AN828

Measuring Temperature with the PIC16F84A Watchdog Timer

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INTRODUCTION

Almost all temperature sensor circuits use some form of discrete component (such as a thermistor or a solid-state sensor) to actually measure the environment's temperature. It is left to the microcontroller to interpret the reading into a human-friendly form for the user's benefit.

It is possible, however, to design a digital thermometer without an external sensor, by using a temperature sensitive property of the microcontroller itself. This Application Note shows how to use the Watchdog Timer (WDT) of a PICmicro® microcontroller for temperature measurement.

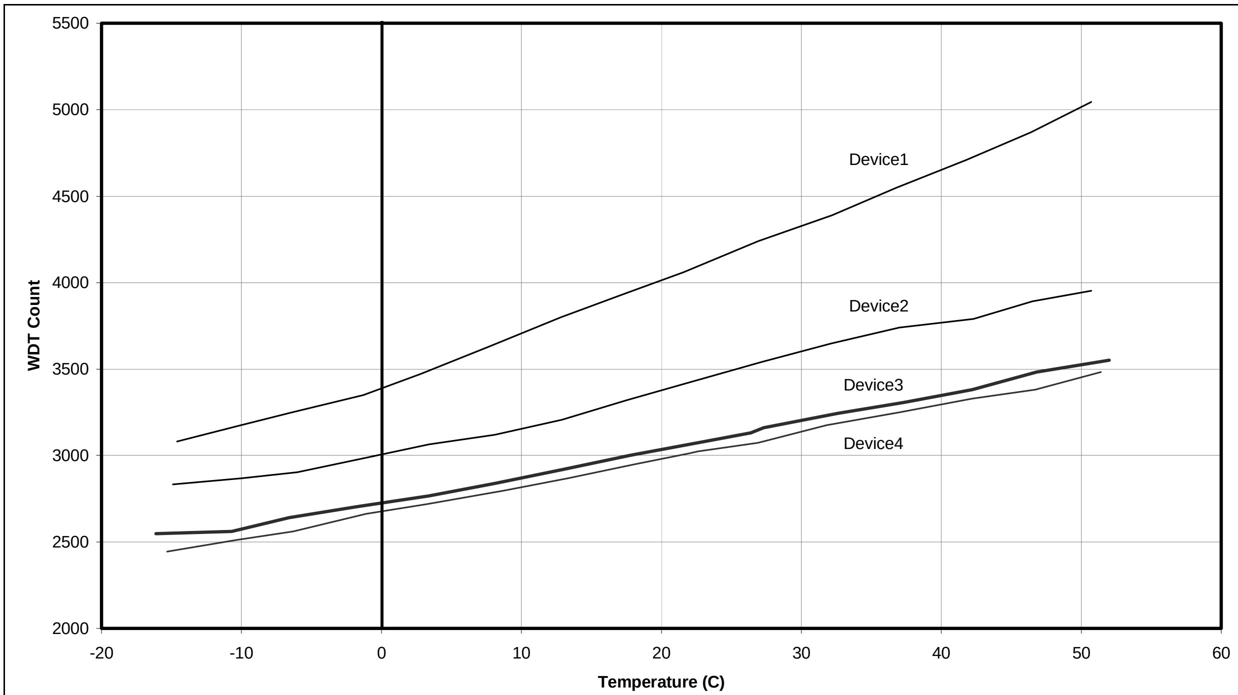
THEORY OF OPERATION

The WDT on all PICmicro microcontrollers has a nominal time-out period of 18 ms. The WDT time-out period varies with temperature, V_{DD} and part-to-part process variations. For a given microcontroller, the WDT exhibits a nearly linear correlation between the time-out period and temperature, assuming that V_{DD} is constant.

Figure 1 shows the time-out count as a function of temperature for four different devices. Note that while each device differs in counts for a given temperature, the slope of the line for each device is essentially constant, and is similar for all devices. The only real difference is the offset (or y-intercept) for each device. In practical terms, this means that the thermometer circuit must be calibrated with the offset value for its controller. For this application, two temperatures at opposite ends of the expected temperature range are used to derive both slope and y-intercept.

The design of the digital WDT thermometer is based on this principle. Without using a separate temperature sensor, it is possible to calculate the temperature with reasonable accuracy using the WDT time-out period.

