AN2092

Using the Temperature Indicator Module

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INTRODUCTION

The Internal Temperature Indicator is a temperature sensing module that is built into most PIC16(L)F1XXX devices. This application note adds to and refines the information in application note AN1333, *Use and Calibration of the Internal Temperature Indicator*. This application note will provide additional, refined information, and updated equations for temperature measurement.

Application Limits

- The accuracy of the module requires at a minimum single-point calibration.
- The equations as defined assume a well regulated supply voltage or a method to measure the supply voltage.
- This module may not be suitable when temperature accuracy of less than 5°C is required.
- Driving high current with output pins can cause variation in the measured temperature due to die temperature gradient and sagging of the internal power supply.
- This module is not recommended for use in critical temperature control applications or for thermal safety applications without a backup method of thermal protection.
- This module is not recommended for measurement of temperatures above 85°C if calibration is performed at room temperature.

Variables

The following are the variables that will be measured or collected for the calculations:

- ADC_RESULT: Integer value captured by the ADC during temperature testing of the temperature indicator
- V_{OUT}: Voltage calculated from the ACD_RESULT
- V_T: Forward diode voltage of a single diode at any temperature
- T_A: Calculated temperature

Constants

The following are the variables that will be measured or collected for the calculations:

- T_C: Temperature coefficient of the diode. This value will likely be defined during the initial development phase testing and will generally be a constant in the application.
- V_F: Forward diode voltage. This voltage is the forward voltage of the diode at a specific current and normalized to 0°C.
- V_{DD}: Supply voltage for the temp indicator. This is generally a constant unless the application uses a means to accurately measure the supply voltage.
- V_{REF}: Reference voltage of the ADC module; usually the same as V_{DD}.
- MODE: The number of diodes in series as set by TSRNG bit. This will always be 2 or 4. The mode will generally always be a constant.
- RES: Range of the ADC defined by the equation 2^n-1, where n is the resolution of the ADC. Typical value is 1023 for devices that have a 10-bit ADC.
- OFFSET: The temperature offset that is defined during calibration.

Equations

The following equations were derived from the equations listed in AN1333. The simplified equations will be derived in sequential order.

The schematic of the temperature indicator is needed for reference to generate the equations.

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FIGURE 1:   TEMPERATURE CIRCUIT
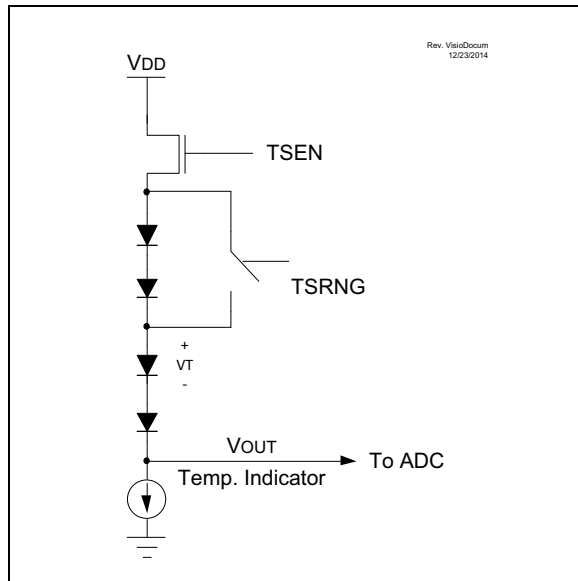
Equation 1 is used to calculate the V_{OUT} term. In most applications V_{REF} term can be replaced by V_{DD}.

EQUATION 1:   SOLUTION FOR V_{OUT}

$$V_{OUT} = \frac{ADC_{RESULT} \times V_{REF}}{RES}$$

Equation 2 calculates the individual voltages in the circuit. Note that the ADC is not measuring the diode string directly, rather it is measuring the remaining voltage (V_{OUT}) on the constant current source.

