AN2798

Using the PIC16F/PIC18F Ground Referenced Temperature Indicator Module

Introduction

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Microchip PIC® microcontrollers have internal temperature indicator solutions.

This application note covers temperature indicators in several families for PIC16F and PIC18F that have the internal temperature indicator referenced to ground. Examples are PIC16F15355 and the PIC18F27K42. This grounded configuration allows more consistent operation with the use of a variable voltage power supply than the previous PIC16F versions that were configured with temperature diodes referenced to V_{DD}. Consult *"Using the Temperature Indicator Module"* (AN2092) for the use and application of PIC16F devices that utilize the V_{DD} reference temperature indicator.

Acronyms and variables used in this document can be found in section 5.

Table of Contents

Introduction......1

1. Theory of Operation for the Temperature Indicator Module......3
    1.1. Application Limits......4
2. Single-Point Calibration Method......5
    2.1. Finalizing the Equations......6
    2.2. Required Constants......6
    2.3. Additional Variables......7
    2.4. Determining V_{REF}......7
    2.5. Determining V_{OUT}......7
    2.6. Calculating T_A (Ambient Temperature)......8
    2.7. Calculating the Value of OFFSET......8
3. Two-Point Calibration Method......10
    3.1. Two-Point Calibration Using the DIA......11
    3.2. Measuring the Results of Two-Point Calibration with DIA calculated T_C......11
4. Additional Tips and Tricks for Accurate Temperature Measurement......13
5. Acronyms and Variables......14

The Microchip Web Site......15

Customer Change Notification Service......15

Customer Support......15

Microchip Devices Code Protection Feature......15

Legal Notice......16

Trademarks......16

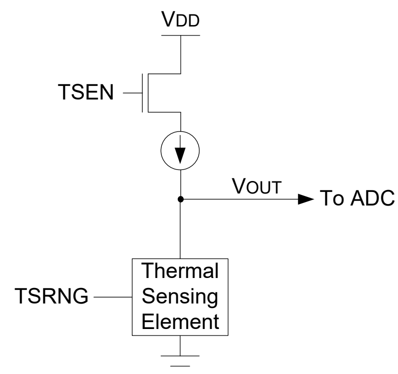
Quality Management System Certified by DNV......17

Worldwide Sales and Service......18

1. Theory of Operation for the Temperature Indicator Module

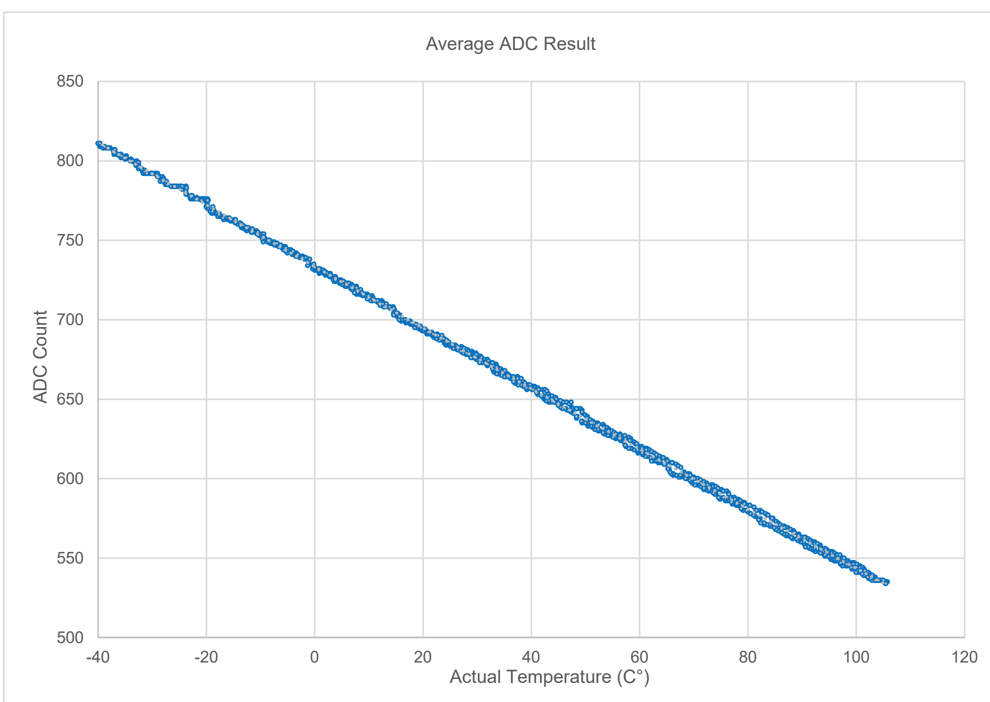
The temperature indicator module uses the property that at a constant current the silicon junctions have a nearly linear negative voltage response when subjected to an increasing temperature change. The temperature indicator module has a thermal sensing element that is supplied by a constant current source. The ADC is used to measure the voltage of the temperature sensor. The sensor is enabled by the TSEN Control bit. The sensor also has the TSRNG Control bit that determines whether the voltage output falls within the high or low range. Most applications will use the high range if the supply voltage is between 2.5V and 5.5V. The low-range setting is used for supply voltages between 1.8V and 2.5V. Note that the ADC reference must be tied to V_{DD} in this application mode.

