response.

If the temperature is measured, the calculation required to get the ideal ADC result value is given in Equation 3, otherwise, for forced temperatures, the result can be compared to a constant ideal result for that temperature. Ideally, the temperature is in the middle of the operating range seen by the application, as this centers the bow tie and minimizes temperature error over the applications operating range. For applications which only need to know a certain temperature, such as a temperature limit, the best accuracy results can be achieved by calibrating at that temperature.

The ADC conversion results may have a dynamic range approaching 8 bits for some combinations of mode and voltage and, as a result, it is recommended to maintain the two-byte ADC result data type. For higher voltage operation, the dynamic range of the ADC result between -40°C to +85°C is small enough that it could be scaled down to an 8-bit number.

With a sample PIC16F1937 device under the following conditions:

- powered at 5V
- high-range $4V_t$ operation
- 25°C forced temperature

The Analog-to-Digital conversion gives a result of 561 decimal.

Typical Analog-to-Digital conversion result at 25°C is calculated as 554 decimal using Equation 3.

For single-point calibration, the difference between the conversion result and the ideal A/D conversion result value is the calibration value.

Thus:

EQUATION 6:

$$Ideal - measured = calibration\ value$$

$$554 - 561 = 7$$

Consequently, for this device the calibration value would be 7. Store this in the nonvolatile program or data EEPROM memory within the device for use when taking temperature measurements.

Single-point calibration assumes that all devices have a similar slope, however, as the temperature moves further from the calibration temperature, the greater the potential error as seen in Figure 6.

When taking measurements, the ADC result is modified by the calibration value to adjust for the offset.

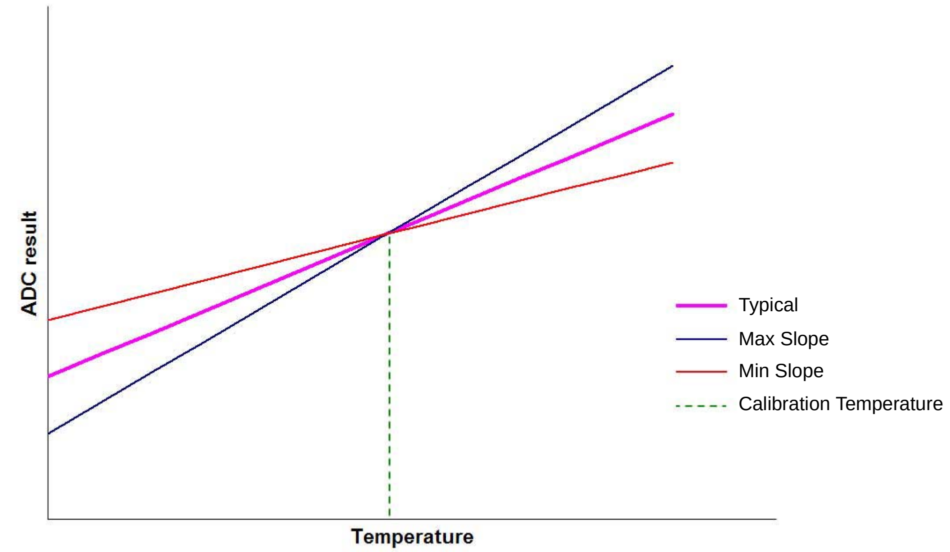
EQUATION 7:

$$Calibrated\ result = ADC\ result - calibration\ value$$

EQUATION 8:

$$Temperature = (ADC\ result - calibration\ value)K$$

FIGURE 6: SINGLE TEMPERATURE CALIBRATION

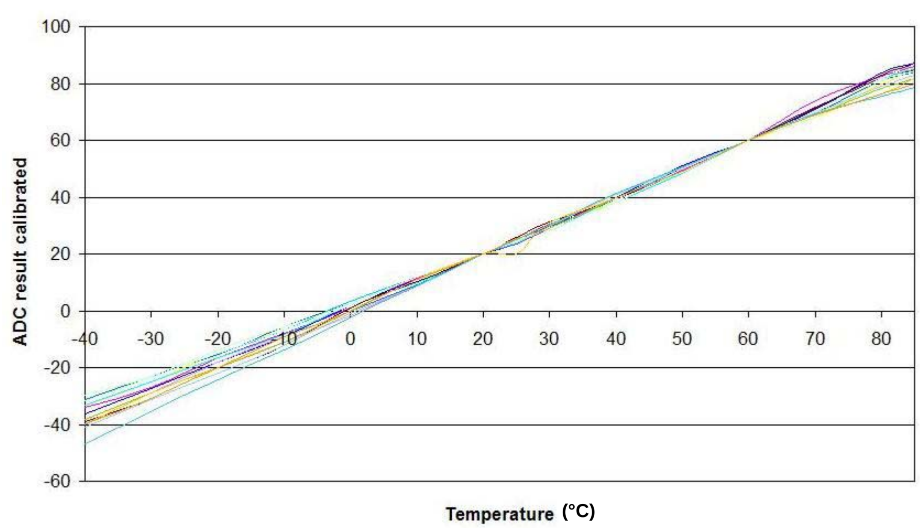


TWO-POINT CALIBRATION

Two-point calibration measures the temperature responsivity of that device, as well as the offset. As a result, it offers increased temperature accuracy by overcoming the assumption of single-point calibration, that all devices have the same temperature response.