EQUATION 2:   SOLUTION FOR DIODE JUNCTION VOLTAGE

$$V_{DD} = (Mode \times V_T) + V_{OUT}$$

$$V_T = \frac{V_{DD} - V_{OUT}}{Mode} \quad \text{Solving for } V_T$$

Equation 3 illustrates the relationship between the diode junction and temperature.

EQUATION 3:   SOLUTION FOR UNCALIBRATED VOLTAGE

$$V_T = (T_C \times T_A) + V_F$$

$$T_A = \left(\frac{V_T}{T_C}\right) - \left(\frac{V_F}{T_C}\right) \quad \text{Solving for } T_A$$

Generally this equation will produce an uncalibrated temperature value that is within 100°C of the actual temperature. Part to part variations and application variation will usually cause the calculated temperature reading to fluctuate. A temperature value for this offset needs to be added to Equation 3 to account for this variation.

EQUATION 4:   SOLUTION FOR UNCALIBRATED TEMPERATURE

$$OFFSET = Actual\ Temperature$$
$$- Uncalibrated\ Temperature$$

Equation 5 shows the addition of the necessary OFFSET term to Equation 3:

EQUATION 5:   TEMPERATURE WITH THE CALIBRATION OFFSET

$$T_A = \left(\frac{V_T}{T_C}\right) - \left(\frac{V_F}{T_C}\right) + OFFSET$$

Equation Sequence

The following sequence of equations will provide a starting point for the product design and code development for any application that uses the temperature indicator.

EQUATION 6:   EQUATION SEQUENCE

$$V_{OUT} = \frac{ADC_{Result} \times V_{REF}}{RES} \qquad \text{Equation 1}$$

$$V_T = \frac{V_{DD} - V_{OUT}}{Mode} \qquad \text{Equation 2}$$

$$T_A = \left(\frac{V_T}{T_C}\right) - \left(\frac{V_F}{T_C}\right) + OFFSET \qquad \text{Equation 5}$$

DETERMINING THE CONSTANTS

At the time of publication of AN1333, only a few PIC$^®$ microcontrollers contained the temperature indicator module. This limited the amount of characterization data available for the module. Since then, the module has been designed in to most F1 PIC devices. This allowed for a more complete collection of characterization data, which was used to further define the constants used in the equations. Figure 2 is the graph of the PIC16F1783 data for the temperature indicator in mode 4 at a fixed reference voltage of 5.5V.

FIGURE 2: **TEMPERATURE INDICATOR AT 6 SIGMA PROCESS LIMITS**
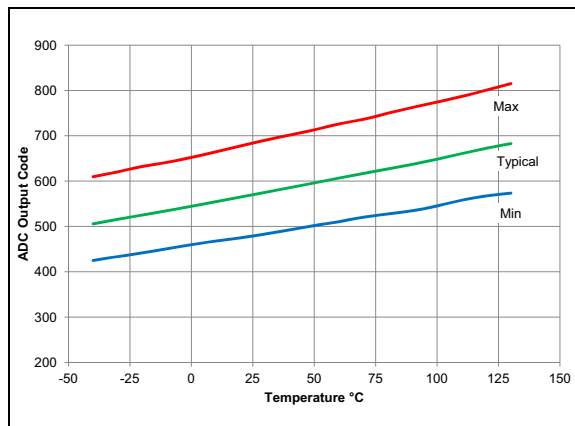
The data used to generate the graph in Figure 2 was inserted into Equation 1 and Equation 2 to produce the graph in Figure 3. The trend line was added to the graph to point out the slope (TC) and the y-intercept (VF).