FIGURE 1: WATCHDOG TIMER COUNT VS. TEMPERATURE FOR FOUR PIC16F84A DEVICES



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To translate the environment temperature into an actual reading, the system must be able to do the following:

- Provide a method for establishing time-out to temperature calibration
- Count the number of WDT time-outs for a given period of time
- Equate the number of time-outs to a temperature

The flow charts showing the firmware implementation of all these steps are presented in Figure 2 and Figure 3. For the sake of brevity, we will only discuss the method for counting WDT time-outs and calculating temperature, in detail. The overall system design also includes wake-on-interrupt key scanning and temperature display, which may not be needed by some users. Those who may be interested in examining these other components are encouraged to download the source code and examine it at their leisure.

FIGURE 2: MAIN FIRMWARE ROUTINE FOR THE WDT THERMOMETER

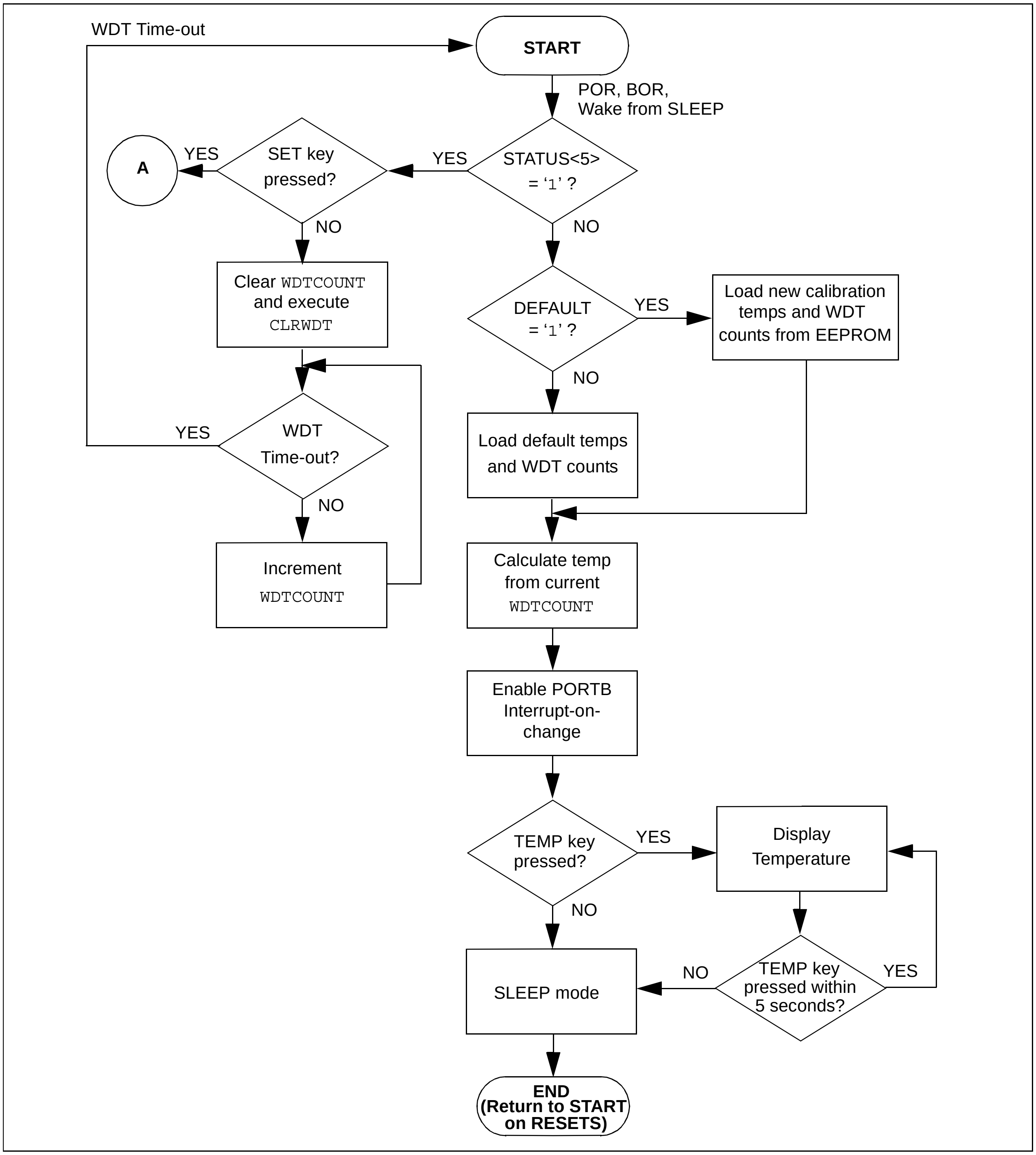

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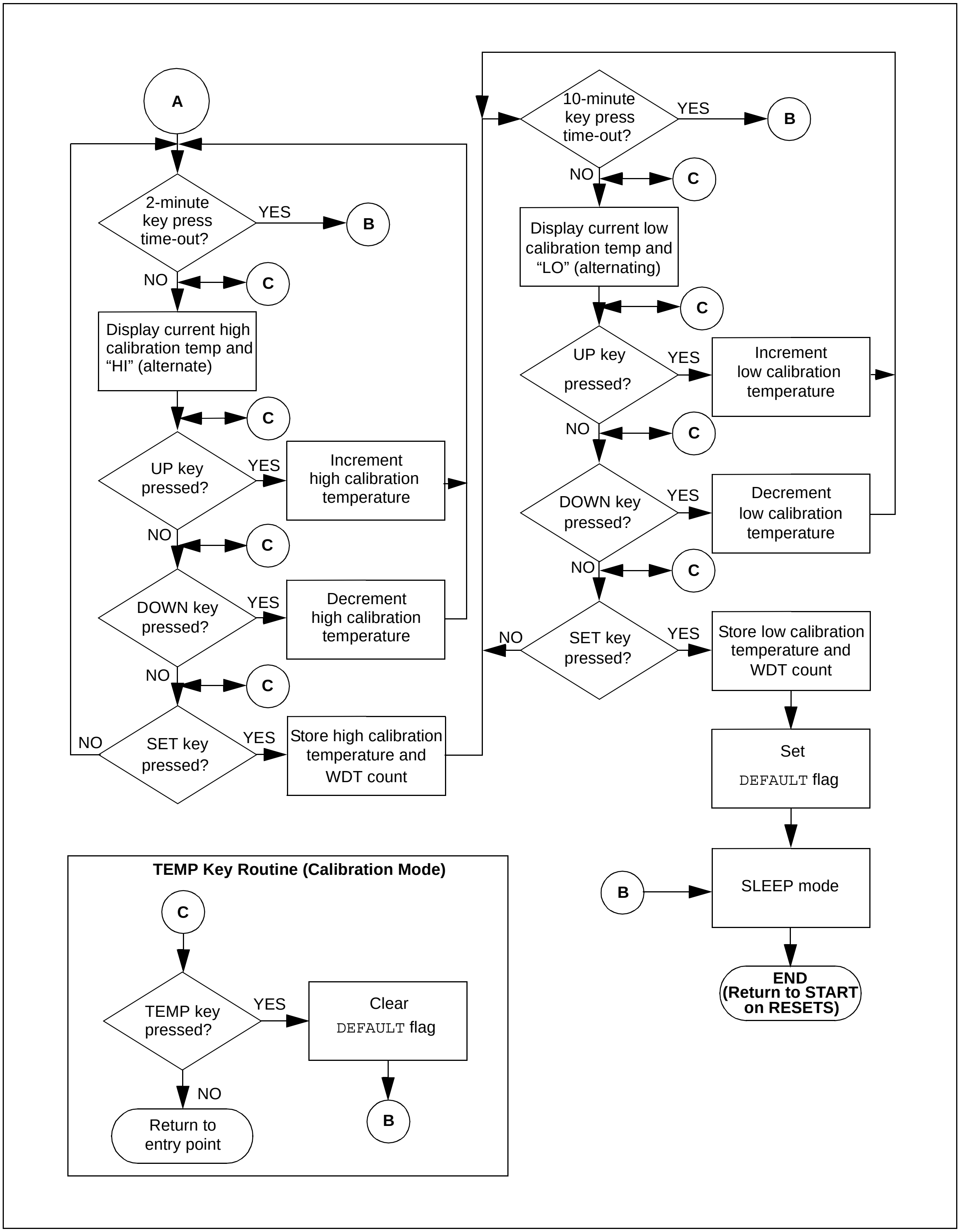
FIGURE 3: CALIBRATION ROUTINE FOR THE WDT THERMOMETER



COUNTING THE WDT TIME-OUTS

The first step to calculate temperature is to count the number of WDT time-outs. This is done running a loop until a time-out occurs, then incrementing a counter. `WDTCOUNT_HI` and `WDTCOUNT_LO` are the two 8-bit registers used to store the 16-bit value of WDT count.