Figure 1-1.



The thermal sensing element is not directly measurable to the end user. Instead, the ADC is used to measure the voltage of the element. Figure 1-2 shows a typical 10-bit ADC response to changing temperature.

Figure 1-2. Average ADC Result



1.1 Application Limits

- The temperature indicator module requires single-point calibration at a minimum. This calibration step can use the calibration information stored in the device.
- This module may not be suitable when an absolute temperature accuracy of less than ±5°C is required.
- Driving high current with output pins can cause variation in the measured temperature due to high die temperature.
- This module is not recommended for use in critical temperature control applications or for thermal safety applications without a suitable backup method of thermal protection.

2. Single-Point Calibration Method

Equation 2-1 is used to convert the measured average integer result recorded from the ADC into an equivalent analog voltage.

Equation 2-1.

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

The V_{OUT} term is part of the solution to solve the linear equation that establishes the relationship to the temperature using the slope intercept method Y = MX + B.

Substituting V_{OUT} for Y, T_C for M and V_F for B gives Equation 2-2 below.

Equation 2-2.

$$V_{OUT} = (T_C * T_A) + V_F$$

A better definition of the variables will be provided in a later section of this document. Solving for temperature gives Equation 2-3.

Equation 2-3.

$$T_A = \frac{(V_{OUT} - V_F)}{T_C}$$

$$T_A = \left(\frac{V_{OUT}}{T_C}\right) - \left(\frac{V_F}{T_C}\right)$$

Process variation adds uncertainty to the V_F constant providing an uncalibrated temperature that is not useful for most applications. An additional temperature offset term is required. This offset variable will be calculated by subtracting the uncalibrated temperature from the actual ambient temperature as shown in Equation 2-4. Several methods of determining the OFFSET will be covered later in this document.

Equation 2-4.

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

This offset is added to the previous equation to create an equation for actual temperature. The offset can be calculated several ways but it is normally calculated once during the manufacturing process and then added to Equation 2-5 as a constant for each production device.

Equation 2-5.

$$T_A = \left(\frac{V_{OUT}}{T_C}\right) - \left(\frac{V_F}{T_C}\right) = OFFSET$$

Equation 2-5 sets could be further consolidated into one equation but there are advantages to keeping the equations in a sequence for readability, code size reduction, and elimination of floating point math. This complete equation is shown in Equation 2-6.

Equation 2-6.

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

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

2.1 Finalizing the Equations

Data taken on several sample devices from different production lots determines the range of most of the constants to find nominal values. These constants should be sufficient to generate usable temperatures with minimal calibration required. These constants will be defined further in the following sections.

ADC_{RESULT}: Analog-to-Digital Conversion Result

Generally, ADC_{RESULT} is determined by a single conversion of the ADC with the temperature indicator channel selected. This usually gives a temperature reading that is adequate for typical control applications. The ADC_{RESULT} is generated after loading the integer value from the ADRESH and ADRESL registers in Right Justified mode. The combined field ADRES is usually available in the header for Equation 2-7.

Equation 2-7.

$$ADC_{RESULT} = (ADRESH \ll 8) + ADRESL$$

In the application the temperature reading may vary several degrees when at a fixed temperature. This variation can be caused by noise on the FVR and by the internal switching noise generated by the CPU core. The user should utilize oversampling of the ADC_{RESULT} to reduce the variation of the temperature result if higher accuracy is necessary.

Usually, 8X oversampling is adequate to limit the variation but the user may also utilize other noise reduction methods as needed. The calculation for the oversampled result is shown in Equation 2-8.