FIGURE 3: **CALCULATED DIODE VOLTAGE AT 6 SIGMA LIMITS**
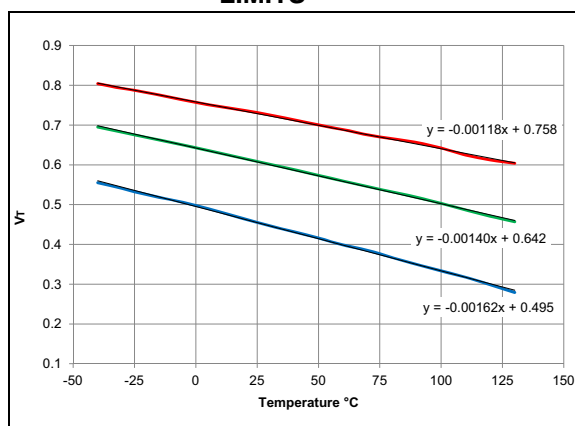
The temperature coefficient (TC) expressed in the "x" term of the equations in Figure 3 ranges from -1.18 mV to -1.62 mV per °C. The forward voltage (VF) expressed in the constant varies from 0.495V to 0.758V. The variation in the equations in Figure 3 point out the need to define TC and VF before the end product is put into production.

The values that were defined in the equations in AN1333 are generally a good starting point for the development process. Numbers derived from the equations in AN1333 give a value for TC of -1.32 mV per °C and a VF of 0.6063V. The value of VF is less of a factor as this variation will be adjusted during factory calibration.

The other constants that need to be defined are generally defined in the application. VDD is generally a fixed value in the design and VREF is generally the same as VDD. The register setting for number of diodes (MODE) will need to be defined when the application voltage is known. The numerical value of the ADC is based on the bit resolution of the particular device.

The last constant to be defined is the temperature offset (OFFSET). The offset value will not be fully defined until the device is calibrated in production.

DEVELOPMENT EVALUATION

Designs that use a TC of -1.32 mV with a VF of 0.6063 as defined in AN1333 may be accurate enough for many applications as long as a factory calibration is performed at a point close to the critical application temperature. Any application that requires a wider temperature range will need additional design evaluation to better determine the correct value of TC and VF. This section will provide guidelines to aid in performing this evaluation.

The first step is to have a fairly complete design. The use of evaluation boards may not completely emulate the thermal environment of the final product. It is crucial that the test code also emulate as much of the product functionality as known at the time of the test. The code should closely match the electrical conditions that the product will see in the field. For instance, a test running on a bare evaluation board in Sleep will not emulate the self heating of a die in closed packaging running at 32 MHz with the 4x PLL.

The test code should have a provision to be able to extract the ADC data at each test point. There are many methods that may be used but the easiest is to write the value to the EUSART module and read via a serial port. The test data below was captured this way using a Microchip PICkit™ Serial Analyzer.

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The final part of the test requires a thermal chamber and a calibrated temperature measurement device. An example of a common calibrated temperature measurement device is a thermocouple probe and a voltmeter. The temperature probe should be placed as close to the PIC16 microcontroller as possible to limit any temperature gradient. Use of an external temperature measurement device is also an option for this step. The test data shown in all the following figures was measured by a Microchip MCP9800 placed in close proximity to the PIC16.

In addition to the device calibration, a design evaluation should be performed on a representative number of boards, to be able to have confidence in the value of T_C and that the equation will meet the requirements of the application. It is also a good practice to have a mix of different production lots during this evaluation, if possible.

EXAMPLE EVALUATION

The example presented uses a PIC16F1716-I/SP on a PICkit 28-Pin Demo Board. A Microchip MCP9800 was attached to this board to be used as a calibrated temperature reference. The test code was written for the demo board that downloaded the indicator's ADC value and the reference temperature. This board was inserted into a thermal chamber capable of a temperature range from -40°C to 125°C. The test data was gathered from two parts, to show the following calibration graphs. Sample 1 was a production part procured from the Microchip stock, and was used as a baseline to determine the value of T_C and V_F. Sample 2 was an early engineering sample that was used to provide the data to verify that the values for T_C and V_F were reasonably accurate.

The data was extracted from both samples at 10°C intervals to generate ADC value as compared to the MCP9800 test temperature.

