DESIGN AND IMPLEMENTATION OF A REFLOW OVEN FOR SMD SOLDERING

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ABSTRACT

DESIGN AND IMPLEMENTATION OF A REFLOW OVEN FOR SMD SOLDERING

Reflow soldering is a process in which components that are placed onto the solder paste applied PCB, are assembled by carefully heating the assembly in order to solder the joints. The assembly may be heated by several methods but the convection reflow seems a prevailing alternative because of its effectiveness in heat transfer and insensitivity to material type or color. Hence, a cheap and industry standard conforming design and implementation of convection reflow oven by using a standard kitchen oven is aimed in this study. For process control, several control algorithms were applied and their results were compared.

ÖZET

SMD LEHİMLEME İÇİN FIRIN DİZAYNI VE UYGULAMASI

Yeniden akıştırma (reflow) ile lehimleme, elektronik baskı kartı (Printed Circuit Board) üzerine yerleştirilmiş parçaların, kartı dikkatli bir ısıtma işleminden geçirerek biraraya lehimlenmesi işlemidir. Elektronik baskı kartı, üzerindeki parçalarla birlikte muhtelif yöntemler kullanılarak ısıtılabilir; ancak konveksiyonel ısıtma, ısı iletiminde verimli olması ve ayrıca malzeme tipi ve rengine duyarsız olması nedeniyle diğerleri arasında öne çıkan bir seçenektir. Bu yüzden, bu çalışmada standart bir mutfak fırını kullanılarak ucuz ve endüstri standartlarına uyumlu bir yeniden akıştırma (reflow) fırını dizayn edilmesi ve sonrasında gerçeklenmesi amaçlandı. Süreç kontrolü için, muhtelif kontrol algoritmaları uygulandı ve elde edilen sonuçlar karşılaştırıldı.

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LIST OF SYMBOLS/ABBREVIATIONS

C	Capacitance
f_c	Cut-off frequency
N	ADC conversion result
R_0	Resistance at reference temperature
R_{gain}	Gain resistance
R_x	Resistance value of resistance x
Ref	Reference voltage
T	Temperature
T_0	Reference temperature
T_{Jx}	Temperature of junction x
T_{REF}	Reference temperature
T_{JREF}	Temperature of reference junction
V_{REF}	Reference voltage
V	Thermoelectric voltage
α	Seebeck coefficient
β	Calibration constant (characteristic temperature of material)
ACLK	Auxilary clock
ADC	Analog to digital converter
JEDEC	Joint Electron Devices Engineering Council
LED	Light emitting diode
LPF	Low pass filter
MCU	Microcontroller unit
MSL	Moisture sensitivity level
NBS	National Bureau of Standards
PCB	Printed Circuit Board
PID	Proportional Integral Derivative
PWM	Pulse width modulation
RTD	Resistance temperature detector

SAC	Sn/Ag/Cu
SMCLK	Submaster clock
SMD	Surface mounted device
TI	Texas Instruments

1. INTRODUCTION

Reflow soldering is a process in which components that are placed onto the solder paste applied PCB, are assembled together by carefully heating the assembly in order to solder the joints. The assembly may be heated by several methods. Some common reflow methods are infrared reflow, vapor phase reflow, forced convection reflow and in-line conduction reflow [1]. Convection reflow is effective in heat transfer and it is not sensitive to material type or color. So it is the prevailing reflow method [1]. This study focuses on reflow soldering by using a carefully controlled oven. Temperature pattern for reflow soldering according to IPC/JEDEC standard is given below.

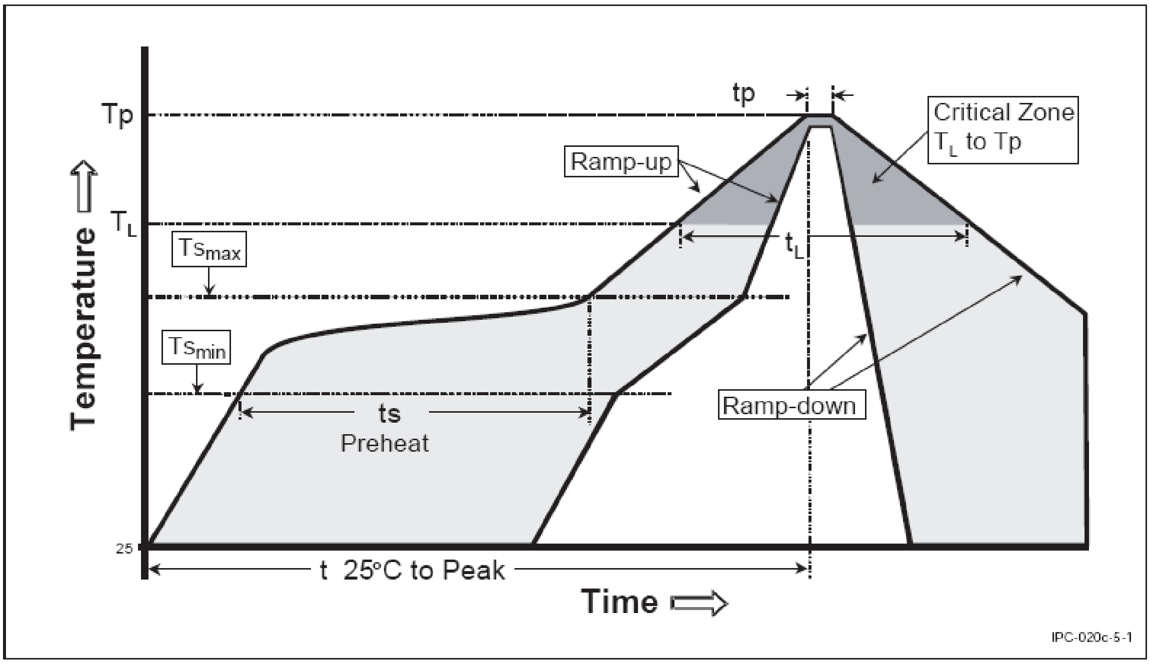


Figure 1.1 Classification Reflow Profile [2]

Table 1.1 Classification Reflow Profiles [2]

Profile Feature	Sn-Pb Eutectic Assembly	Pb-Free Assembly
Average Ramp-Up Rate (Ts_{max} to Tp)	3 °C/second max.	3° C/second max.
Preheat – Temperature Min (Ts_{min}) – Temperature Max (Ts_{max}) – Time (ts_{min} to ts_{max})	 100 °C 150 °C 60-120 seconds	 150 °C 200 °C 60-180 seconds
Time maintained above: – Temperature (T_L) – Time (t_L)	 183 °C 60-150 seconds	 217 °C 60-150 seconds
Peak/Classification Temperature (Tp)	See Table 4.1	See Table 4.2
Time within 5 °C of actual Peak Temperature (tp)	10-30 seconds	20-40 seconds
Ramp-Down Rate	6 °C/second max.	6 °C/second max.
Time 25 °C to Peak Temperature	6 minutes max.	8 minutes max.

Note 1: All temperatures refer to topside of the package, measured on the package body surface.

Table 4-1 SnPb Eutectic Process – Package Peak Reflow Temperatures

Package Thickness	Volume mm^3 <350	Volume mm^3 ≥ 350
<2.5 mm	240 +0/-5 °C	225 +0/-5 °C
≥ 2.5 mm	225 +0/-5 °C	225 +0/-5 °C

Table 4-2 Pb-free Process – Package Classification Reflow Temperatures

Package Thickness	Volume mm^3 <350	Volume mm^3 350 - 2000	Volume mm^3 >2000
<1.6 mm	260 +0 °C *	260 +0 °C *	260 +0 °C *
1.6 mm - 2.5 mm	260 +0 °C *	250 +0 °C *	245 +0 °C *
≥2.5 mm	250 +0 °C *	245 +0 °C *	245 +0 °C *

* Tolerance: The device manufacturer/supplier **shall** assure process compatibility up to and including the stated classification temperature (this means Peak reflow temperature +0 °C. For example 260 °C+0 °C) at the rated MSL level.

Note 1: The profiling tolerance is + 0 °C, -X °C (based on machine variation capability) whatever is required to control the profile process but at no time will it exceed - 5 °C. The producer assures process compatibility at the peak reflow profile temperatures defined in Table 4.2.
Note 2: Package volume excludes external terminals (balls, bumps, lands, leads) and/or nonintegral heat sinks.
Note 3: The maximum component temperature reached during reflow depends on package thickness and volume. The use of convection reflow processes reduces the thermal gradients between packages. However, thermal gradients due to differences in thermal mass of SMD packages may still exist.
Note 4: Components intended for use in a "lead-free" assembly process **shall** be evaluated using the "lead free" classification temperatures and profiles defined in Tables 4-1, 4.2 and 5-2 whether or not lead free.

1.1 Moisture sensitivity level and storage

When a moist package is exposed to a reflow temperature profile, the moisture inside the package is likely to turn into steam, expanding in a very short time. This can cause delamination and pop corn effect. Delamination is damage to inside of the package, and pop corn effect is the cracking of the semiconductor package body. The package characteristics and the temperature during the reflow soldering are the factors that a package's sensitivity to moisture or Moisture Sensitivity Level (MSL) depends on.

Standardized tests can be used to determine the MSL of semiconductor packages. In these tests, first, the packages are moisturized to a certain level and then they are exposed to a temperature profile. According to studies, during reflow, small and thin packages rise to higher temperatures than larger ones. Thus, it is better to classify small and thin packages at higher reflow temperatures.

Temperature of packages is always measured on the package body surface which is facing up. This orientation is described as live-bug orientation in the IPC/JEDEC standards.

After the standardized tests, according to the damage, an MSL of 1, meaning that it is not sensitive to moisture, to 6 (very sensitive to moisture) is added to the semiconductor package. On the shipping box, every product has this MSL on its packing label. Under SnPb and Pb-free soldering conditions, each package is evaluated at two temperatures. An example of a packing label is given below.

Figure 1.2 Example of MSL information on packing label [3]

An MSL is equivalent to a certain out-of-bag time (or floor life). When semiconductor packages are taken out from their sealed dry-bags and not soldered within their out-of-bag time, it is necessary to bake them before reflow so that any moisture that might have passed through the package can be removed. It is always necessary to respect MSLs and temperatures on the packing labels. Also, this may have a meaning that semiconductor packages with a critical MSL are likely not to stay on the placement machine between assembly runs. Moreover, partly-assembled boards should not be kept longer than shown by the MSL level between two reflow steps.

Table below shows the semiconductor package floor life as a function of the MSL.

Table 1.2 Floor life as a function of MSL [3]

MSL	Floor life	
	Time	Conditions
1	unlimited	≤ 30 °C/85 % RH
2	1 year	≤ 30 °C/60 % RH
2a	4 weeks	≤ 30 °C/60 % RH
3	168 hours	≤ 30 °C/60 % RH
4	72 hours	≤ 30 °C/60 % RH
5	48 hours	≤ 30 °C/60 % RH
5a	24 hours	≤ 30 °C/60 % RH
6	6 hours	≤ 30 °C/60 % RH

1.2 Surface Mounting Process

1.2.1 Solder Paste Printing

For a solder paste printing, a stencil aperture is required to be entirely filled with paste. When the board is released from the stencil, the solder paste is likely to cling to the board in order to have all the paste be released from the stencil and have a proper solder paste left-over on the board. Under the best circumstances, the volumes of solder paste on the board and the stencil aperture should be equalized.

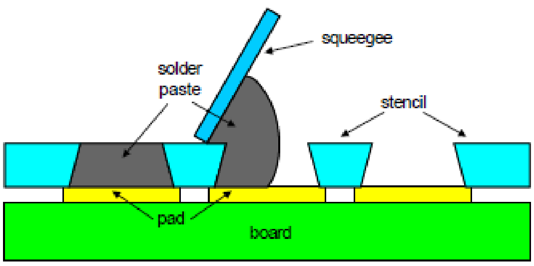


Figure 1.3 Stencil printing [3]

1.2.2 Package Placement

The required placement accuracy of a package is determined by several factors including package size and the package type.

For package placement, usually two different types of machines are used. If placement accuracy is the main concern, then slower but more accurate machines should be used. On the other hand, if the main concern is the speed and if the high placement accuracy is not necessary, then fast component mounters or chip shooters can be used.

Another important criterion for some packages may also be the placement force. Theoretically, a semiconductor package is pushed down into the solder paste up to the time that a single layer of solder paste powder particles are left- the remaining solder paste is pushed aside. As a consequence, bridges with the remaining of adjoining solder paste may appear [3].

1.2.3 Reflow soldering

In the process of reflow soldering, the most significant step is the reflow itself. Solder paste melts and, as a result, soldered joints are created by having the boards passed through an oven, of which temperature profile alters in time.

According to application note “Surface mount reflow soldering description” by NXP semiconductors, a temperature profile is composed of three main stages:

- Preheat: the assembly is heated up to a temperature that is lower than the melting point of the solder alloy. In the book “Reflow Soldering Process and Troubleshooting”, this stage is referred as two separate stages: preheat stage and soak stage. A typical temperature range for soak stage is referred as between 150°C and 175°C. In this stage, solvents are evaporated and the flux is activated [1]. Preheat stage is referred as the stage up to soaking stage.
- Reflow: the board is heated to a temperature that is above the melting point of the solder alloy but on the other hand, below the temperature at which the components

are damaged. A minimum peak temperature of 200°C is recommended for the minimum acceptable joint quality. However, 210°C is suggested whenever possible [1].