The selection of a 16-bit counter for WDT time-out is based on both the system clock and the WDT prescaler ratio. For the system described in this application note, a clock frequency of 2 MHz and a WDT prescaler ratio of 1:2 was used. With this configuration, it was observed that the value of the WDT count never exceeded 16 bits over the entire temperature range (-40°C to 85°C). If a longer time-out period is required, a prescaler ratio of up to 1:128 can be assigned under software control by writing to the three Least Significant bits of the OPTION register. At the highest setting, a time-out period of as long as 2.3 seconds can be realized.

The firmware calculation of the WDT time-out, as well as the size of the register, are based on this clock frequency and WDT prescaler ratio. Changing these values requires changes to the algorithm; in addition, increasing the prescaler ratio will require a longer calculation and more time, and may require a larger WDT time-out counter register. It is the user's responsibility to determine what the appropriate WDT rate and time-out register size is for a particular application, and make the appropriate changes. Note that the basic counting method will always stay the same.

To demonstrate this, let's look at a few examples. In these cases, the following assumptions are made:

- Each four-instruction loop incrementing the WDT counter takes five clocks cycles (one for each instruction, plus an addition cycle for the `GOTO` instruction, as it increments the program counter)
- The worst-case Watchdog Timer Reset time (T_{WDT}) is 40 ms. (This is well outside of the maximum value of 33 ms specified for the PIC16F84A; we will use this value to provide a margin of comfort in calculating the register size.)

For the system described here, the 2 MHz system clock gives us a clock cycle of 2 µs, which means a single loop executes in 10 µs (5 x 2 µs). The WDT prescaler ration of 1:2 gives us an actual time-to-reset of 80 ms, or 80,000 µs. Thus, a single RESET would generate a count of 80,000/10, or 8,000. As this is less than 65,536 (2^{16}), this means that the WDT count can be accommodated in 16 bits, or a two-byte register.

On the other hand, let's examine a system using a 20 MHz clock and a prescaler ratio of 1:128. In this case, the clock cycle is 0.2 µs, and the loop executes in 1 µs. The WDT prescaler ratio yields an actual time-to-reset of 5120 ms (40 µs x 128), or 5,120,000 µs. This gives us 5,120,000 counts per RESET (5,120,000 µs / 1 µs), which would require a minimum of 23 bits (2^{23}, or 8,388,608, being the smallest power of 2 that is larger than the value) to represent. In practical terms, this means a three-byte (24-bit) register.

At start-up, the program checks if the RESET is a Power-on Reset (POR) or a WDT time-out. It does this by checking the $\overline{\text{TO}}$ bit of the STATUS register. (See Table 1 for details on the $\overline{\text{TO}}$ and $\overline{\text{PD}}$ bits and their significance.) If the RESET is a POR ($\overline{\text{TO}}$ equal to '`1`'), the system determines the present temperature by measuring the WDT time-out time.

This is done by first clearing the `WDTCOUNT_HI:WDTCOUNT_LO` register pair, and then by doing a 16-bit increment within the loop. Since the WDT is not cleared in the loop, the WDT will eventually time-out and cause a WDT Reset. This RESET will cause the Program Counter to be loaded with 0000h and a WDT Reset will be executed on the PIC16F84A. Subsequently, the program will branch back to 'Start'.

When the STATUS register is checked this time, the $\overline{\text{TO}}$ bit will be '`0`', indicating that a WDT time-out (and not a POR) has occurred. The value now stored in the `WDTCOUNT_HI:WDTCOUNT_LO` register pair corresponds to the WDT time (and thus the present temperature) of the PIC16F84A.