**FIGURE 4:** **SAMPLE 1 ADC VALUE**
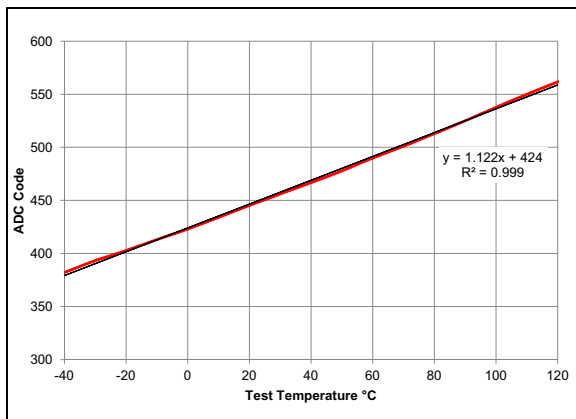
**FIGURE 5:** **SAMPLE 2 ADC VALUE**
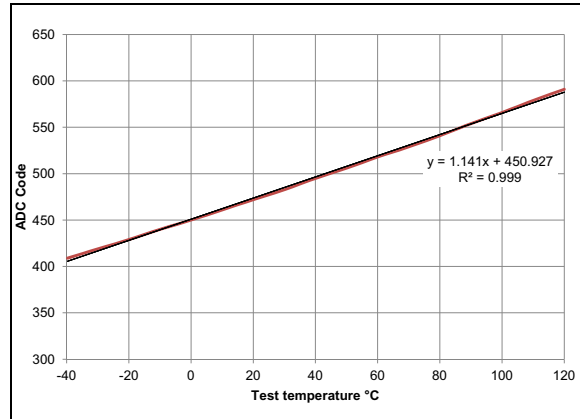
The graphs show that the temperature response is very linear when verified at 10° intervals.

The next step is to graph the diode voltage over temperature to determine a value for T_C. This was accomplished by putting the ADC value into Equation 1 to determine V_{OUT} and the putting V_{OUT} into Equation 2 to calculate V_T.

FIGURE 6: **SAMPLE 1 DIODE VOLTAGE**
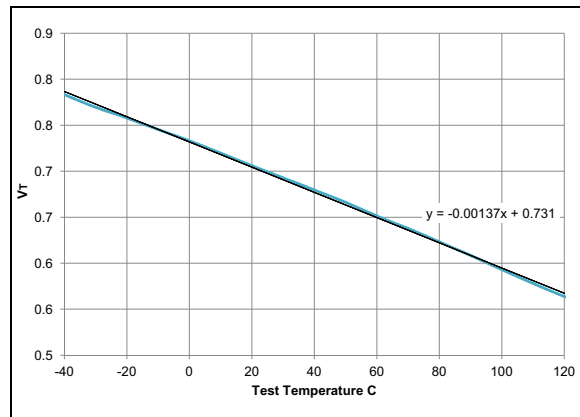

FIGURE 7: **SAMPLE 2 DIODE VOLTAGE**
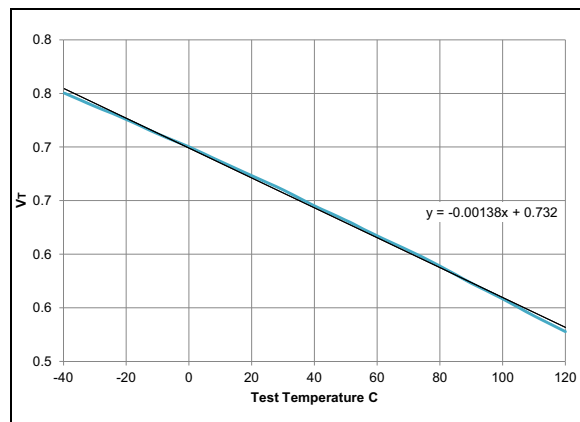
The linear equations shown in Figure 6 and Figure 7 suggest a slight difference in Tc between the two parts with Sample 1 having a Tc of -1.37 mV and Sample 2 having a Tc of -1.38 mV. This illustrates the necessity to test parts from different production lots to get the best average value for Tc. The Tc from Sample 1 was used for Equation 3 for simplicity.

The next step is to use Equation 3 to determine the uncalibrated temperature and to calculate the offset at one data point for each sample. This example uses readings from 20°C for each part to simulate a typical factory single-point calibration. Figure 8 and Figure 9 show the results of this process.