- Cooling down: the board is rapidly cooled down in order to freeze the soldered joints. Components should be assembled to the board before the assembly exits the soldering oven.

The maximum allowed temperature for a component during reflow soldering has upper and lower limits:

- Lower limit: Lower limit of peak temperature is always measured at the solder joint. Lower limit must be well above the melting point of solder alloy to allow reliable solder joints and determined by the solder paste characteristics.
- Upper limit: Upper limit of the peak temperature is always measured at the top of the component package. Upper limit of the peak temperature must be lower than:
  - MSL test temperature
  - The temperature at which board will be damaged [3]

Recommended minimum peak temperatures for SnPb and SAC alloys are roughly displayed in table given below. Nevertheless, it is recommended to verify these values with solder paste supplier's values.

Table 1.3 Typical solder paste characteristics [3]

Solder	Melting temperature	Minimum peak reflow temperature
SAC	217 °C	235 °C
SnPb	183 °C	215 °C

When a board is faced with the profile temperature, temperature of certain areas increases more than others. That is to say; there become hot regions and cold regions on a board. Cold regions are likely to be located in parts of the board which densely includes large components. These large components absorb a lot of heat, and as a result temperature of these regions becomes colder than others. On the other hand, areas made up of few or small components and with little copper include hot regions. Lastly, the location of hot and cold regions is also likely to be affected by the board orientation in the oven.

The temperature of the hottest region on a board must not be higher than the maximum peak temperature. In a similar manner, the temperature of the coldest region must not be lower than the minimum peak temperature.

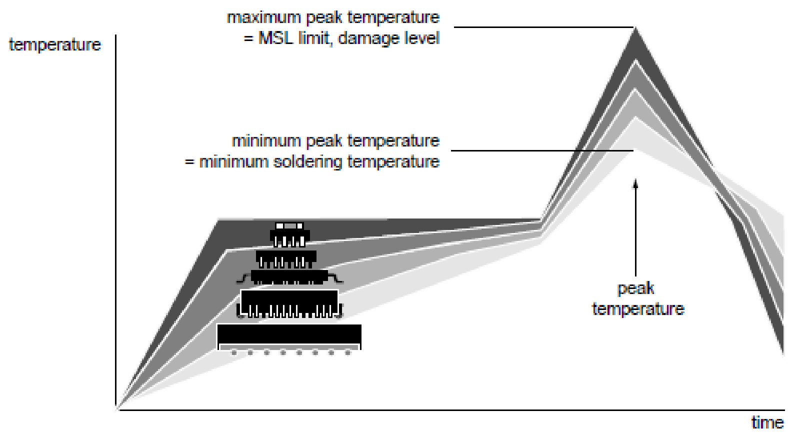


Figure 1.4 Temperature profiles for large and small components [3]

As it can be seen in the figure above, cold regions are represented by the grey band with the large components and hot regions are represented by the dark bands, which are at the top, with the small components. Firstly, in both of the cases, temperature which is measured at the top of the component body is represented in the graph. In the first stage, which is the preheat stage; temperature of the hot regions will speedily increase to a temperature which is not higher than the melting point of the solder alloy. They are likely to preserve this temperature for some time. However, it is better not to keep solder paste at an intermediate temperature for a long time as their activator may dry up. Thus, for solder paste, a fast temperature profile is chosen. The temperature of cold regions will increase slowly.

It is better to plan oven settings in order to have both cold and hot regions reached almost the same temperature at the end of the first stage. The reflow zone is the second stage in the reflow profile. The solder melts and soldered joints are formed in this stage. The lowest peak temperature, which all solder joints that cold and hot regions include, must reach is determined by the solder alloy. However, no region can exceed the highest peak temperature as it may bring about component or board damage. The hot regions will reach a higher peak temperature than the cold ones even though they are almost at the same temperature at the beginning.

However, both the hot and cold regions must stay in the allowed peak temperature range. For this to happen, fine-tuning temperature settings of the oven and if applicable conveyor belt speeds may be needed. On certain occasions, in order to restrain the temperature difference between the cold and hot regions, it may be better to optimize the board layout [3].

During reflow soldering, it is never recommended for peak temperature to go beyond the temperature which the components and the board are likely to be impaired at. The moisture sensitivity of the components determines the highest peak temperature for components to some degree. For reflow soldering by using SnPb solder, the maximum temperature should not be lower than 215°C. On the other hand, when soldering with SAC, the maximum temperature should not be lower 235°C, however; it should not go beyond 260°C [3]. Pay attention to that a smaller process window for Pb-free soldering is implied by this most of the time, so a tighter process control is needed.

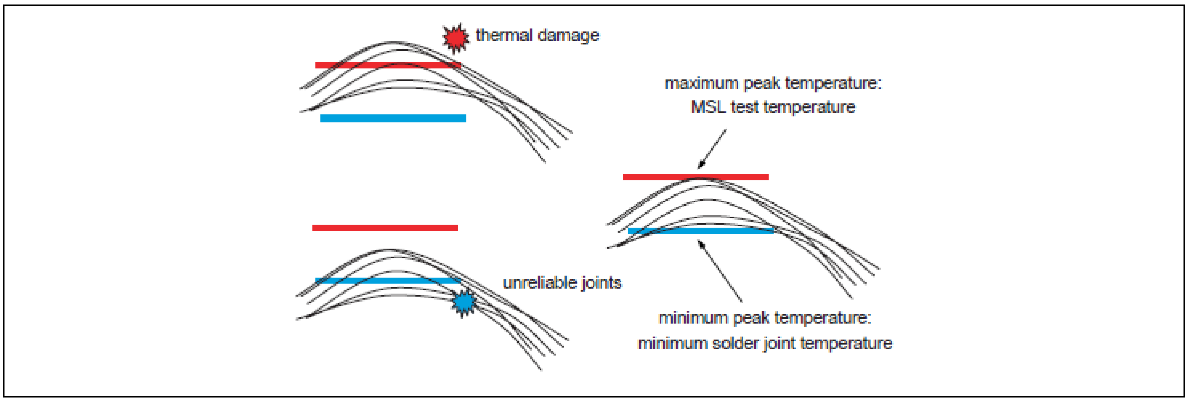


Figure 1.5 Hot and cold region temperatures [3]

In the figure above, the thin lines show the real temperature profiles of several distinct temperature regions on a board. The coldest and hottest regions are shown by the lowest and highest thin lines, respectively. The blue line is the sign of the lowest peak temperature and the red line shows the highest peak temperature. At the top of the left side are represented some regions on the board which are exposed to too high temperatures, proceeding MSL qualification conditions. At the bottom of the left side, the figure shows some regions on the board which go under too low temperatures, causing unreliable joints. The right side of the figure shows all the regions on the board which have peak temperatures shifting between the upper and lower limits.

It is possible to carry out reflow in air or in nitrogen. Generally, it is not necessary to do it in nitrogen; air is likely to be preferred as an alternative due to the lower cost. Also, convection reflow ovens, some of which have extra infrared heating, are one of the alternatives where reflow can be carried out. Moreover, in order to reduce temperature differences on a board, vapor phase reflow soldering can be used [3]. In vapor phase reflow soldering, overheating or cold joints will not be observed as long as a sufficient dwell time above liquidous temperature is provided at reflow phase. No tedious profiling work is needed. Air is expelled by the inert fluorocarbon vapor, so soldering process is realized under an oxygen-free environment [1].

Most of the time, application boards are populated with components in both sides of the board, which means that the board is likely to need to go through a soldering process for two times. Thus, it is of importance to take the following details into consideration before a double-sided reflow process in order to block the impairment or breakdown of the components.

- Components should be able to withstand more than one reflow cycles. MSL classified components are guaranteed to withstand three reflow cycles.
- Time between reflow cycles should not exceed the floor life of the component with the shortest floor life. If so, the board must be dried before the second reflow. If the board is kept in a special condition such as in a nitrogen cabinet, then the drying step can be eliminated.
- Heavy components mounted at the first reflow process can be glued to the board before the second reflow process, because they are likely to drop from the board during the second reflow process due to their weight.

2. DESIGN

In order to design a reflow oven by using a standard kitchen oven, temperature inside the oven must be carefully monitored with temperature sensors. Analog values generated by temperature sensors must be converted into digital values so that a microcontroller can process this information. An analog to digital converter is required in order to convert analog values generated by temperature sensors into digital values so that a microcontroller can process them. Microcontroller uses this digital representation of analog values generated by temperature sensor for calculating temperature according to transfer function of the temperature sensor.

Once the temperature is calculated on the microcontroller, it is compared with the desired temperature of the oven. Based on the control algorithm used, microcontroller decides the control action to perform. This action may be simply turning on or off the electrical power to the heater of the oven, or a more complex method which determines the amount of electrical power delivered to the heater.

Controlling a high voltage alternating current (AC) device such as an oven, with a digital microcontroller requires a special switching circuit. Interfacing a microcontroller with a high voltage direct current (DC) device is relatively straightforward: A power transistor can handle such a switching requirement. But switching a high voltage alternating current (AC) device requires more complex solutions.

Also it is important to isolate control part of the circuit from the rest. High voltage at the oven side can damage electrically sensitive low voltage components at the control part. Isolation also provides electrical safety for operators who may use control part of the circuit as an interface.

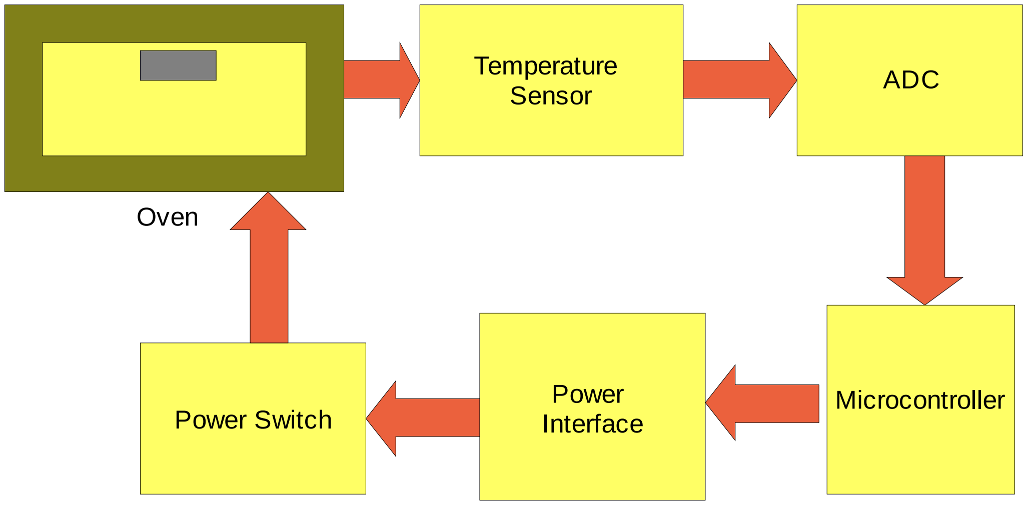


Figure 2.1 High level design

2.1. Temperature Sensors

Temperature sensors appear in a wide range of devices that need monitoring and control of temperature. These sensors use various physical phenomena that are related to temperature such as electrical resistance, voltage difference and pressure etc. to indirectly measure temperature. Some common temperature sensors are introduced in the following subsections [4].

2.1.1. Liquid-in-Glass Thermometer

These are very thin glass pipes, closed at the two ends, and one end has a small bulb filled with liquid which is usually alcohol or mercury. Temperature is measured according to thermal expansion of liquid. They are non-electric sensors.

2.1.2. Bimetallic Strip

Bimetallic strip includes two or more different layers of metals which have different coefficient of thermal expansion. Since metals have different thermal expansion coefficients, one of the metals expands or shrinks more than the other along with the temperature change. As a result, a deflection in the shape of the metallic strip occurs. Deflection is a function of coefficients of thermal expansion that two metals have and temperature. They are usually used in thermostats where deflection makes or breaks a contact with electrical components in order to turn on or off a heating or cooling system.

2.1.3. Electrical Resistance Thermometer

A resistance temperature device (RTD) has a resistance that rises with temperature. Temperature-resistance relationship is approximated by the function:

$$R = R_0[1 + \alpha(T - T_0)]$$

Where:

T_0 is a reference temperature

R_0 is resistance at the reference temperature

α is calibration constant [4].

A thermistor is a semiconductor device resistance of which dramatically changes with temperature. Its resistance is expressed by the equation:

$$R = R_0 \, e^{[\beta\left(\frac{1}{T} - \frac{1}{T_o}\right)]}$$

Where:

T_0 is a reference temperature

R_0 is resistance at the reference temperature

β is calibration constant (characteristic temperature of material) [4].

2.1.4. Thermocouple

Thermocouples depend on a principle called Seebeck effect. Alciatore and Histand define Seebeck effect as: “Two dissimilar metals in contact form a thermoelectric junction that produces a voltage proportional to the temperature of the junction.” [4]. Thermoelectric junctions appear in pairs, bringing about the term thermocouple [4]. The figure below shows a thermoelectric circuit with two junctions.