> **Note:** RESETS do not affect the values stored in RAM (i.e., `WDTCOUNT_HI` and `WDTCOUNT_LO`).

TABLE 1: STATUS BITS AND THEIR SIGNIFICANCE IN RESET STATES

$\overline{\text{TO}}$	$\overline{\text{PD}}$	Condition
1	1	Power-on Reset
0	Unknown	Illegal
Unknown	0	Illegal
1	1	Brown-out Reset
0	1	WDT Reset
0	0	WDT Wake-up
1	0	$\overline{\text{MCLR}}$ Reset during SLEEP or interrupt wake-up from SLEEP
Unchanged	Unchanged	$\overline{\text{MCLR}}$ Reset during normal operation

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EXAMPLE 1: CODE FOR COUNTING WDT TIME-OUTS

```
Start                               ; Main start of the program
        movf    WDTCOUNT_HI,w       ; (WDTCOUNT_HI:WDTCOUNT_LO)-final value of 16-bit WDT counter
        movwf   TEMP1               ; (TEMP1:TEMP0)- value for calculation of temperature
        movf    WDTCOUNT_LO,w
        movwf   TEMP0

        btfss   STATUS,NOT_TO       ; Reset by power-on, new WDT count.
        goto    MeasureTemp         ; Reset by WDT time-out, calculate present temperature.

Initialization code for WDT         ; Select Prescaler for WDT in OPTION_REG
                                    ; PSA = 1, Prescaler is assigned to the WDT
:
:
        clrf    WDTCOUNT_HI         ; Clear 16 bit count for WDT time-out period
        clrf    WDTCOUNT_LO         ;
        clrwdt                      ; Clear Watch Dog Timer
WDT_LOOP
        incfsz  WDTCOUNT_LO,f       ; Lower 8 bit of WDT Time-out count
        goto    CALWDT1
        incf    WDTCOUNT_HI,f       ; Upper 8 bit of WDT Time-out count
CALWDT1
        goto    WDT_LOOP
MeasureTemp
:
; Code for calculation and display of temperature and other routine
:
```

CALCULATING TEMPERATURE WITH WDT COUNT

The calculation of temperature is based on the two calibrated temperatures and their corresponding WDT counts. Since the relationship between temperature and WDT time is nearly a straight line, two points are sufficient to determine the slope. Both temperatures and WDT counts must be determined and stored in EEPROM locations. These values remain the same for a given device.

In order to determine the two points on the straight line, the user will have to find the WDT time values for two known temperatures by executing the calibration process. To obtain the most accurate calculation of the slope, the difference between the two calibration temperatures must be at least 20°C. For production testing, multiple units should be tested in parallel, using the Calibration mode in the source code.

To calibrate the system, the WDT time-out count was collected with the device in the precision thermistors at two different temperatures (13°C and 37°C). With the time-out counts and temperatures at two different points, the temperature between these points can be calculated by simple linear regression.

For the standard equation for a straight line:

$$y = mx + b$$

where ‘y’ represents the WDT count and ‘x’ represents the temperature, we can solve for ‘m’ to give the number of time-outs per degree Celsius:

$$m = \frac{(y_2 - y_1)}{(x_2 - x_1)}$$

We can also solve for the temperature for a given WDT time-out value with the equation:

$$x_1 = x_2 - \left(\frac{(y_2 - y_1)}{m}\right)$$

As an example, say that 3208 WDT time-outs were counted at 13°C, and 3740 were counted at 37°C. In this case, the slope is:

$$m = \frac{3740 - 3208}{37 - 13}$$
$$= 22.17$$

For a temperature with 3300 time-outs, we use the higher known temperature and its count as x_2 and y_2, and solve for x_1 to get:

$$x_1 = \left(37 - \left(\frac{3740 - 3300}{22.17}\right)\right)$$
$$= 17.2$$

which rounds off to 17°C.