FIGURE 8: **SAMPLE 1 CALCULATED TEMPERATURE vs. ACTUAL TEST TEMPERATURE**
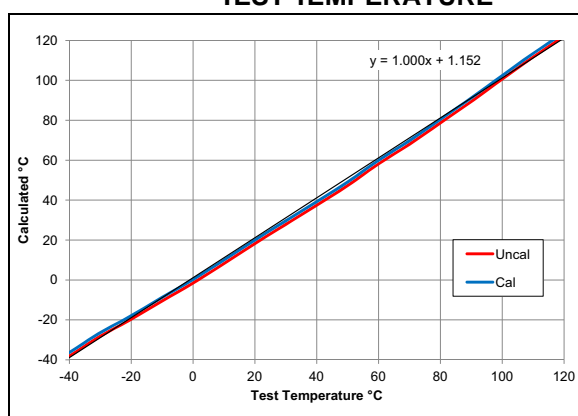
FIGURE 9: **SAMPLE 2 CALCULATED TEMPERATURE vs. ACTUAL TEST TEMPERATURE**
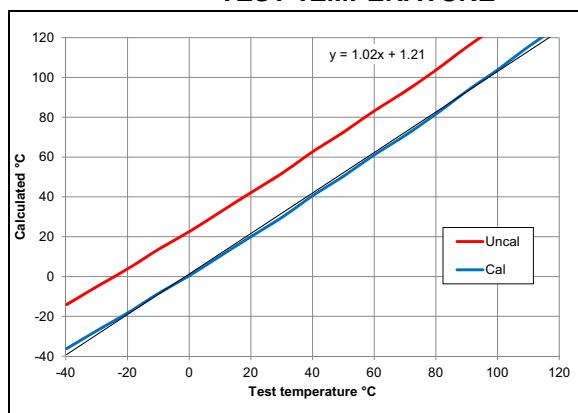
The offset between the Uncalibrated line and the calibrated line in Figure 9 illustrates the need to perform an offset calibration on every part.

IMPLEMENTING EQUATIONS

The sequence of algebraic equations shown in Equation 6 can now be completed to allow programming into the final production code. While all the terms could stay variable, it is usually better to define these as global constants to reduce the demand for RAM in the final code.

The product constants and the Tc and VF information are added to the equations to give the following sequence of equations. The only variable is the ADC result and the only undefined constant is the offset. The offset will be determined at calibration.

EQUATION 7: **INCLUDING Tc AND OFFSET CONSTANTS TO EQUATION 6**

$$V_{OUT} = \frac{ADC_{Result} \times 5.0}{1023}$$

$$V_T = \frac{5.0 - V_{OUT}}{4}$$

$$T_A = (-730 \bullet V_T) + 534 + OFFSET$$

Tc was factored into the equation to simplify the final equation of the sequence. This step is optional but should allow smaller code size.

PUTTING THE EQUATIONS TO TEST

How well do these equations work? A good way to determine the performance is to take a large number of data points at many temperatures. The data can be graphed to visually see the variation. Regression function in many statistic analysis software packages can also be used if better statistics are preferred. The recommended method to run the tests is to automate the data collection. The code that was created for development evaluation had this ability integrated. The thermal chamber used in this experiment was programmed to provide a slow ramping temperature. The test was allowed to run for several hours, accumulating several full-temperature cycles and around 4000 data points. The temperature profile is shown in Figure 10.