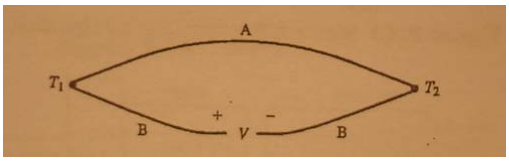


Figure 2.2 Thermocouple circuit [4]

Physical properties of both metals forming the thermoelectric junction (metal A and metal B in this case) and temperature difference between junctions are the things that thermocouple voltage V is dependent on. If the temperatures at the junctions are T_1 and T_2 respectively, then the thermocouple voltage V becomes:

$$V = \alpha(T_1 - T_2)$$

Where α is called Seebeck coefficient. Voltage-temperature difference does not, in fact, have a linear relationship. However, for a small temperature range, it can be assumed to be linear [4].

Secondary thermoelectric effects are called the Peltier and Thompson effects. Peltier and Thompson effects are related with current flow in the thermocouple circuit. However, these are likely to neglect when compared to Seebeck effect in measurement systems since the current flow is small in a termocouple circuit [4].

The five fundamental laws of thermocouple behavior that are important to understand are explained below:

- Law of leadwire temperatures: In the figure below, thermoelectric voltage, V, is depend only on T_1 and T_2, but not on T_3, T_4 or T_5. Therefore, it is not necessary to shield the leadwires from environmental conditions.

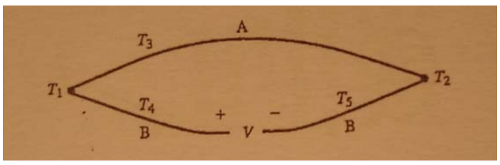


Figure 2.3 Law of leadwire temperatures [4]

- Law of intermediate leadwire metals: In the figure below, a third metal -C- is added to the circuit which forms two additional junctions. If $T_3 = T_4$ then, addition of this third metal has no effect on thermoelectric voltage, V. As a result, a measurement device which adds two additional junctions can be connected to the thermocouple without changing the resulting voltage since its input pins would be nearly at the same temperature.

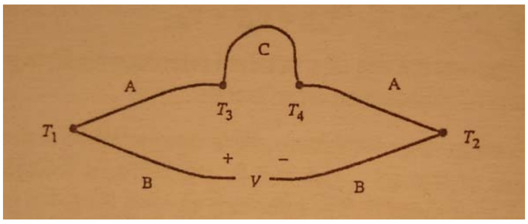


Figure 2.4 Law of intermediate leadwire metals [4]

- Law of intermediate junction metals: In the figure below, if $T_1 = T_3$ then, resulting voltage does not change.

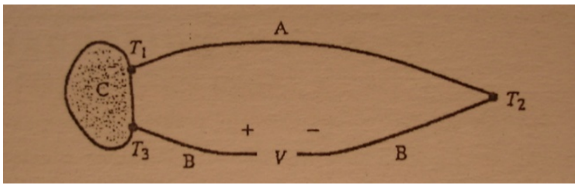


Figure 2.5 Law of intermediate junction metals [4]

- Law of intermediate temperatures: In the figure below, $V_{1/3} = V_{1/2} + V_{1/3}$

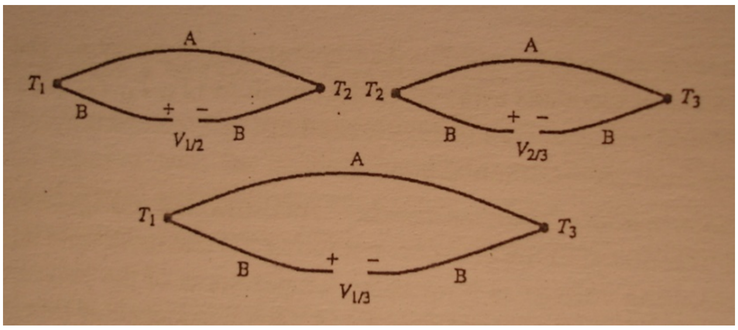


Figure 2.6 Law of intermediate temperatures [4]

- Law of intermediate metals: Thermocouple voltage between A and B is equal to the sum of thermocouple voltages of A and B relative to a third metal C. In the figure below, $V_{A/B} = V_{A/C} + V_{B/C}$.

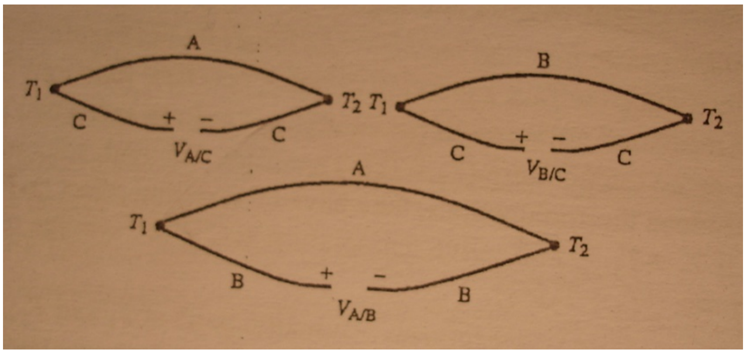


Figure 2.7 Law of intermediate metals [4]

A standard configuration for thermocouple measurement is as below. One of the junctions is used to provide a reference temperature. One way to do this is to put the reference junction into an ice-water mixture which is nearly at 0 °C. Since terminals of the thermocouple would be nearly at the same temperature at the measuring device end, there would be no additional thermocouple effect at these junctions, which is a result of the law of intermediate leadwire metals.

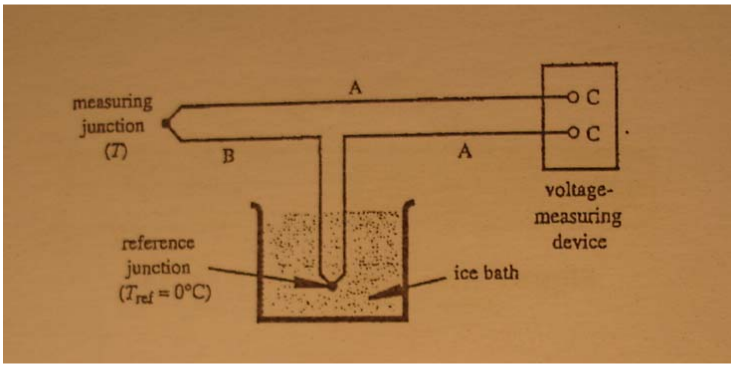


Figure 2.8 Standard thermocouple configuration [4]

Using a semiconductor reference is an alternative to ice bath reference. A semiconductor reference electrically establishes the reference temperature which is found on principles of solid state physics. Generally, these reference devices are added to thermocouples to exterminate the need for an external reference temperature.

The letters E, J, K, R, S and T indicate the six most commonly used thermocouple metal pairs [4]. The 0 °C reference junction calibration, which is nonlinear for each of the types, can be approximated with a polynomial. The table below displays the metals in the junction pair, the thermoelectric polarity, the commonly used color code, operating range, the accuracy and the polynomial order and coefficients for each type. The general form for the polynomial using the coefficients in the table is:

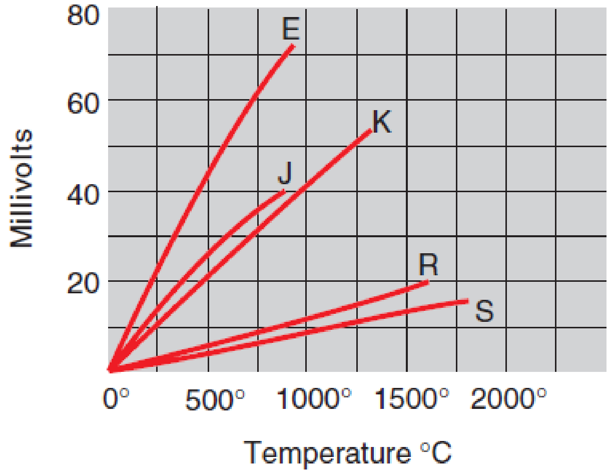
$$T = \sum_{i=0}^{9} \mathrm{c_i}\, \mathrm{V^i} = \mathrm{c_0 V^0} + \ldots + \mathrm{c_9 V^9}$$

Where V is the thermoelectric voltage measured in volts and T is the measuring junction temperature in Celsius degree when a 0°C reference junction is assumed [4].

Even though a ninth-order polynomial is used to represent the temperature-voltage relation, it is actually close to linear as predicted by the Seebeck effect [4].

Table 2.1 Thermocouple data [5]

	TYPE E	TYPE J	TYPE K	TYPE R	TYPE S	TYPE T
	Nickel-10% Chromium(+) Versus Constantan(-)	Iron(+) Versus Constantan(-)	Nickel-10% Chromium(+) Versus Nickel-5%(-) (Aluminum Silicon)	Platinum-13% Rhodium(+) Versus Platinum(-)	Platinum-10% Rhodium(+) Versus Platinum(-)	Copper(+) Versus Constantan(-)
	-100°C to 1000°C ± 0.5°C 9th order	0°C to 760°C ± 0.1°C 5th order	0°C to 1370°C ± 0.7°C 8th order	0°C to 1000°C ± 0.5°C 8th order	0°C to 1750°C ± 1°C 9th order	-160°C to 400°C ±0.5°C 7th order
a_0	0.104967248	-0.048868252	0.226584602	0.263632917	0.927763167	0.100860910
a_1	17189.45282	19873.14503	24152.10900	179075.491	169526.5150	25727.94369
a_2	-282639. 0850	-218614.5353	67233.4248	-48840341.37	-31568363.94	-767345.8295
a_3	12695339.5	11569199.78	2210340.682	1.90002E + 10	8990730663	78025595.81
a_4	-448703084.6	-264917531.4	-860963914.9	-4.82704E + 12	-1.63565E + 12	-9247486589
a_5	1.10866E + 10	2018441314	4.83506E + 10	7.62091E + 14	1.88027E + 14	6.97688E + 11
a_6	-1. 76807E + 11		-1. 18452E + 12	-7.20026E + 16	-1.37241E + 16	-2.66192E + 13
a_7	1.71842E + 12		1.38690E + 13	3.71496E + 18	6.17501E + 17	3.94078E + 14
a_8	-9.19278E + 12		-6.33708E + 13	-8.03104E + 19	-1.56105E + 19	
a_9	2.06132E + 13				1.69535E + 20	



Type	Metals (+ vs. −)
E	Chromel vs. Constantan
J	Iron vs. Constantan
K	Chromel vs. Alumel
R	Platinum vs. Platinum 13% Rhodium
S	Platinum vs. Platinum 10% Rhodium
T	Copper vs. Constantan

Figure 2.9 Thermocouple temperature vs. voltage graph [5]

Due to its relatively high accuracy, relatively good sensitivity (0.054mV/°C), and availability in market, type J (Fe-Const) thermocouples are used in this study.

2.1.4.1. Measuring Thermocouple Voltage. Connecting a thermocouple to a measuring device creates additional thermoelectric junctions. The figure below is an example of a voltmeter connected across a copper-constantan (Type T) thermocouple and the voltage output.

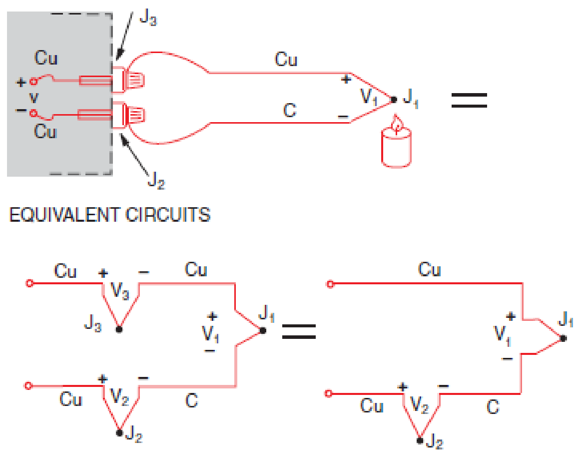


Figure 2.10 Measuring junction voltage with a measuring device [5]

The voltmeter is wanted to read only V_1, but when the voltmeter is connected to measure the output of junction J_1, two more thermoelectric junctions, J_2 and J_3, are created.

J_3, which is a copper-to-copper junction, does not create any voltage difference which means V_3 is zero. However, J_2, a copper-to-constantan junction, will create a voltage difference unlike J_1. The resulting circuit is a standard copper-constantan thermocouple and the output voltage will depend on the temperature difference between junctions J_1 and J_2. In other words, temperature of J_1 can be calculated only if the temperature of junction J_2 is known.