Two-point calibration requires two distinctively different temperatures across the applications temperature range. As with single-point calibration, these temperatures can either be forced or measured, though forced temperatures again simplify the required calculations.

FIGURE 7: TWO-POINT CALIBRATION



For unregulated supply voltages, designers must calculate the temperature responsivity of the diode, which requires additional steps.

EQUATION 9:

$$ADC\ Result\ calibrated = A + (B * ADC\ Result)$$

Calibration is required to determine A and B, which modifies the ADC result for the variation in diode V_t and temperature response. The ideal ADC result for each calibration temperature can be stored as a constant if the temperature is forced to known levels, otherwise the ideal must be calculated if it is measured externally during calibration. The calibrated result can then be used in Equation 5 to calculate the temperature.

EQUATION 10:

$$A = (Ideal @ T1 - Ideal @ T2)/(Actual @ T1 - Actual @ T2)$$

$$B = Actual @ T1 - (A * Ideal @ T1)$$

Where:

T1 calibration temperature 1

T2 calibration temperature 2

This two-point calibration significantly reduces the effect of variations in temperature response of the diodes, but is dependent on being able to accurately calculate the responsivity.

SINGLE-POINT CALIBRATION FOR UNREGULATED VOLTAGES

For regulated voltages, the calibration can be simplified down to an adjustment to the ADC result.

For unregulated supplies, the calibration is also a function of VDD causing a change in the ADC result, and the V_t temperature offset must be calculated. This requires that VDD be known along with the calibration temperature and ADC result. From Equation 3, substituting α for the V_t offset:

The V_t offset can be calculated by performing a single ADC conversion at a known temperature and voltage. For unregulated applications, the supply voltage can be determined from a conversion of the internal fixed voltage reference or by supplying a known voltage during calibration.

When measuring the temperature the supply voltage must also be calculated and the V_t offset from the calibration used.

During calibration, α is calculated and stored in nonvolatile memory for use during operation. The results of the A/D conversion are inserted into Equation 10 along with the supply voltage to give the operating temperature.

EQUATION 11:

$$Temperature = \frac{\alpha - \frac{VDD}{4} * \left(1 - \frac{ADC_{Result}}{1023}\right)}{0.00132} - 40$$

EQUATION 12:

$$ADC_{Result} = \frac{VDD - 4 * [\alpha - ((Temperature \quad °C + 40) * 0.0132)]}{VDD} * 1023$$

Re-arranging:

EQUATION 13:

$$\alpha = \left[\frac{VDD}{4} * \left(1 - \frac{ADC_{Result}}{1023}\right)\right] + [(Temperature \quad °C + 40) * 0.00132]$$

TWO-POINT CALIBRATION FOR UNREGULATED VOLTAGES

For unregulated supply, such as direct connection to a battery, we need to calculate VDD once or twice, if it varies between the two calibration temperatures, such as reduced battery voltage with temperatures.

From the operation of the temperature indicator we have the following:

EQUATION 14:

$$V_{temp} = VDD - 4 * (\alpha - (Temperature \quad °C + 40)\beta)$$

$$ADC_{Result} = \frac{V_{temp}}{VDD} * (2^n - 1)$$

$$V_{temp} = \frac{ADC_{Result}}{1023} * VDD$$

Where, for two-point calibration with an unregulated voltage, we need to calculate alpha (α) and beta (β). Re-arranging the equations and calibrating at two temperatures (Equation 14):

Key points to consider:

- The results are most accurate between the calibration temperatures.
- The calibration temperatures need to be suitably far apart to allow an accurate calculation of the slope given the ADC resolution. Calibration temperatures around 20% and 80% of the operating temperature range are recommended.
- Any error in calibration temperature or voltage significantly increases the error of the readings due to the inaccurate slope and offset.
- Regulated voltage, calibration performed at 20°C and 60°C.

Temperature error will be minimized at the calibration temperatures as shown Figure 8 for a sample batch of devices, where the maximum temperature error between the calibration temperatures is 5°C.