FIGURE 10: CYCLING TEMPERATURE PROFILE
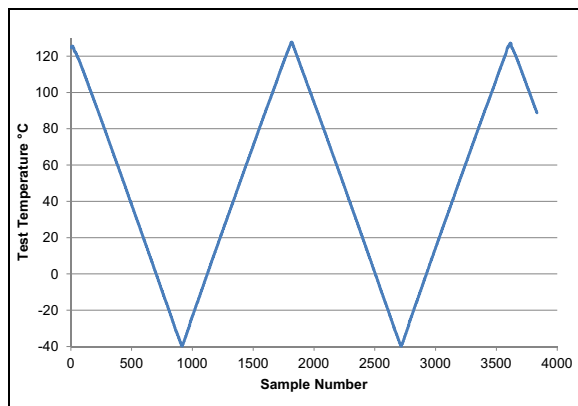
The calculated temperature was determined from the ADC results accumulated during this test. Figure 11 shows the data graphed into a scatter diagram:

FIGURE 11: SAMPLE 1 CALCULATED TEMPERATURE vs. ACTUAL TEST TEMPERATURE
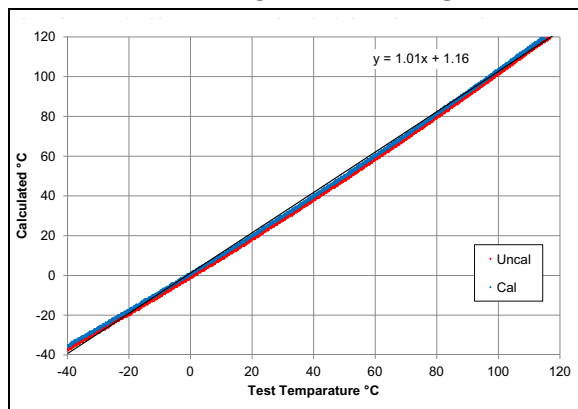
The graph looks reasonable when first viewed but much of the measurement error is lost in the scale of the graph. A better option is to look as a scatter diagram of the error of the individual data points to understand the measurement limits. Figure 12 includes a best fit equation to help understand the relationship between the error and the temperature. This step is optional.

**FIGURE 12: SAMPLE 1 MEASUREMENT ERROR SCATTER DIAGRAM**
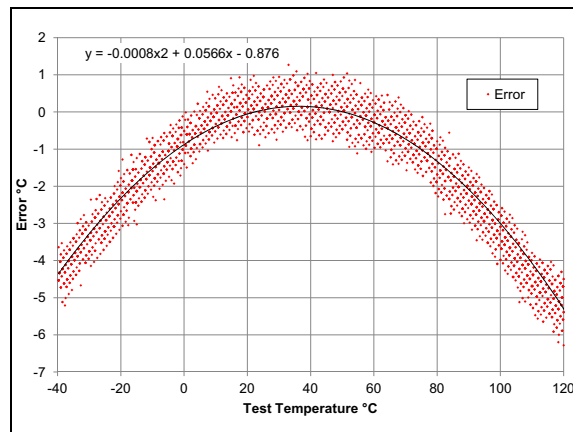
The date in Figure 12 shows that even under ideal conditions there are limits to the repeatability of measurements and the skew of the error over temperature. These limits need to be evaluated in each application. Additionally, the data gathered on one device may not always be representative of production. Additional devices should be evaluated to insure that the calculated limit for T_C works on a spread of devices. In order to illustrate this factor, the data for several more devices has been included for review.

Figure 13, Figure 14, Figure 15, and Figure 16 contain the results for four additional devices.
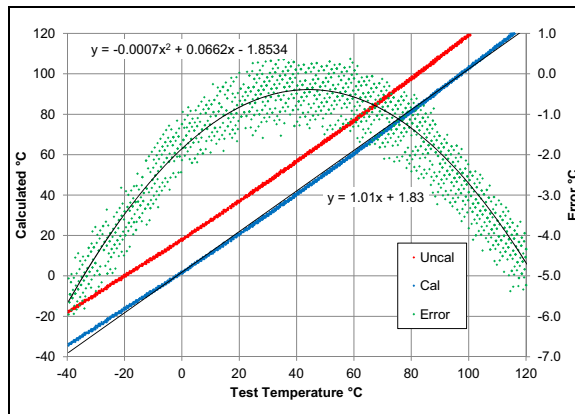