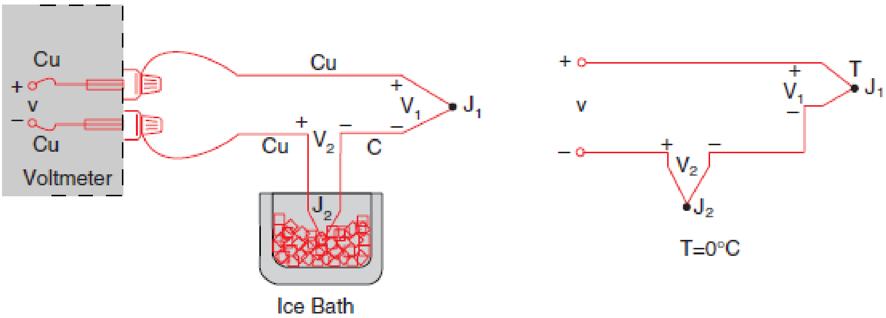


Figure 2.11 External Reference Junction [5]

If the junction J_2 is put into a water ice bath, its temperature is known to be at nearly 0°C. Now, junction J_2 is called as reference junction and the output voltage read by the voltmeter is:

$$V = (V_1 - V_2) \approx \alpha(T_{J1} - T_{J2})$$

where T_{J1} and T_{J2} are temperature in °C.

Since the temperature of junction J_2 is 0°C, then voltage output read by the voltmeter becomes:

$$V = V_1 - V_2 = \alpha\,(T_{J1} - 0)$$
$$V = \alpha T_{J1}$$

As the ice point temperature is likely to be controlled precisely, this is a very accurate method. Since the National Bureau of Standards (NBS) uses the ice point as the basic reference point for their thermocouple tables, it is enough to have a look at these tables and turn voltage V into temperature T_{J1}.

When an iron-constantan (Type J) thermocouple is used in place of the copper-constantan, an additional thermoelectric junction appears between the thermocouple and measuring device as you can see in the figure below as junction J_3.

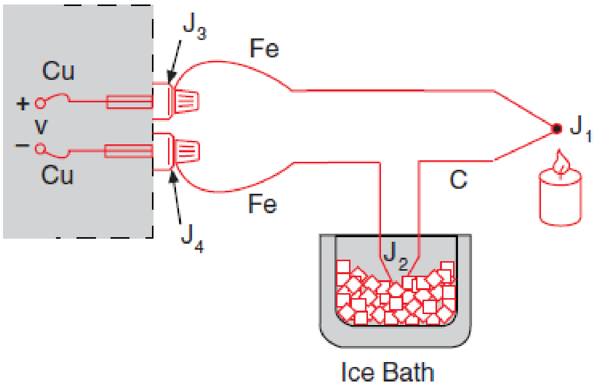


Figure 2.12 Iron-Constantan couple [5]

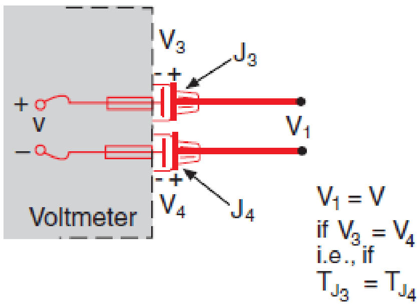


Figure 2.13 Junction voltage cancellation [5]

There is likely to be an error when both of the measuring device terminals do not have the same temperature. If a more accurate measurement is wanted, the leads of the copper voltmeter should be extended so that the copper-to-iron junctions are formed on an isothermal block.

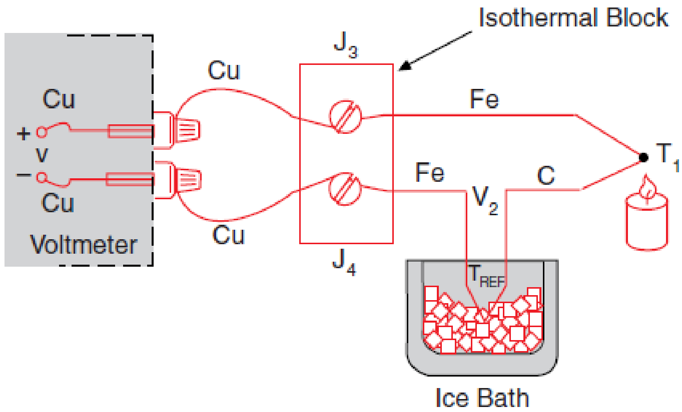


Figure 2.14 Removing junctions from measuring device terminals [5]

Although the isothermal block is an electrical insulator, it is a good heat conductor and of use to keep J_3 and J_4 at the same temperature. As the two Cu-Fe junctions cancel voltages of each others, the block temperature is not of importance. We still have:

$$V = \alpha\,(T_1 - T_{REF})$$

If the ice bath is replaced with another isothermal block, figure below is obtained.

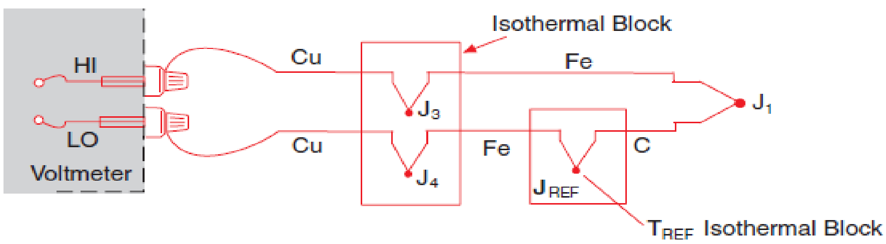


Figure 2.15 Eliminating the ice bath [5]

In the figure above, only the water ice bath is replaced with an isothermal block. Thus, output voltage read by the measuring device does not change.

Now, assume that the temperature of both isothermal blocks is the same. Then, all the three thermoelectric junctions can be combined on the same isothermal block as in the figure below.

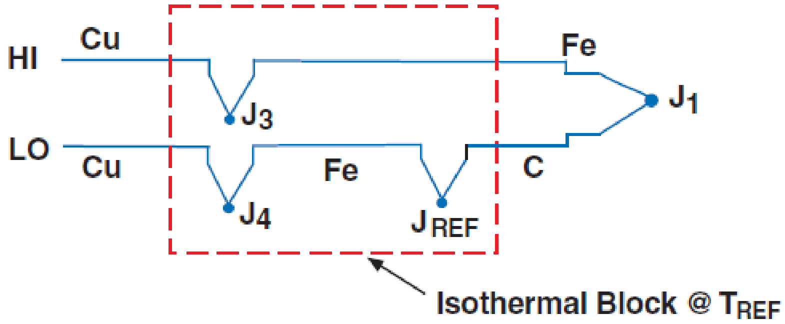


Figure 2.16 Joining the isothermal blocks [5]

The output voltage read by the measuring device has not been changed.

$$V = \alpha\,(T_{J1} - T_{JREF})$$

In order to remove the extra junction, the law of intermediate metals is called upon. According to this law [5], when a third metal (in this case, iron) is inserted between the two different metals of a thermocouple junction, no effect will be observed on the output voltage on condition that the two junctions which are formed by the additional metal have the same temperature.

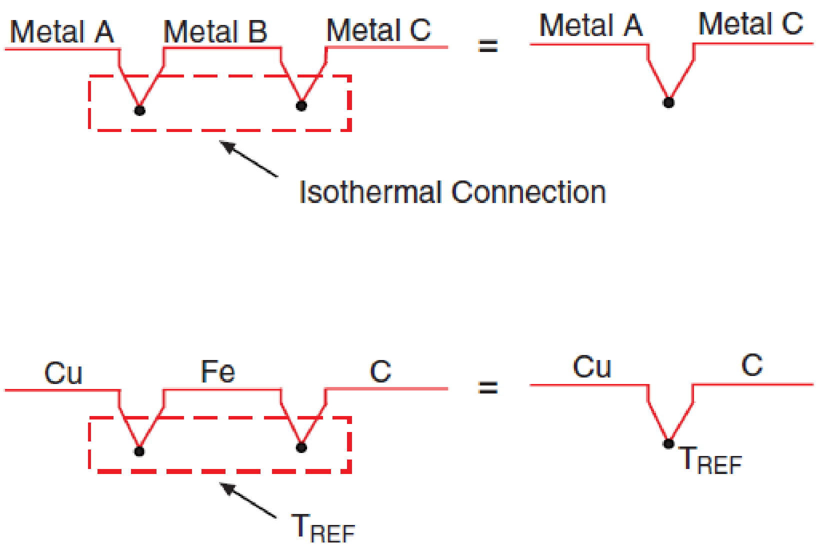


Figure 2.17 Law of intermediate metals [5]

Resulting circuit is shown in the figure below.

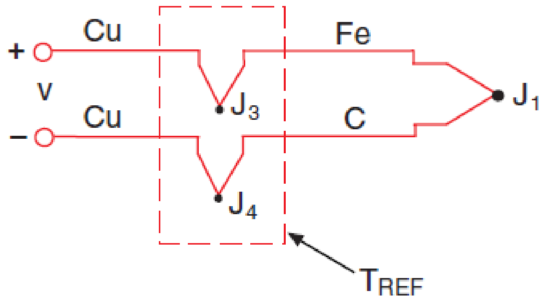


Figure 2.18 Equivalent Circuit [5]

Output voltage read by the voltmeter is still:

$$V = \alpha\ (T_{J1} - T_{REF})$$

where α is the Seebeck coefficient for an iron-constantan thermocouple.

The next step is to measure the temperature of the isothermal block and use this information to calculate the temperature of junction J_1.

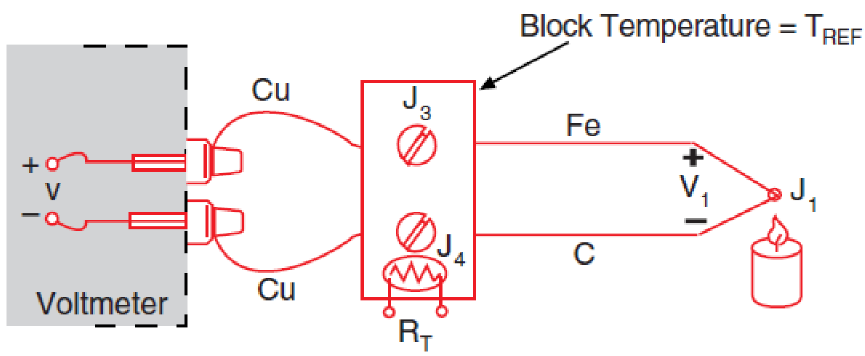


Figure 2.19 External reference junction - no ice bath [5]

For measuring isothermal block temperature any temperature sensor such as an RTD, a thermistor or an integrated circuit sensor which has a characteristic in proportion to absolute temperature can be used. In the figure above, a thermistor is used as an example. A thermistor is a semiconductor device and its resistance exponentially changes with temperature. According to Omega technical notes “Using Thermocouples”, with the help of a digital multimeter under computer control, temperature of junction J_1 can be calculated as follow:

- Measure indirect sensor output, calculate temperature of the isothermal block so the cold junction, and find corresponding reference junction voltage at that temperature.
- Measure thermocouple output voltage and then add calculated reference junction voltage. Use this final value to calculate temperature at junction J_1.

This method is called as Software compensation as it uses the software of a computer to make up for the effect of the reference junction.

Although temperature sensors like thermistors or RTDs can measure absolute temperature, temperature range that can be measured by these devices is much more limited than temperature range that can be measured by thermocouples [5]. So using only a thermistor or RTD may not be enough.

Thermocouples are more durable than thermistors as they are usually welded to a metal part. By soldering or welding, they can be produced easily and immediately. Briefly, thermocouples are the most versatile ones among the temperature transducers [5].

To measure temperatures with thermocouples, software compensation is the most versatile technique [5].The computer carries out all the conversions. One drawback is that a little amount of extra time is required to measure the reference junction temperature. Hardware compensation can be used for the highest speed.

In hardware compensation, a battery is added to the thermocouple circuit in order to cancel the offset voltage of the reference junction. Despite of its compensation speed, main disadvantage of hardware compensation is the unique hardware circuit needed for each type of thermocouples.

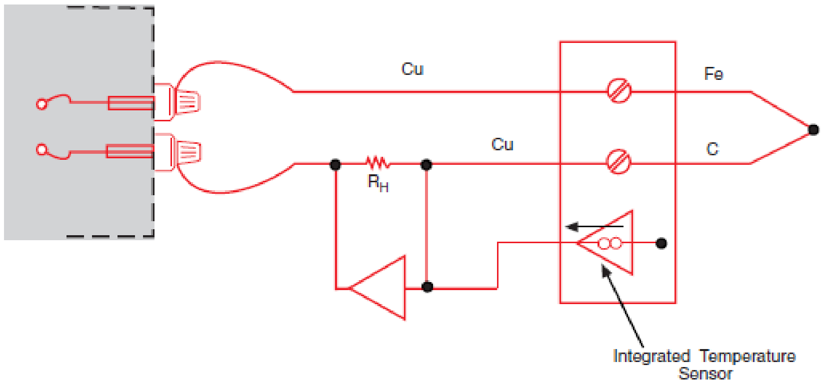


Figure 2.20 External reference junction - no ice bath [5]

2.2. Temperature Measurement

In this study, internal temperature sensor of the MSP430 is used for measuring the cold junction (reference junction) temperature. In the device data sheet, not much information is given about the type of the sensor. But in the sample codes supplied by the TI web site, it is mentioned as a temperature diode. Once the cold junction measurement is done, software compensation is used for the thermocouple, but not in the same way as mentioned above, that is:

- Measure indirect sensor output to find T_{REF} and convert T_{REF} to its equivalent reference junction voltage, V_{REF}.