EQUATION 15:

$$\alpha = \frac{\left[V_1 * (Temp_2 + 40) * \left(1 - \frac{ADC_{Result1}}{1023}\right)\right] - \left[V_2 * (Temp_1 + 40) * \left(1 - \frac{ADC_{Result2}}{1023}\right)\right]}{4 * (Temp_2 - Temp_1)}$$

$$\beta = \frac{V_1 - V_2 + \frac{1}{1023} * [(V_2 * ADC_{Result2}) - (V_1 * ADC_{Result1})]}{4 * (Temp_2 - Temp_1)}$$

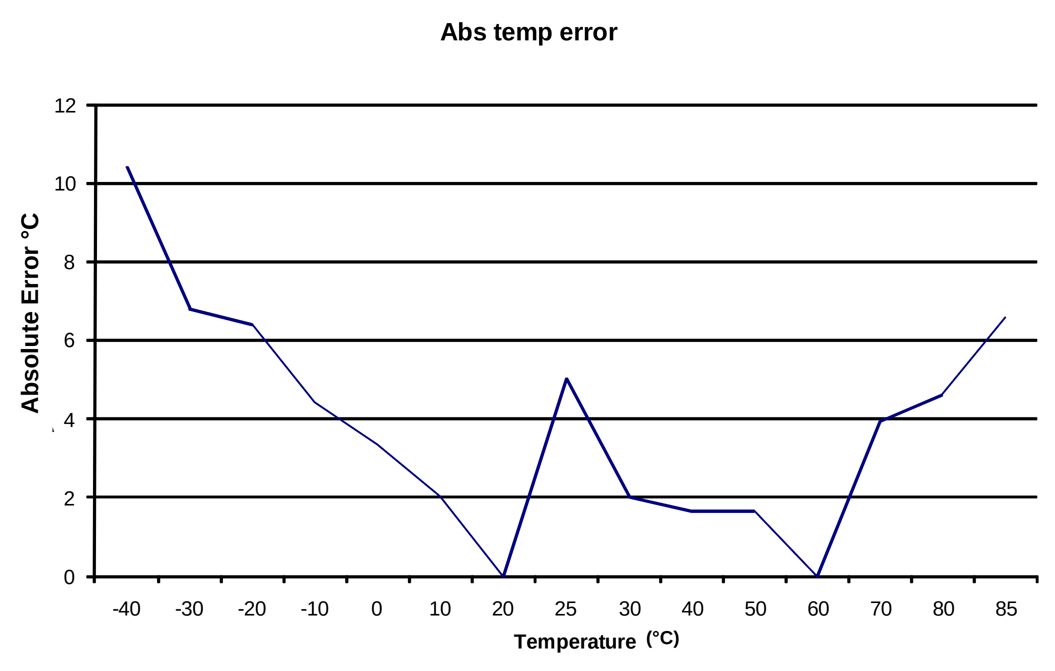
Where:

Temp1, Temp2	calibration temperatures
V1, V2	VDD voltage at Temp1 and Temp2
ADCresult1, ADCresult2	A/D Convertor result at Temp1 and Temp2

EQUATION 16:

$$Temperature\ ^{\circ}C = \frac{\alpha - \frac{VDD}{4} * \left(1 - \frac{ADC_{Result}}{1023}\right)}{\beta} - 40$$

FIGURE 8: ABS TEMPERATURE ERROR



CONCLUSION

The on-board temperature indicator can be used to measure the device temperature, which will correspond to the temperature in its environment with some delay. The indicator is measured using the ADC and can be used uncalibrated for coarse temperature measurements. For more precise temperature measurements, calibration is required to account for device parameter variation. Depending on the application, calibration measurements at one or two temperatures may be required. Since the ADC results are dependent on its provided references, the fixed references need to be supplied either by using the onboard fixed references, or by using a regulated supply. Otherwise, the device supply voltage must be calculated using the fixed voltage reference.

NOTES:

ISBN: 978-1-60932-475-9

Microchip received ISO/TS-16949:2002 certification for its worldwide headquarters, design and wafer fabrication facilities in Chandler and Tempe, Arizona; Gresham, Oregon and design centers in California and India. The Company's quality system processes and procedures are for its PIC® MCUs and dsPIC® DSCs, KEELOQ® code hopping devices, Serial EEPROMs, microperipherals, nonvolatile memory and analog products. In addition, Microchip's quality system for the design and manufacture of development systems is ISO 9001:2000 certified.