FIGURE 13: **SAMPLE 2 TEST TEMPERATURE vs. CALCULATED AND ERROR**
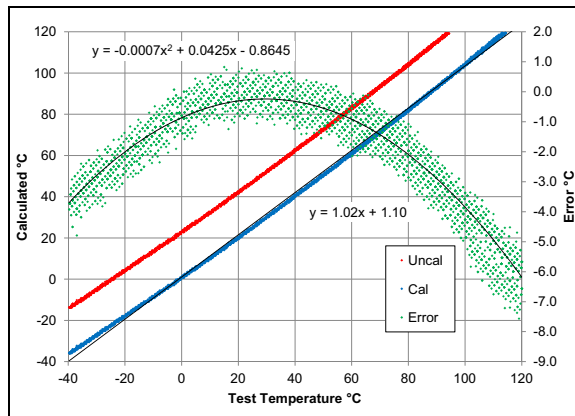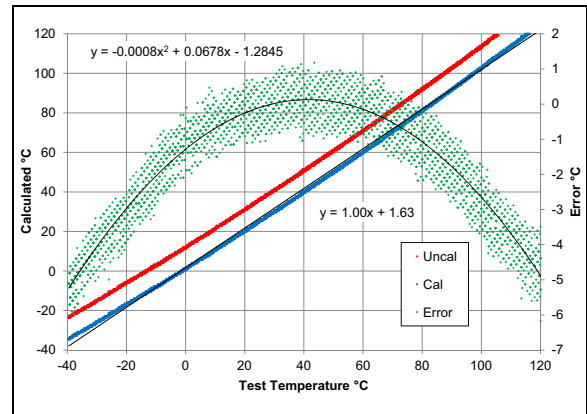

FIGURE 15: **SAMPLE 4 TEST TEMPERATURE vs. CALCULATED AND ERROR**
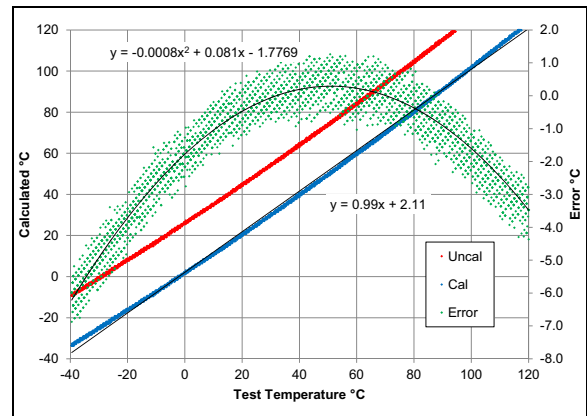
FIGURE 14: **SAMPLE 3 TEST TEMPERATURE vs. CALCULATED AND ERROR**

FIGURE 16: **SAMPLE 5 TEST TEMPERATURE vs. CALCULATED AND ERROR**

CALIBRATION TECHNIQUES

There are many methods to perform a product calibration. The common factor is that the actual temperature needs to be compared to the uncalibrated value to determine offset, which will vary on every device. The method used in this document was to measure the ambient temperature and read the uncalibrated value from the part via the EUSART. Make sure that the power supply voltage used during calibration matches the application. The offset value can then be uploaded into the device by the same method and written to data Flash PFM or to EEPROM. Data Flash or EEPROM can also be written externally by the programmer. The method used will be dependent on the application. It is also wise to read the calibrated temperature and compare it to the ambient temperature to verify that the calibration was performed correctly.

PROGRAMMING TIPS AND TRICKS FOR ACCURATE TEMPERATURE MEASUREMENT

- Insert a 200 µs delay when switching from a different ADC channel or if the temperature indicator has not been used for several milliseconds.
- The ADC conversion can be performed in Sleep to reduce system noise generated by the CPU clock.
- Oversample the temperature indicator and average the result to reduce the error in noisy environments.
- Perform the ADC measurement of the temperature indicator in repeatable conditions.
- Perform the conversion with the same F_{OSC} and SLEEP condition used in calibration to limit temperature skew due to localized die heating.
- Build the calibration routine into the production code if possible.

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