Equation 2-8.

$$ADC_{SUM} = \sum_{i=0}^{7} ((ADRESH \ll 8) + ADRESL)$$

$$ADC_{RESULT} = ADC_{SUM} \gg 3$$

Or

$$ADC_{SUM} = \sum_{i=0}^{7} ADRES$$

$$ADC_{RESULT} = ADC_{SUM} \gg 3$$

2.2 Required Constants

- **V_{REF}**: Reference voltage of the ADC module

The ADC needs a stable reference to be able to accurately measure the voltage of the temperature sensor. The only two valid references for measuring temperature are the following:

- 2X fixed voltage reference (FVR)
- Supply voltage (V_{DD})

Most applications will use the 2X FVR as the reference. The 2X FVR is nominally 2.048V but can vary ±4% with process variation. The actual voltage of the FVR is recorded in the FVRA2X memory location in the DIA during testing. The DIA has an integer measurement of the FVR voltage in millivolts. Consult the data sheet for additional information on the specifications and reading of the DIA.

V_{DD} will normally only be used when the supply voltage range is between 2.0V and 2.5V. The 2X FVR does not regulate well enough in this range to ensure accurate voltage measurement. The user must ensure that the supply voltage is well regulated or must provide the means to measure the voltage with the ADC at the point when the temperature calculation is needed.

V_{REF} will be treated as a variable in the equation for these reasons.

- **RES**: Resolution of the ADC

The total integer resolution of the ADC is defined by the equation 2^n-1, where 'n' is the number of bits of resolution of the ADC. The value for RES will be either 1023 for the 10-bit ADC or 4095 for the 12-bit ADC. The user *may* want to keep these values as variables for portability but generally it is simpler to set constants and use different production code for 10-bit or 12-bit solutions.

- **T_C**: Temperature coefficient of the sensor module

The temperature coefficient will be different depending on the setting of the TSRNG bit. The high setting will vary from part to part between -3.5 to -3.9 mV/°C with normal process variation. The low-range setting will vary between -2.2 to -2.6 mV/°C. Almost every application will use the high-range setting. The exception for low range is when the supply voltage is below 2.5V and temperatures are below 0°C. The basic equation will use the midband points of -3.7 mV/°C and -2.4 mV/°C. This number is reasonably critical as this slope is not adjusted with single-point calibration.

- **V_F**: Forward voltage of sensor module at 0°C

The sensor module has a bias established by the constant current flow. This bias was measured on multiple lots at 0°C to establish a range. The voltage ranges from 1.4 to 1.6V at high range and 0.9 to 1.1 on low range. The equations will use 1.5V and 1.0V for convenience. The exact number is not critical at this stage because the temperature calibration step will adjust temperature to accommodate the exact bias of each device.

2.3 Additional Variables

The remaining terms are the variables that will be captured and calculated during the measurement process.

- **V_{OUT}**: Voltage calculated from the ADC_{RESULT}
- **OFFSET**: The temperature offset error

The last term is the solution.

- **T_A**: Calculated temperature

2.4 Determining V_{REF}

The value of V_{REF} is nominally 2.048 volts. Optionally, the user can utilize a Flash read to acquire the value from the DIA in FVRA2X location. The value is in millivolts and will require scaling to get to volts.

The user will need to determine the value of V_{REF} if V_{DD} is in use as the reference.

2.5 Determining V_{OUT}

To simplify the equations, this example will be for the 10-bit ADC. Adding the constants gives Equation 2-9.

Equation 2-9.

$$V_{OUT} = \frac{ADC_{RESULT} * V_{REF}}{1023}$$

2.6 Calculating T_A (Ambient Temperature)

Adding the constants to the second equation gives Equation 2-10.

Equation 2-10.

$$T_A = \left(\frac{V_{OUT}}{-0.0037}\right) - \left(\frac{1.5}{-0.0037}\right) + OFFSET$$

Further refinement gives Equation 2-11.

Equation 2-11.

$$T_A = 405 - (V_{OUT} * 270) + OFFSET$$

2.7 Calculating the Value of OFFSET

Room temperature calibration requires the use of the completed equation sequence with the OFFSET value set to zero. The user then utilizes Equation 2-4 to calculate the OFFSET. The temperature offset error is determined during the calibration process. This offset will vary from device to device and is reasonably constant across all temperatures. The two main methods of calculating the offset are to perform a room temperature calibration or to use information provided in the DIA. Room temperature calibration will generally provide an accurate measurement at or near the calibration point.