- Measure thermocouple voltage and add V_{REF} to find compensated thermocouple voltage, V_1; and convert thermocouple voltage, V_1, to absolute temperature of hot junction, T_{J1}.

Since a microcontroller circuit is used for measuring temperature in this study instead of a digital volt meter, the extra step of converting cold junction (reference junction) temperature (T_{REF}), to its equivalent reference junction voltage (V_{REF}), can be eliminated. Instead, cold junction (reference junction) temperature is directly added to calculated temperature of uncompensated hot junction. In this way, absolute temperature of the hot junction can be measured.

Internal temperature sensor of MSP430x4xx family produces a fixed amount of voltage per a unit change in temperature. Its transfer function is given as below, but calibration is recommended for most applications.

$$V_{sensor} = 0.00355 \times (\text{Temp in Celsius}) + 0.986\ \text{V}$$

For calibration, several measurements at two different temperatures are taken and averaged into two separate values. Transfer function is then calculated by linearly interpolating these two averaged points. While choosing the temperature points, it is paid attention to selecting one of the temperatures to be at an average room temperature and selecting the other one as far as possible to first temperature in order to minimize error in linear interpolation.

Two temperature points which are used for calibration and the corresponding average of 20 measurements where each measurement itself is actually average of 1000 successive measurements taken by the microcontroller is present in the table below. Table also includes the calculated voltage values that correspond to the average ADC value at that temperature.

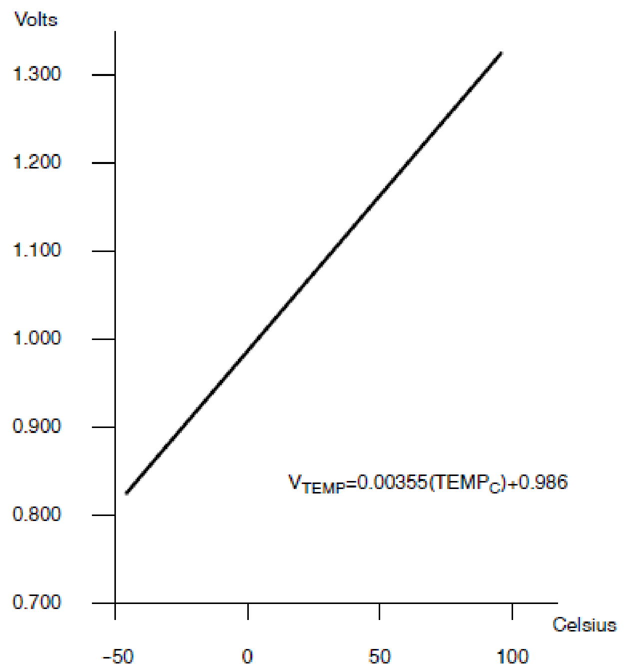


Figure 2.21 Typical transfer function of the internal temperature sensor of MSP430x4xx[6]

Table 2.2 Average ADC values obtained by calibration values

Temperature (°C)	Average 12 bit ADC Value	Corresponding Sensor Voltage (mV)
29	2785	1068.131868
-17	2442	896.7032967

In the light of the table above, sensitivity as mV per Celsius (slope of the transfer function) can be calculated as below:

Sensitivity as mV per Celsius = ((Sensor voltage at 29°C) – (Sensor voltage at -17°C)) / (29°C – (-17°C))

Sensitivity = 3.726708075 mV/°C

Once the slope of the transfer function is calculated, then the function can be formulized as follows:

$$V_{sensor} = (V_{sensor} \text{ at low temperature}) + (\text{temp}-(\text{low temperature})) \times (\text{Sensitivity as mV/°C})$$

$$V_{sensor} = (896.7032967\text{mV}) + (\text{temp}-(-17°\text{C})) \times (3.726708075\text{mV/°C})$$

By using the formula above; V_{sensor} at 0°C is calculated as:

$$(V_{sensor} \text{ at } 0°\text{C}) = (896.7032967\text{mV}) + ((0°\text{C}) - (-17°\text{C})) \times (3.726708075 \text{ mV/°C})$$

$$(V_{sensor} \text{ at } 0°\text{C}) = 960.057334 \text{ mV}$$

Transfer function becomes:

$$V_{sensor} = (V_{sensor} \text{ at } 0°\text{C}) + (\text{temp} \times (\text{Sensitivity as mV per °C}))$$

$$V_{sensor} = 960.057334 \text{ mV} + (\text{temp} \times (3.726708075 \text{ mV/°C}))$$

After measuring the sensor output, the corresponding temperature in degree Celsius can be calculated as the linear equation:

$$DegC = (V_{sensor} - (V_{sensor} \text{ at } 0°C)) / (\text{Sensitivity as mV per } °C)$$

$$DegC = (V_{sensor} - (V_{sensor} \text{ at } 0°C)) / (3.726708075 \text{ mV}/°C)$$

$$DegC = (V_{sensor} - 960.057334 \text{ mV}) / (3.726708075 \text{ mV}/°C)$$

Where Vsensor is defined as:

$$V_{sensor} = 1500mV / 4095 \times adcValue \approx 0.3663 \times adcValue$$

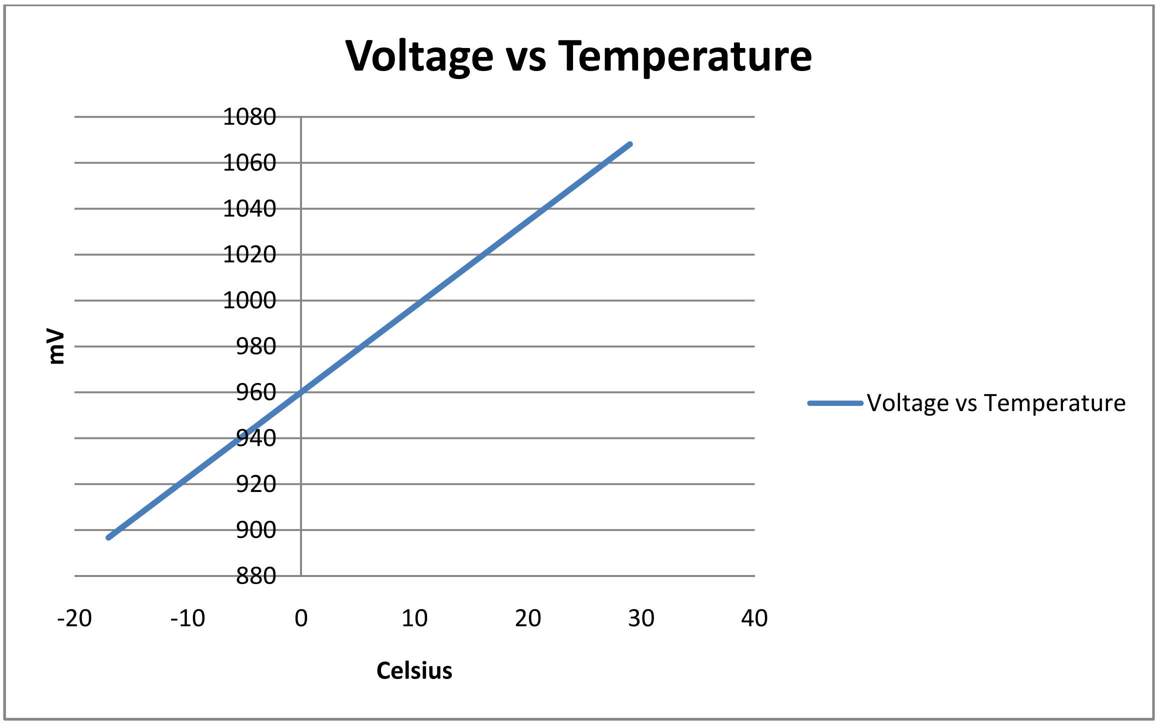


Figure 2.22 Calibrated transfer function of the internal temperature sensor of MSP430x4xx

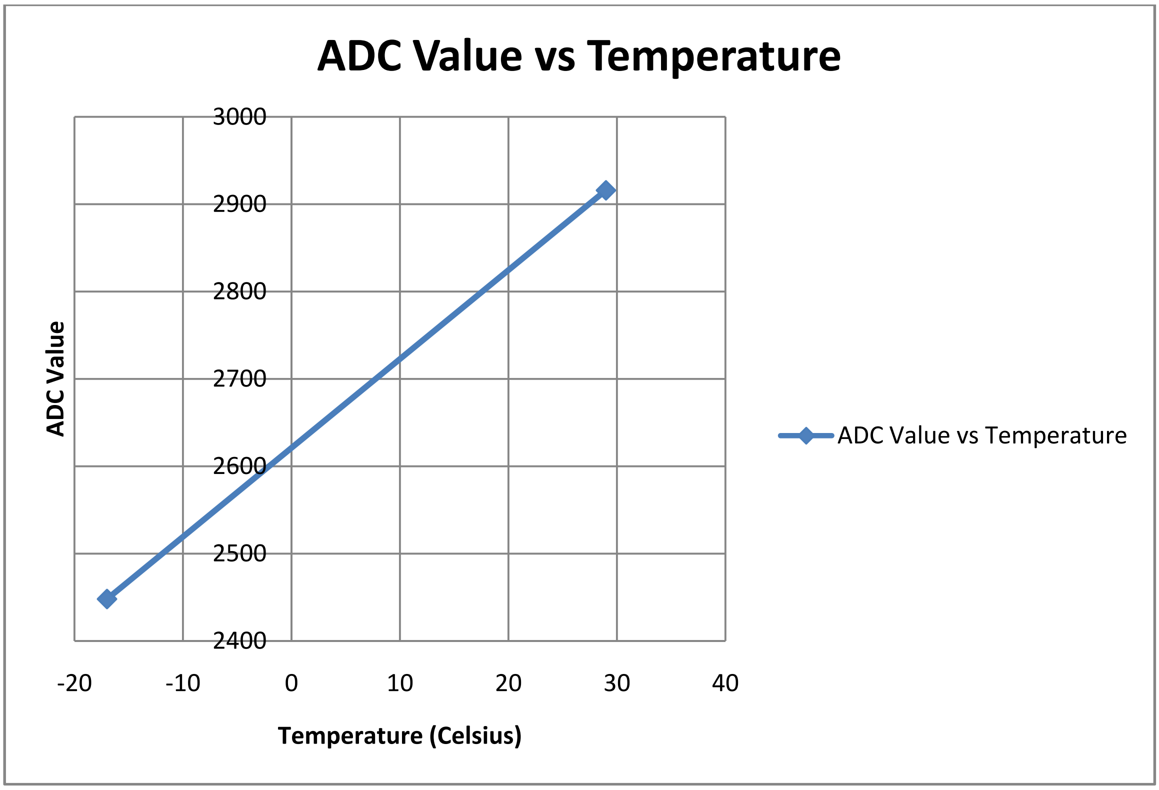


Figure 2.23 Calibrated ADC value vs. temperature relation of the internal temperature sensor of MSP430x4xx

Thermocouple is a J-type Fe-Const thermocouple which is commonly available at the market. It has a relatively high sensitivity, which is amount of output signal produced in response to a unit change in temperature. It produces a voltage difference at the non-welded ends relative to the temperature difference between non-welded and welded ends. So, it is not enough to just measure thermocouple output to determine the correct temperature of the welded end. Thermocouple output only provides information to determine temperature difference between the welded and non-welded ends. Temperature of the non-welded ends must also be measured so that the correct value of the welded end can be determined. Connection of the non-welded ends to measuring device is called as the cold junction, and process of including cold junction temperature to determination of the welded end temperature is known as cold junction compensation. So, internal temperature sensor of the MSP430 is used for cold junction as mentioned before.

Thermocouple output voltages are standardized by National Institute of Standards and Technology, and are available by web. The data table for J-type thermocouple voltages between 0°C and 310°C can be found in appendix.

Transducers like thermocouples convert physical quantities into currents or voltages. But, usually the signals from the transducers are not in the form that we would like them to be. They may be too small, too noisy or have a DC offset. In order to handle these problems, an appropriate analog signal processing can be applied and the desired signal information can be extracted. The most common form of the analog signal processing is amplification [4].

An ideal amplifier amplifies the amplitude of a signal without effecting phase relationships of different components of the signal, and normally shows amplitude linearity which means that the gain is constant for all frequency components [4].

Because thermocouple output is too small, it should be amplified before processing. For amplifying thermocouple signal, an instrumentation amplifier (INA 128P from Texas Instruments) is used. An instrumentation amplifier is a type of differential amplifier with very high common mode rejection ratio and very high input impedance.