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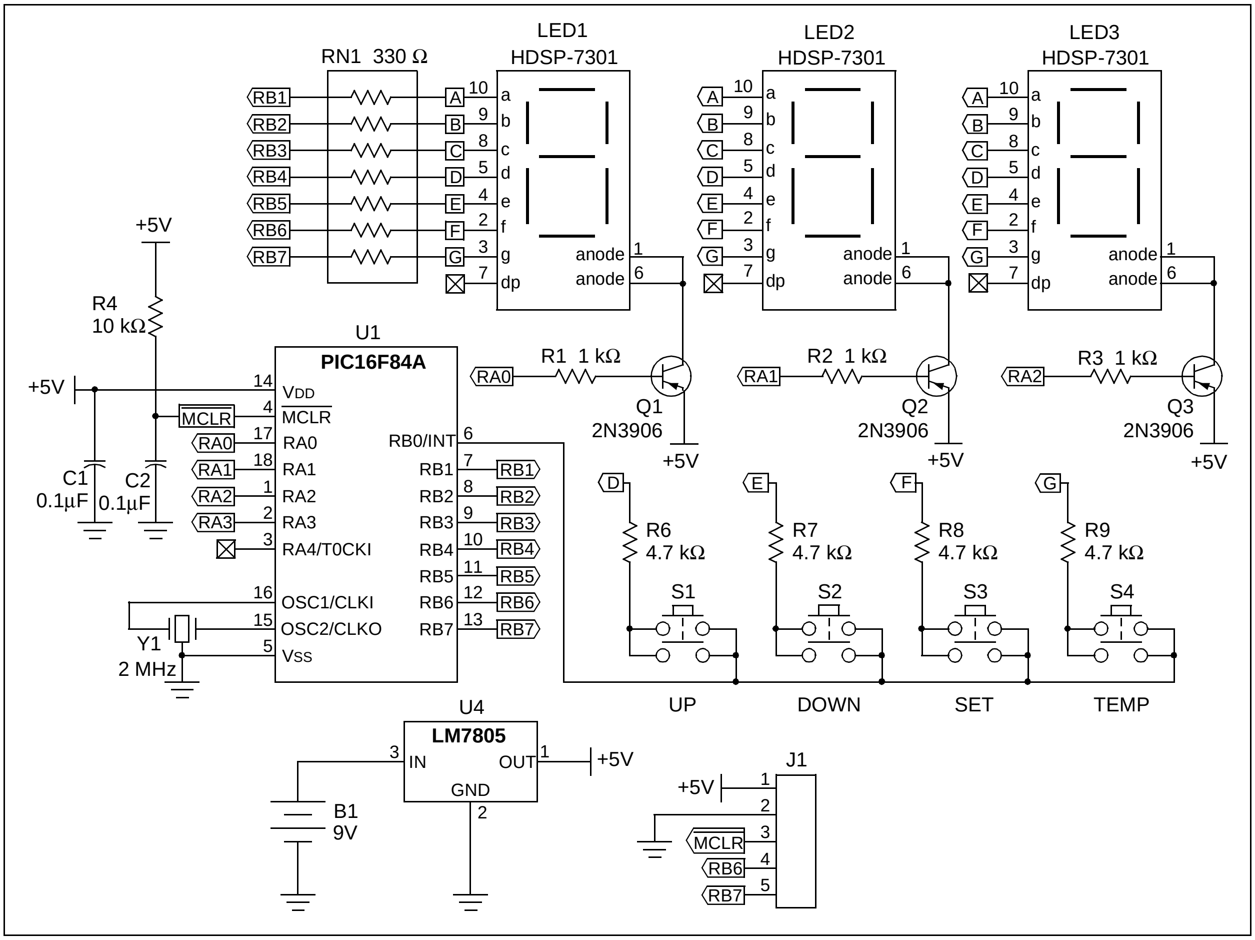
DESCRIPTION OF THE CIRCUIT

The circuit hardware (schematic shown in Figure 4) is built around a PIC16F84A microcontroller, three seven-segment LEDs to display temperature, and assorted support components. The common anode of each LCD is connected to PORTA<2:0> through PNP transistors, which are used to source the current for each digit. The entire device operates on a single 9V battery.

Four control keys (SET, TEMP, UP and DOWN) are provided to display and calibrate the temperature. The keys are connected to PORTB <7:4> of the microcontroller. Because these four pins (RB7:RB4) have an interrupt-on-change feature, pressing any of the keys can wake-up the device from SLEEP.

The PIC16F84A is normally in SLEEP mode, consuming very little operating current. If any key is pressed, it ‘wakes up’ from SLEEP and updates the WDT count, and checks for additional key presses. If there are none, it returns to SLEEP mode. In such applications, putting the controller into SLEEP mode during inactive states can greatly extend battery life.