Calculating OFFSET Value Using Information Stored in DIA

The DIA calibration value is the actual ADC value captured at 90°C during production testing. The DIA value will generally be better when the high temperature error needs to be limited. The user calculates a value for the OFFSET by utilizing the DIA information stored in TSLR2 or TSHR2 (see Equation 2-12).

Equation 2-12.

$$V_{OUT} = \frac{TSHR2 * V_{REF}}{2^n - 1}$$

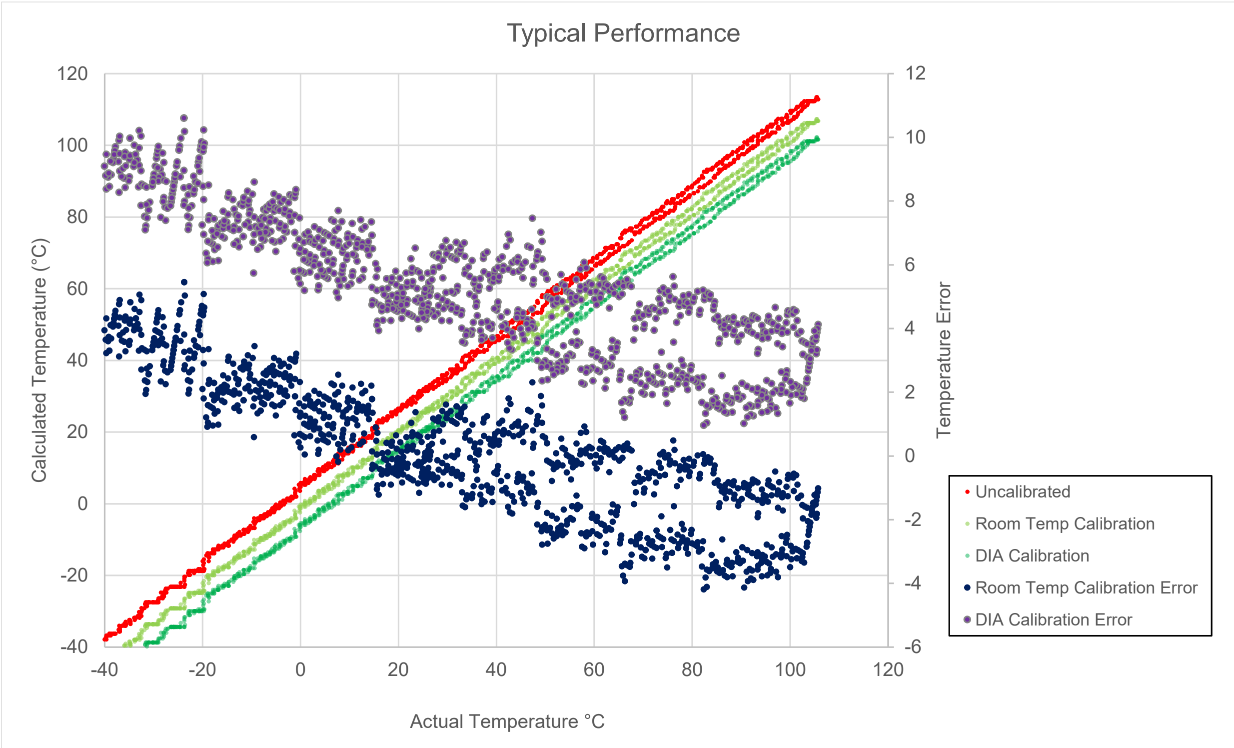
Or

$$V_{OUT} = \frac{TSLR2 * V_{REF}}{2^n - 1}$$

$$OFFSET = 90 - (405 - (V_{OUT} * 270))$$

Using the DIA data will generate a slightly different offset from the room temperature calibration. The error is dependent on the error in the temperature slope. Either of these methods to calculate the OFFSET is acceptable but it is generally better to use the value that is nearest to the critical application temperature to determine the best method for calibration.

Figure 2-1. Typical Performance for Single-Point Calibration



3. Two-Point Calibration Method

The previous section mentioned that the slope of the internal temperature sensor could vary between -3.5 to -3.9 mV/°C in high range or between -2.2 to -2.6 mV/°C in low range. Slight variations in semiconductor processing cause this difference in slope. Two-point calibration permits the user to compensate for this variation in slope to allow better temperature measurement performance over a wider range. Two-point calibration requires additional effort during the production process because of the need to acquire an additional data point. Generally, it is recommended that the two data points bracket the needed temperature range, but an argument can be made to keep one of the data points at room temperature for an easier calibration process. The second data point needs to be removed from the first data point to get the highest confidence in the calculated slope.