A typical instrumentation amplifier schematic is given in the *Figure 2.25 Typical Instrumantation Amplifier Schematic*. Gain is given by the equation:

$$V_{out}/(V_2 - V_1) = (1 + 2R_1/R_{gain})(R_3/R_2)$$

Schematic of the instrumentation amplifier TI INA128P is given *Figure 2.26 Instrumentation Amplifier - TI INA128P* [7]. It has an R_1 value of 25k, R_2 and R_3 value of 40k, which results in a gain equation of:

$$Gain = 1 + (50k\Omega/R_G)$$

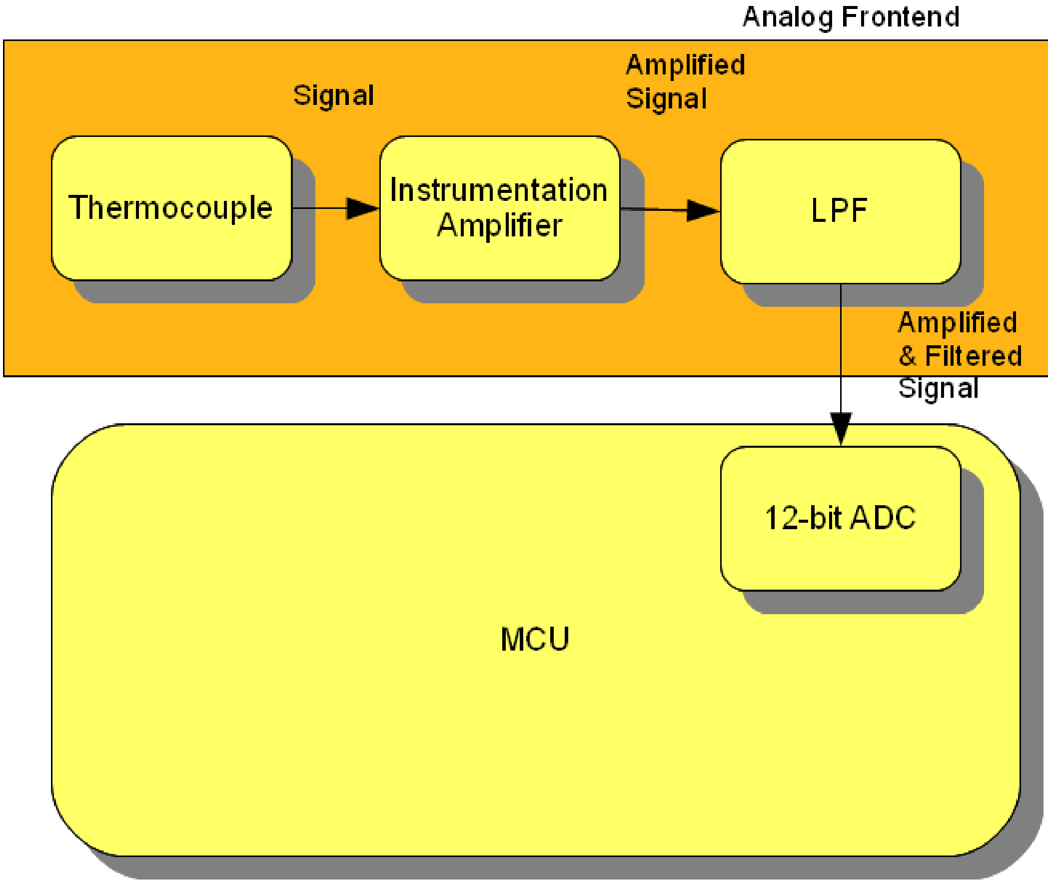


Figure 2.24 Analog Front End

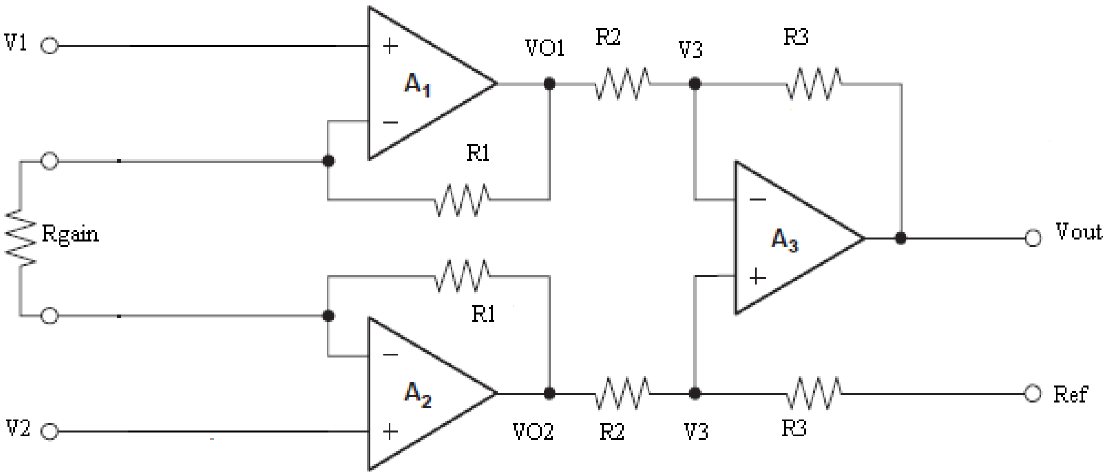


Figure 2.25 Typical Instrumantation Amplifier Schematic

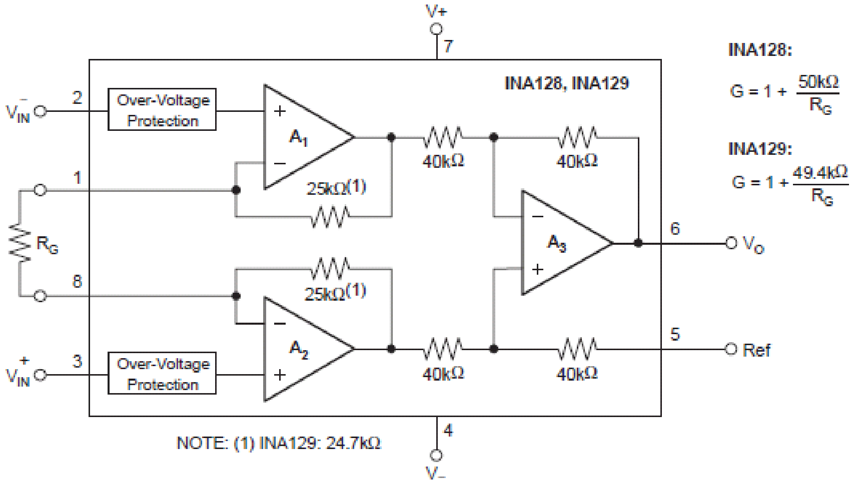


Figure 2.26 Instrumentation Amplifier - TI INA128P [7]

Needed gain requires a calculation. According to IPC/JEDEC Moisture/Reflow Sensitivity Classification for Nonhermetic Solid State Surface Mount Devices standard, maximum temperature a device can reach during reflow soldering is stated as 260°C for users. Then it is enough for the purpose of this study to measure temperatures below and equal to 260°C. According to thermocouple output voltages standardized by the National Institute of Standards and Technology, thermocouple output at 260°C is 14.110 mV. It will be amplified with the gain of the instrumentation amplifier and then will be fed into the analog to digital converter. Since analog to digital converter reference voltages are 1.5 V for positive reference and 0 V for negative reference, output of the instrumentation amplifier must be equal or smaller than 1.5 V when the temperature is 260°C which corresponds to a thermocouple output of 14.110 mV. Then maximum gain that can be applied is:

$$\text{Maximum gain} = 1500 \text{ mV} / 14.110 \text{ mV}$$

$$\text{Maximum gain} \approx 106$$

Then choosing an R_G value of 500Ω, which is a parallel combination of two 1kΩ resistor, result in a gain of 101 as shown below.

$$\text{Gain} = 1 + (50k\Omega/R_G)$$

$$Gain = 1 + (50k\Omega/500\Omega)$$

$$Gain = 101$$

This gain is close enough to the maximum applicable gain of 106, and also provides a safety margin that allows a temperature measurement of up to 273°C. According to thermocouple output voltages standardized by the National Institute of Standards and Technology, thermocouple output at 273°C is 14.831 mV. With a gain of 101 at the instrumentation amplifier, it results in 1497.931 mV at the analog to digital converter input, which is just below the positive reference voltage of 1.5 V of the analog to digital converter.

A simple RC filter is used for eliminating high frequency noises, specifically the radio frequency noises in the amplified thermocouple signal. Cut off frequency for a simple RC low pass filter is defined as:

$$f_c = 1 / 2\pi RC$$

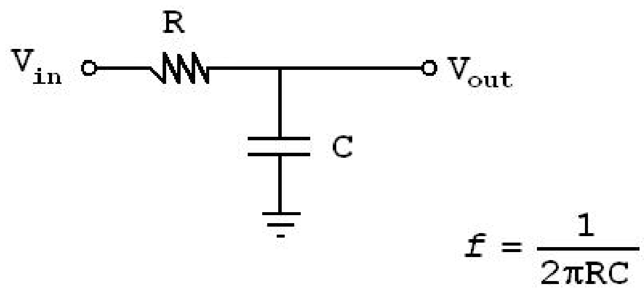


Figure 2.27 Low pass filter [8]

Resistance and capacitor values used in the filter are 10 kΩ and 0.1μF respectively, which result in a cut of frequency of:

$$f_c = 1 / 2\pi(10k\Omega)(0.1\mu F)$$

$$f_c \approx 160 \text{ Hz}$$

An analog signal must be converted to a digital value before it can be processed by a computer system such as a microcontroller. A device converting analog signals into digital values is called analog-to-digital converter (ADC). Fortunately, MSP430x4xx family microcontrollers have an integrated ADC peripheral. 12-bit ADC peripheral of MSP430FG439G device is used for analog to digital conversion in this study.

This ADC converts an analog voltage to its 12-bit digital counterpart, and stores this value in a conversion memory. It uses two reference voltages: one for the upper limit and another for the lower limit of input voltage. Reference voltage for upper limit is denoted as V_{R+} and the lower limit is denoted as V_{R-}. Any input value equal or larger than the upper limit is evaluated as full scale (0FFFh); and any input value equal and lower than the lower limit is evaluated as zero (0000h). Conversion result of the ADC is obtained by using the following equation, where N represents the ADC conversion result:

$$N_{ADC} = 4095 \times (V_{in} - V_{R-}) / (V_{R+} - V_{R-}); \quad \text{if } V_{R-} < V_{in} < V_{R+}$$

$$N_{ADC} = 0; \quad \text{if } V_{in} < V_{R-}$$

$$N_{ADC} = 4095; \quad \text{if } V_{in} > V_{R+}$$

Internal 1.5V voltage reference of the ADC12 is used for the reference voltage. This means V_{R+} = 1500 mV and V_{R-} = 0 mV. Then conversion result of the ADC becomes:

$$N_{ADC} = 4095 \times (V_{in}) / 1500 \text{ mV}; \quad \text{if } 0 \text{ mV} < V_{in} < 1500 \text{ mV}$$

$$N_{ADC} = 0; \quad \text{if } V_{in} < 0 \text{ mV}$$

$$N_{ADC} = 4095; \quad \text{if } V_{in} > 1500 \text{ mV}$$

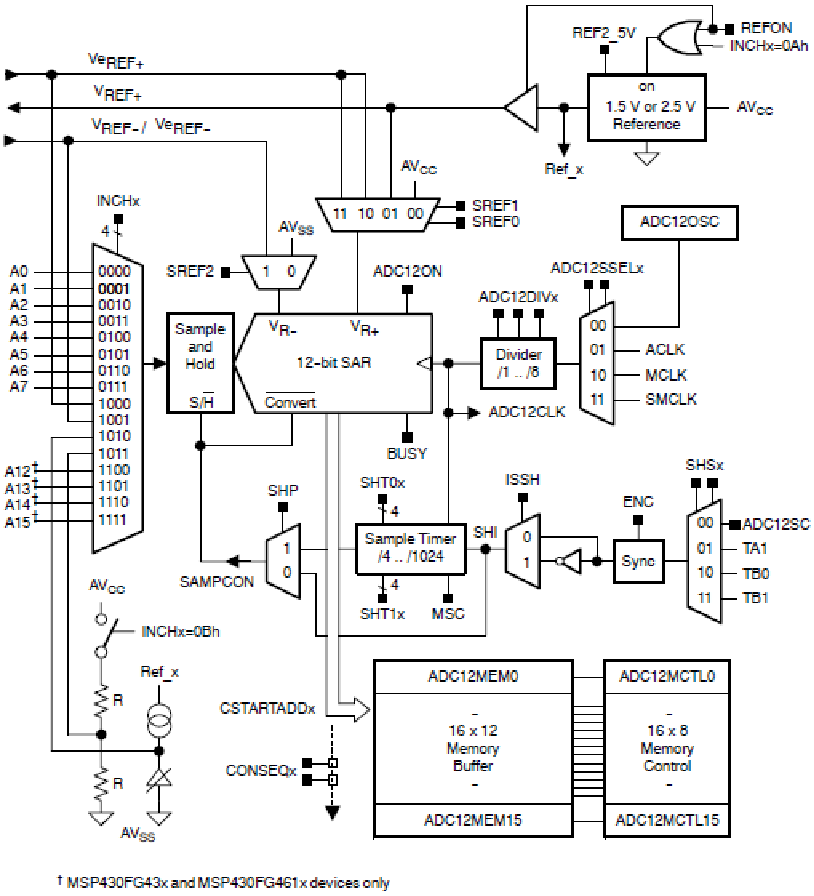


Figure 2.28 ADC12 Block Diagram in MSP430x4xx family [6]

In the process of sampling, N sample is obtained and averaged into a mean value from amplified and filtered thermocouple output. This mean value is used for calculation of uncompensated hot junction temperature. In the same time, another M sample is obtained from the temperature sensor at the cold junction, so that cold junction temperature can be measured and compensated.