FIGURE 4: WDT THERMOMETER SCHEMATIC



MODES OF OPERATION

The WDT Thermometer has three distinct operating modes.

SLEEP Mode: This is the default mode the system starts in when power is applied, and when it is not in the other modes. There is no display or other sign of activity.

Display Mode: When the TEMP key is pressed, the system wakes up and the LEDs show the temperature in degrees Centigrade. If the TEMP key is not pressed again within 5 seconds, the system will return to SLEEP mode.

It is important to note that the system will not automatically update the display with temperature changes that occur while it is in Display mode. To update the display with the current temperature, it is necessary to press TEMP again, after the system has returned to SLEEP mode.

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Calibration Mode: This mode creates a set of new calibration values, in addition to those present in the firmware. To do this, it is necessary to place the device in an environment where the temperature is known, such as a precision temperature forcing system.

> **Note:** Before setting the temperature, the system should be allowed to equilibrate at a particular temperature for at least 5 to 10 minutes, to get the proper WDT counts for high and low temperatures; otherwise, a correct calibration will not be possible.

To calibrate the device:

1. Place the system in the temperature forcing system at the higher of the two calibration temperatures, and wait 5 minutes for the temperature to stabilize.
2. Press and hold the SET key while applying power to the system. The display will alternately flash ‘HI’ and the current high calibration temperature.
3. Press either the UP or DOWN key to increase or decrease the displayed temperature setting by one degree (within a range of 0 to 70), to match the actual temperature.
4. Press the SET key. The new high temperature calibration is stored in data EEPROM. At this point, the display will alternately flash ‘LO’ and the current low calibration temperature.
5. Change the temperature of the forcing system to the low calibration temperature. Allow 5 minutes for the temperature to stabilize.
6. Press either the UP or DOWN key to increase or decrease the displayed temperature setting by one degree (within a range of 0 to 70), to match the current temperature.
7. Press the SET key. The new low temperature calibration is stored in data EEPROM, and the firmware sets a flag (`Default`) to indicate that new calibration information is available. At this point, the system returns to SLEEP mode.
8. To return to the preprogrammed calibration at any time during this process, press the TEMP key. The unit ignores any new calibration data entered, and returns to SLEEP mode.

The system continuously checks for key presses during Calibration mode. If no key presses occur for two minutes during the high temperature calibration, or for ten minutes during the low temperature calibration, the unit returns to SLEEP mode.

ACCURACY OF THE SYSTEM

To verify the accuracy of the design, the test system was kept under a precision temperature forcing system over a range of temperatures; a thermal soak time of 5 minutes was used for each step. When calculated and actual temperatures were compared (shown in Table 2), it was found that the WDT calculated temperature was generally accurate within ±1°C.

It should be noted that these results are for a relatively small sample of systems. Results may vary across a larger sample. Accuracy may be enhanced by using a narrower range of calibration temperatures, restricted to the expected operating range of the system; this restricts measurement to a more linear part of the temperature vs. WDT count line, and allows for a more accurate calculation.

TABLE 2: CALCULATED AND ACTUAL TEMPERATURES FOR THE WDT THERMOMETER

Calculated Temperature (°C)	Actual Measured Temperature (°C)
-39	-40
-29	-30
-20	-20
-10	-10
0	0
10	10
22	20
28	30
39	40
49	50
54	55

MEMORY USAGE

The firmware for the WDT thermometer uses the following memory resources:

Program Memory: 601 bytes

Data RAM: 48 bytes

Data EEPROM: 7 bytes

The hardware design uses a total of 11 I/O pins (10 for combined I/O and one for interrupt-on-change to wake-up).

CONCLUSION

There may be situations where it is necessary to measure temperature with an absolute minimum part count. Using a PIC16F84A to both measure and interpret the temperature, provides a simple solution with a very low part count and a good degree of accuracy.

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APPENDIX A: SOFTWARE DISCUSSED IN THIS APPLICATION NOTE

Because of its overall length, a complete source file listing for the WDT thermometer is not provided. The complete source code is available as a single WinZip archive file, which may be downloaded from the Microchip corporate web site at:

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