Section 2. Single-Point Calibration Method gave Equation 3-1 for the output voltage of the sensor.

Equation 3-1.

$$V_{OUT} = (T_C * T_A) + V_F$$

Solving for ambient temperature provides Equation 3-2.

Equation 3-2.

$$T_A = \frac{(V_{OUT} - V_F)}{T_C}$$

The typical solution would be to solve for the slope using Equation 3-3 to get the voltage slope in mV, the same as utilized in the single-point method.

Equation 3-3.

$$T_C = \frac{V_{OUT2} - V_{OUT1}}{T_{A2} - T_{A1}}$$

A better alternative is to directly use two ADC_{RESULT} readings to determine the slope of the ADC output, as shown in Equation 3-4.

Equation 3-4.

$$ADC_{TC} = \frac{ADC_{RESULT2} - ADC_{RESULT1}}{T_{A2} - T_{A1}}$$

The main advantage is that the ADC_{RESULT} terms are integer numbers, simplifying the 8-bit math. The slope for the temperature equation is then determined with Equation 3-5.

Equation 3-5.

$$T_C = \frac{ADC_{TC} * V_{REF}}{RES}$$

Inserting the slope equation into temperature equation condenses to Equation 3-6.

Equation 3-6.

$$T_A = \frac{(V_{OUT} - V_F) * RES}{ADC_{TC} * V_{REF}}$$

This method will produce a large whole number in the numerator and a small integer number in the denominator simplifying the math on an 8-bit device. The temperature calculated from this equation will still have some temperature offset error. This offset error is because the forward voltage term V_F is a process average and each individual device will vary slightly from the process average. As in the single-point method, add offset correction term to Equation 3-7.

Equation 3-7.

$$T_A = \left(\frac{(V_{OUT} - V_F) * RES}{ADC_{TC} * V_{REF}}\right) + OFFSET$$

The offset term is like the offset in the single-point calibration process in Equation 2-4. Make use of one of the two temperatures utilized to calculate the temperature coefficient to calculate the offset. In general, use the temperature that is the closest to the critical application temperature.

3.1 Two-Point Calibration Using the DIA

As stated previously, the two-point calibration method gives a more accurate slope term for the temperature calculation at the expense of a more complicated calibration process. A variation of the two-point method is to use either the TSHR2 or TSLR2 calibration value as a 90°C data point. The data from the DIA memory are loaded into equation Equation 3-4 replacing the terms for $ADC_{RESULT2}$ and T_{A2} to get Equation 3-8.

Equation 3-8.