In addition to sampling hot junction and cold junction sensor values, also ADC value, when the input of ADC is grounded, is measured. This value represents the offset of the ADC. For determining offset value, another P sample should be carried, and then averaged.

Average offset value obtained according to the procedure above must be subtracted from the thermocouple and cold junction temperature sensor ADC values in order to eliminate offset voltage of ADC.

Once the thermocouple and internal temperature sensor temperatures are measured, they are summed and so absolute hot junction temperature is obtained.

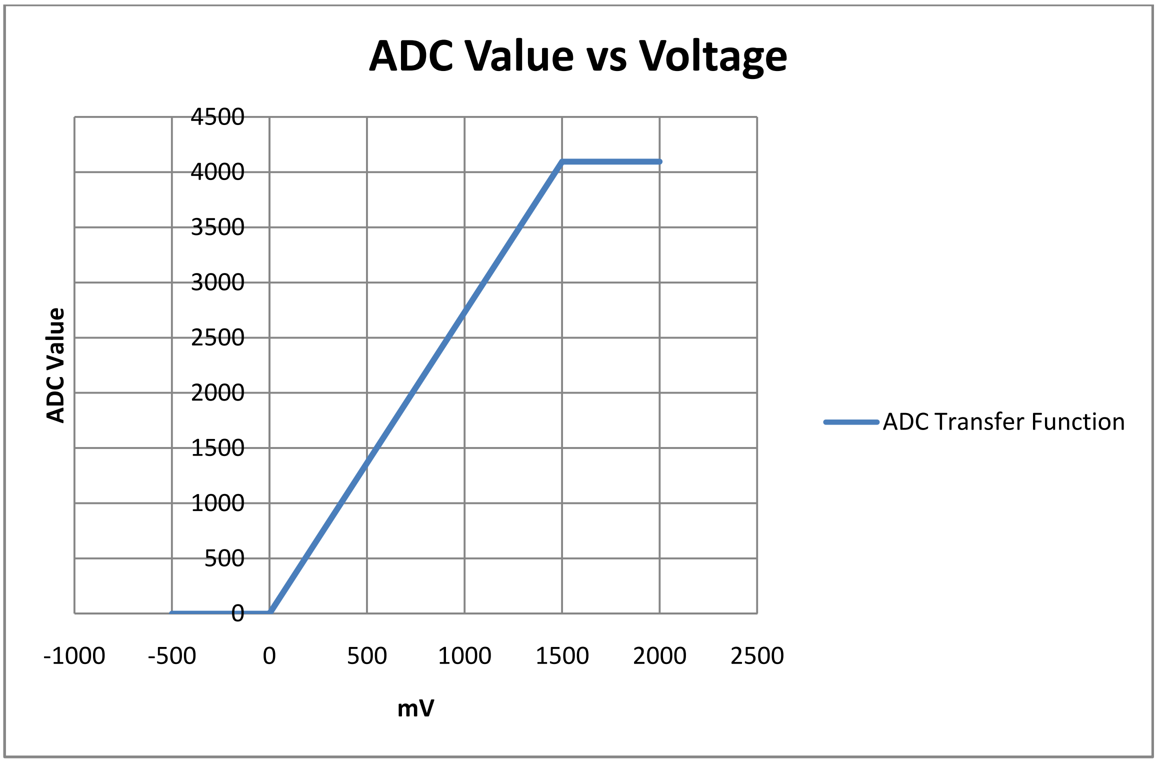


Figure 2.29 Transfer function of 12-bit ADC with V_{R+}=1.5V and V_{R-}=0V

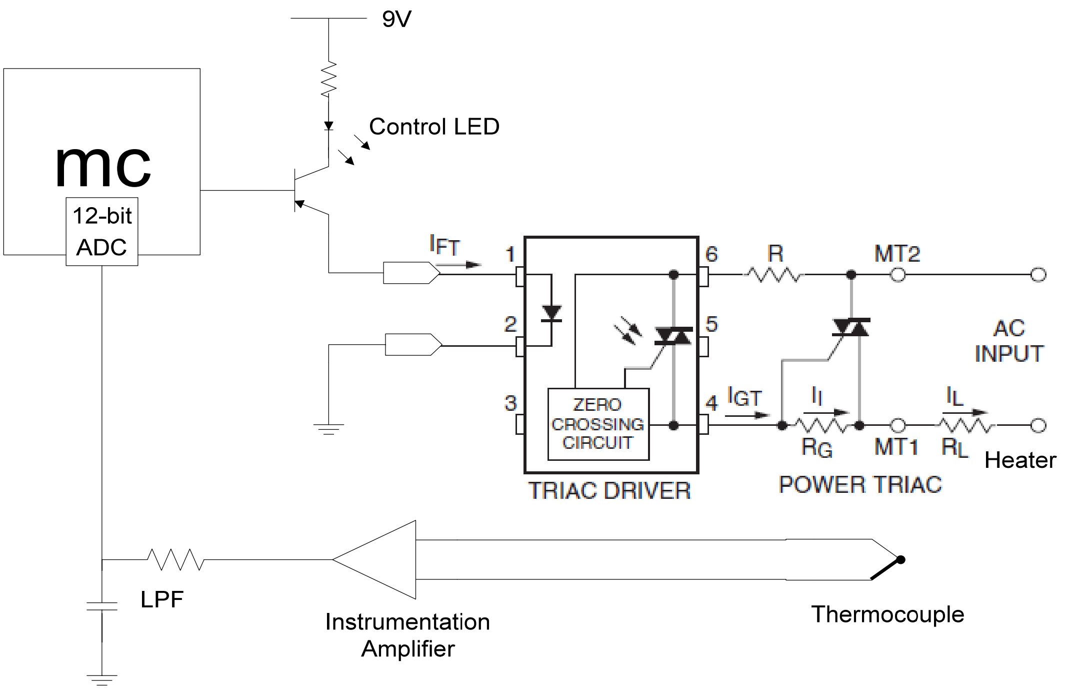


Figure 2.30 Simple schematic

2.3. Power Circuit

2.3.1. Power Switch

An alternating current (AC) power switch is needed in order to turn on/off the heater, and this switch could be controlled by the controller circuit. Since the heater that will be controlled uses alternating current, simply using a power transistor does not solve the problem.

Using a relay is one solution. But since relays work mechanically, they have relatively short life-time, long response time and also they have an undesirable switching noise.

A triac can also be used to switch an alternating current supply to high-current devices like motors and heaters. As a triac includes mainly two thyristors which are joined back to back, it enables current to flow in either direction, which means that the triac is likely to provide with conduction during both halves of the AC cycle. When the triac is triggered, it conducts for the remaining of the half cycle [9].

When triac is used as a power switch, there may occur a problem. While its status switches from on to off or vice versa, high frequency components are generated in the power line and these components may widely disperse through the mains-line. When the power signal has higher amplitude during the switching, the result is even worse. When triac is triggered at almost 0V, consequent high frequency components would be at minimum. Hence, for triggering the triac, a zero voltage switch is recommended [9]. It is provided by an integral part of the optoisolator component used in this study as mentioned below.

2.3.2. Power Interface

In this study, control part of the circuit is isolated from the rest of the circuit by using an optoisolator. Optoisolators provide an electrical isolation between input and output circuits by using optical communication instead of electrical communication. An optoisolator consists of an LED and a phototransistor which are separated by a small gap between them. LED and phototransistor are sealed in a lightproof capsule. When the LED is on, it emits light; and this light causes phototransistor to conduct current across itself. Output circuit may have a different reference ground and a supply voltage [4].

Optoisolator used in this study is MOC 3043. It has a maximum of 400 V off-state terminal voltages, but can withstand a 7500 V of isolation surge voltage for duration of 1 second at 60 Hz [10]. Beside the optoisolator circuit, it also includes a zero voltage crossing triac driver.

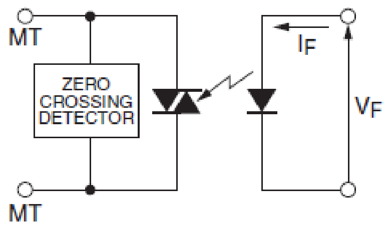


Figure 2.31 Simplified schematic of optoisolator MOC 3043 [10]

Typical circuit for hot line switching is given in the figure below. R_{in} is chosen so that the current through input circuit would be between the rated current, 5 mA, and maximum continuous forward current, 60 mA, of the input led of the optoisolator.

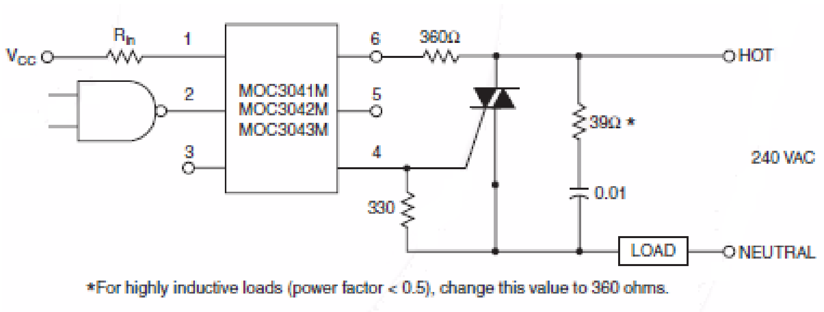


Figure 2.32 Hot-line switching application circuit [10]

Basic driving circuit and waveforms are given in the figure below.

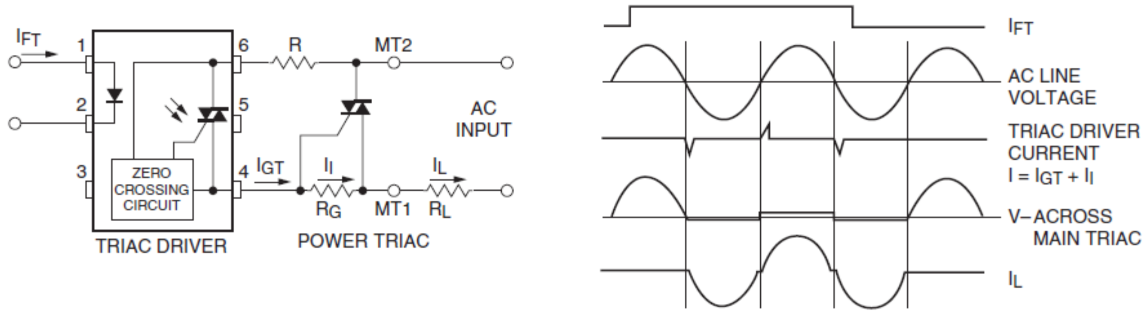


Figure 2.33 Waveforms of a basic driving circuit [11]

2.4. Timing

In this design, temperature of the oven is calculated each second, control action is determined and this control action is applied to the system during that second. Timing required for these steps is provided by Timer_A, a timer that is present on the MSP430 family microcontrollers.

Timer_A is a 16-bit timer/counter with multiple capture/compare registers. It supports PWM that is needed for controlling the power delivered to the oven in this study.

Timer clock can be sourced from ACLK, SMCLK or externally. Selected clock source can be divided before applied to Timer_A. Timer has four modes of operation: stop mode, up mode, continuous mode and up/down mode.

In this study, timer is used in the up mode, in which it repeatedly counts from zero to a user defined value hold in the register called TACCR0, as shown in the figure below.