Worldwide Sales and Service

AMERICAS

Corporate Office
2355 West Chandler Blvd.
Chandler, AZ 85224-6199
Tel: 480-792-7200
Fax: 480-792-7277
Technical Support:
http://support.microchip.com
Web Address:
www.microchip.com

Atlanta
Duluth, GA
Tel: 678-957-9614
Fax: 678-957-1455

Boston
Westborough, MA
Tel: 774-760-0087
Fax: 774-760-0088

Chicago
Itasca, IL
Tel: 630-285-0071
Fax: 630-285-0075

Cleveland
Independence, OH
Tel: 216-447-0464
Fax: 216-447-0643

Dallas
Addison, TX
Tel: 972-818-7423
Fax: 972-818-2924

Detroit
Farmington Hills, MI
Tel: 248-538-2250
Fax: 248-538-2260

Kokomo
Kokomo, IN
Tel: 765-864-8360
Fax: 765-864-8387

Los Angeles
Mission Viejo, CA
Tel: 949-462-9523
Fax: 949-462-9608

Santa Clara
Santa Clara, CA
Tel: 408-961-6444
Fax: 408-961-6445

Toronto
Mississauga, Ontario,
Canada
Tel: 905-673-0699
Fax: 905-673-6509

ASIA/PACIFIC

Asia Pacific Office
Suites 3707-14, 37th Floor
Tower 6, The Gateway
Harbour City, Kowloon
Hong Kong
Tel: 852-2401-1200
Fax: 852-2401-3431

Australia - Sydney
Tel: 61-2-9868-6733
Fax: 61-2-9868-6755

China - Beijing
Tel: 86-10-8528-2100
Fax: 86-10-8528-2104

China - Chengdu
Tel: 86-28-8665-5511
Fax: 86-28-8665-7889

China - Chongqing
Tel: 86-23-8980-9588
Fax: 86-23-8980-9500

China - Hong Kong SAR
Tel: 852-2401-1200
Fax: 852-2401-3431

China - Nanjing
Tel: 86-25-8473-2460
Fax: 86-25-8473-2470

China - Qingdao
Tel: 86-532-8502-7355
Fax: 86-532-8502-7205

China - Shanghai
Tel: 86-21-5407-5533
Fax: 86-21-5407-5066

China - Shenyang
Tel: 86-24-2334-2829
Fax: 86-24-2334-2393

China - Shenzhen
Tel: 86-755-8203-2660
Fax: 86-755-8203-1760

China - Wuhan
Tel: 86-27-5980-5300
Fax: 86-27-5980-5118

China - Xian
Tel: 86-29-8833-7252
Fax: 86-29-8833-7256

China - Xiamen
Tel: 86-592-2388138
Fax: 86-592-2388130

China - Zhuhai
Tel: 86-756-3210040
Fax: 86-756-3210049

ASIA/PACIFIC

India - Bangalore
Tel: 91-80-3090-4444
Fax: 91-80-3090-4123

India - New Delhi
Tel: 91-11-4160-8631
Fax: 91-11-4160-8632

India - Pune
Tel: 91-20-2566-1512
Fax: 91-20-2566-1513

Japan - Yokohama
Tel: 81-45-471- 6166
Fax: 81-45-471-6122

Korea - Daegu
Tel: 82-53-744-4301
Fax: 82-53-744-4302

Korea - Seoul
Tel: 82-2-554-7200
Fax: 82-2-558-5932 or
82-2-558-5934

Malaysia - Kuala Lumpur
Tel: 60-3-6201-9857
Fax: 60-3-6201-9859

Malaysia - Penang
Tel: 60-4-227-8870
Fax: 60-4-227-4068

Philippines - Manila
Tel: 63-2-634-9065
Fax: 63-2-634-9069

Singapore
Tel: 65-6334-8870
Fax: 65-6334-8850

Taiwan - Hsin Chu
Tel: 886-3-6578-300
Fax: 886-3-6578-370

Taiwan - Kaohsiung
Tel: 886-7-213-7830
Fax: 886-7-330-9305

Taiwan - Taipei
Tel: 886-2-2500-6610
Fax: 886-2-2508-0102

Thailand - Bangkok
Tel: 66-2-694-1351
Fax: 66-2-694-1350

EUROPE

Austria - Wels
Tel: 43-7242-2244-39
Fax: 43-7242-2244-393

Denmark - Copenhagen
Tel: 45-4450-2828
Fax: 45-4485-2829

France - Paris
Tel: 33-1-69-53-63-20
Fax: 33-1-69-30-90-79

Germany - Munich
Tel: 49-89-627-144-0
Fax: 49-89-627-144-44

Italy - Milan
Tel: 39-0331-742611
Fax: 39-0331-466781

Netherlands - Drunen
Tel: 31-416-690399
Fax: 31-416-690340

Spain - Madrid
Tel: 34-91-708-08-90
Fax: 34-91-708-08-91

UK - Wokingham
Tel: 44-118-921-5869
Fax: 44-118-921-5820

08/04/10