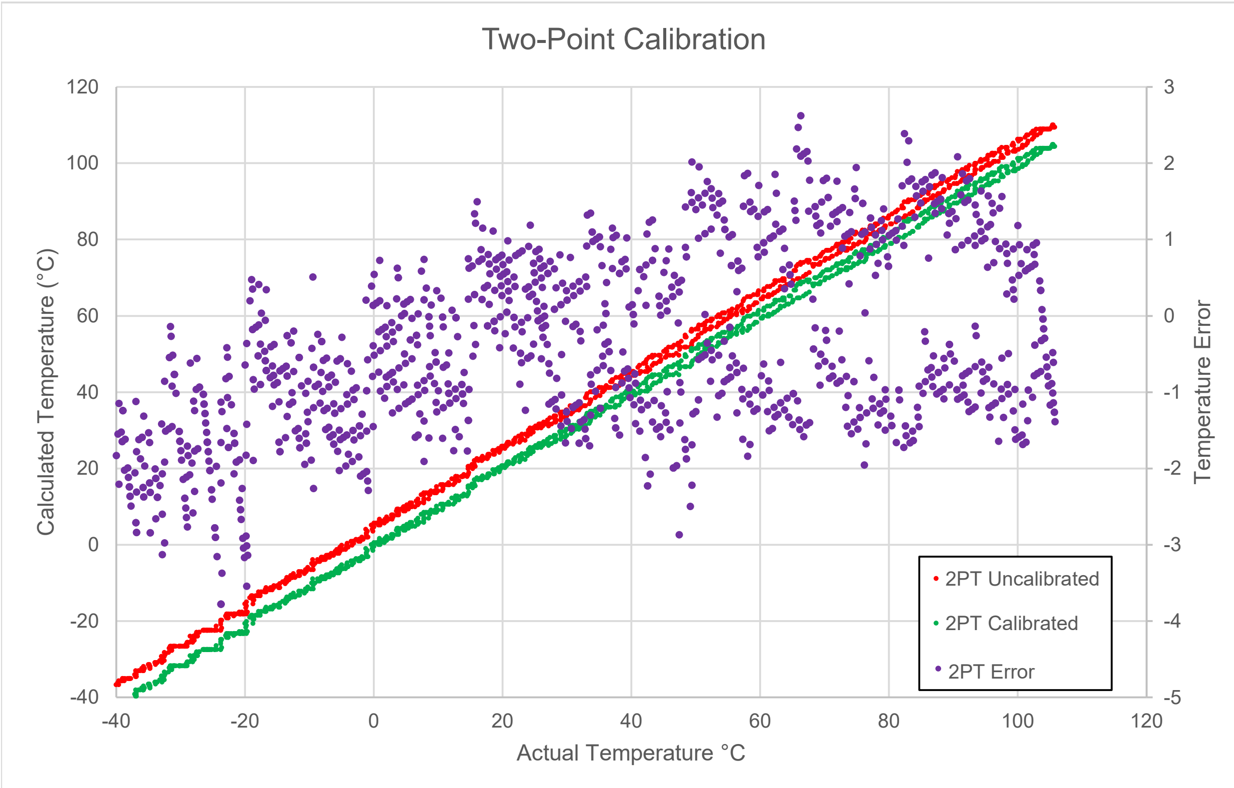
$$ADC_{TC} = \frac{DIA_{VALUE} - ADC_{RoomTemp}}{90 - RoomTemp}$$

The only calibration step needed will be the room temperature calibration process, as described in section 2. Single-Point Calibration Method. This operation only works if the 2X FVR is used for V_{REF} because the DIA (TSHR2 or TSLR2) is captured at the 2X setting. This method should produce a result that is almost as good as the two-point calibration but only limited by application specific conditions. As with the single-point method, oversampling may be needed to limit the affects of internal noise in the conversion. The temperature offset term will still need to be added for this calculation. The offset can be calculated either from the room temperature calibration or from the ADC count recorded in the DIA value.

3.2 Measuring the Results of Two-Point Calibration with DIA calculated T_C

The results presented in the following graph show that the overall temperature error is less than a single-point calibration process with some additional code overhead. Individual results may vary depending on user conditions.

Figure 3-1. Typical Performance for Two-Point Calibration



4. Additional Tips and Tricks for Accurate Temperature Measurement

- Insert a minimum of 50 µs delay when switching from a different ADC channel or if the temperature indicator has not been used for several milliseconds.
- Select the V_{SS} channel of the ADC right before selecting the temperature channel if the ADC was used to measure a signal level higher than 1.5V.
- The ADC conversion can be performed in Sleep to reduce system noise generated by the CPU clock.
- Oversampling and averaging the temperature indicator results reduces the temperature error in noisy environments.
- Perform the ADC measurement of the temperature indicator in repeatable conditions whenever possible.
- Perform the conversion with the same F_{OSC} and Sleep mode used in calibration to limit temperature skew due to localized die heating.
- Build the calibration routine into the production code if possible.

5. Acronyms and Variables

TSEN: Temperature Indicator Control bit

TSRNG: Temperature Indicator Range Selection bit

V_{OUT}: Voltage output of thermal sensing element; V_{DD}: Supply voltage

ADC: Analog-to-Digital Converter

ADC_{RESULT}: Combined digital output of both ADC conversion registers

ADRESH: Upper byte of ADC conversion; ADRESL: Lower byte of ADC conversion

V_{REF}: Reference voltage used by ADC

FVR: Fixed Voltage Reference

RES: Total resolution as calculated by 2^n-1

T_C: Temperature coefficient; T_A: Variable ambient temperature

V_F: Constant forward voltage of typical temperature sense element at 0°C

OFFSET: Constant for a temperature correction calculated at calibration

ADC_{SUM}: Combined value of several consecutive ADC conversions

DIA: Device Information Area location in memory with tested constant information

TSHR2: Temperature indicator high-range ADC_{RESULT} at 90°C

TSLR2: Temperature indicator low-range ADC_{RESULT} at 90°C

FVRA2X: ADC FVR1 output voltage for 2X setting

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