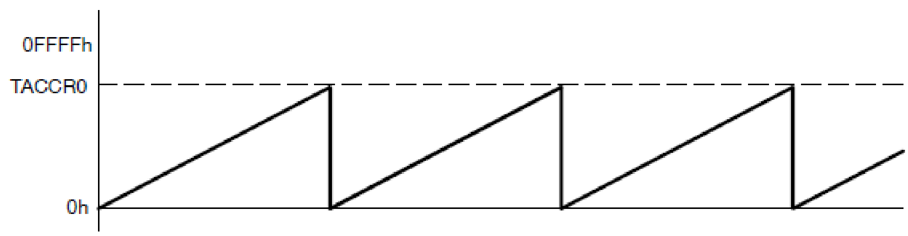


Figure 2.34 Up mode [6]

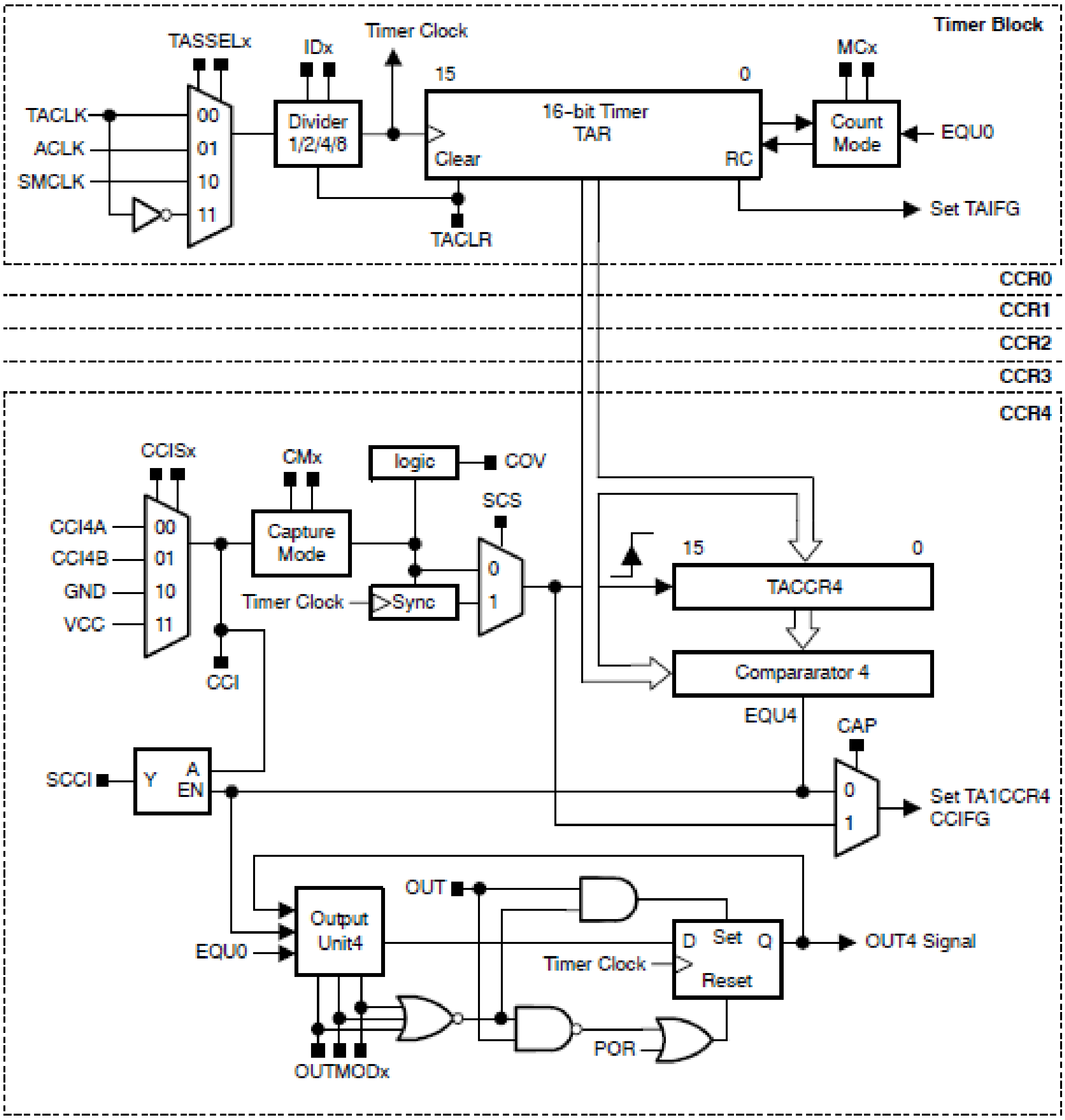


Figure 2.35 Timer_A block diagram [6]

Compare mode is used to generate PWM output. Each capture/compare block contains an output unit, and PWM output is applied by using that output unit. Each output unit has 8 operating modes. In this mode, output is reset when the timer counts to a software defined TACCRx and it is set when the timer counts to another software defined value hold in a register called TACCR0.

Period of timer is chosen as 32768, which corresponds to 1 second time interval since the timer is sourced from 32 kHz ACLK. PWM duty cycle is calculated by the control algorithm used at the end of each second, and applied during the next second.

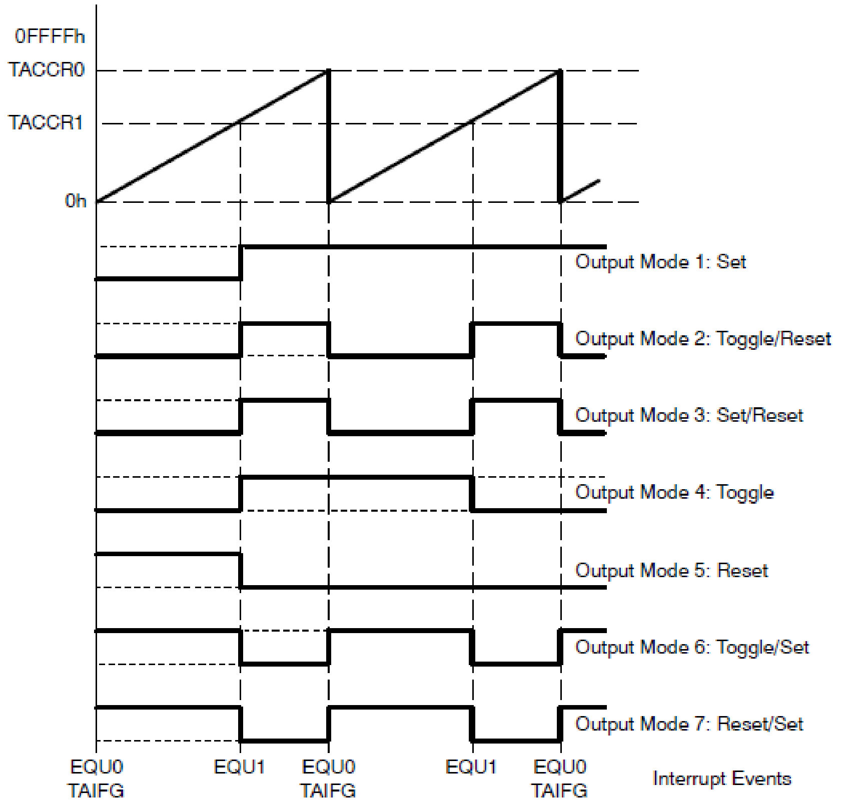


Figure 2.36 Output examples when the timer is in up mode [6]

2.5. Control Approach

Control approach decides how much power will be applied to the oven during next second by using various available information. In the control approach, various control algorithms were implemented and results were recorded for comparison.

The simplest algorithm used is the on-off control. In this algorithm, power of the oven is fully turned on when the temperature of the oven is lower than the set point and it is turned off when the temperature of the oven is equal or larger than the set point.

Proportional control determines how much power will be delivered to the oven according to the difference between the desired temperature and the actual temperature.

Integral term uses total error until that moment and it determines a control action in proportion to total error. Error is the difference between the desired temperature and the actual one. Likewise, derivative term uses change in error and determines its contribution in proportional to this change.

2.6. Data Acquisition

Temperature of the oven is recorded at each 5th second, although it is calculated each second. Calculated temperature at each 5th second is stored in an integer array which accommodates in RAM. After all measurements are done, the part of the RAM containing the integer array composed of recorded oven temperature is exported to a computer, which is allowed by the debugger. Once the start and end addresses of the desired RAM part is provided to the debugger, it exports data in addresses between them in a text file in hexadecimal format.

Example content of hexadecimal data in an exported file is provided below. Data in first line specifies the start address of the exported data. Then each line contains 16 chunks each of which represents an individual byte. Since temperature information is held in an integer array and because integer data type is represented by 16 bit in the compiler used for this study, each two chunk represent a temperature value. Value is represented in little endian format in the text file. In other words, first chunk represents the least significant byte (LSB) and the second chunk represents the most significant byte. Negative numbers are represented by the two's complement method. Character "q" at the last line specifies the end of exported data.

A java program is written for converting hexadecimal data in the exported file to base-10 representation. This program also formats the converted file in such a way that each line contains only one temperature value so that the content can be easily imported to excel for drawing graphs.

```
@46c
1c 00 1c 00 1c 00 1c 00 1c 00 1c 00 1e 00 1f 00
20 00 22 00 23 00 25 00 27 00 28 00 2a 00 2c 00
2e 00 2f 00 31 00 33 00 35 00 37 00 39 00 3b 00
3d 00 3f 00 41 00 43 00 46 00 48 00 4a 00 4c 00
4e 00 51 00 53 00 55 00 57 00 5a 00 5c 00 5e 00
61 00 63 00 66 00 68 00 6b 00 6d 00 70 00 72 00
74 00 77 00 7a 00 7c 00 7e 00 81 00 83 00 86 00
88 00 8b 00 8e 00 90 00 93 00 95 00 98 00 9b 00
9d 00 a0 00 a2 00 a5 00 a8 00 aa 00 ad 00 af 00
b2 00 b5 00 b7 00 ba 00 bc 00 bf 00 c2 00 c4 00
c6 00 c7 00 c8 00 c9 00 ca 00 ca 00 cb 00 cb 00
cb 00 cc 00 cc 00 cc 00 cc 00 cc 00 cc 00 cc 00
cc 00 cc 00 cc 00 cc 00 cc 00 cc 00 cc 00 cb 00
q
```

Figure 2.37 Hexadecimal content of an example exported file

3. RESULTS

Below is an open loop response of an 1300 watt kitchen oven. Temperature of the oven is calculated once a second, but calculated temperature is recorded only once in every five seconds.

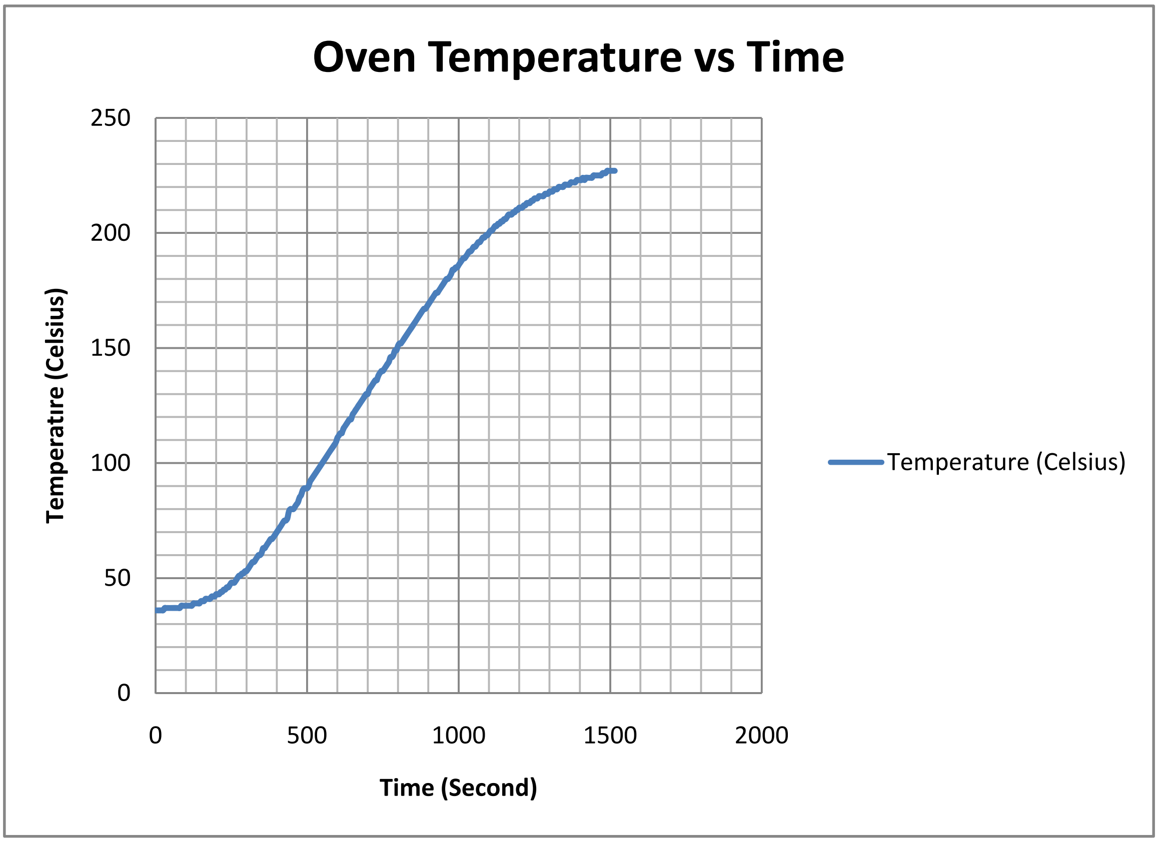


Figure 3.1 Open loop response of the oven

When the curve in the figure above is examined, it is shown that temperature at the 400th second is about 70°C and temperature at the 800th second is about 150°C. This results in an average temperature rise of 0.2°C per second. Time passed until the oven temperature to reach at 183°C degree that is the melting point of the SnPb alloy is roughly read as 960 seconds. According to NXP application note “Surface mount reflow soldering description”, minimum peak reflow temperature for SnPb alloy is stated as 215°C. Time required for the oven temperature to reach at this temperature is read as about 1280 seconds. On the other hand, maximum time allowed for 25°C to peak temperature is given as 6 minutes for SnPb alloy in the IPC/JEDEC joint industry standards "Moisture/Reflow Sensitivity Classification for Nonhermetic Solid State Surface Mount Devices". It is obvious that this oven does not satisfy the IPC/JEDEC requirements.

Open-loop response of another 1300 watt oven was recorded as follows.

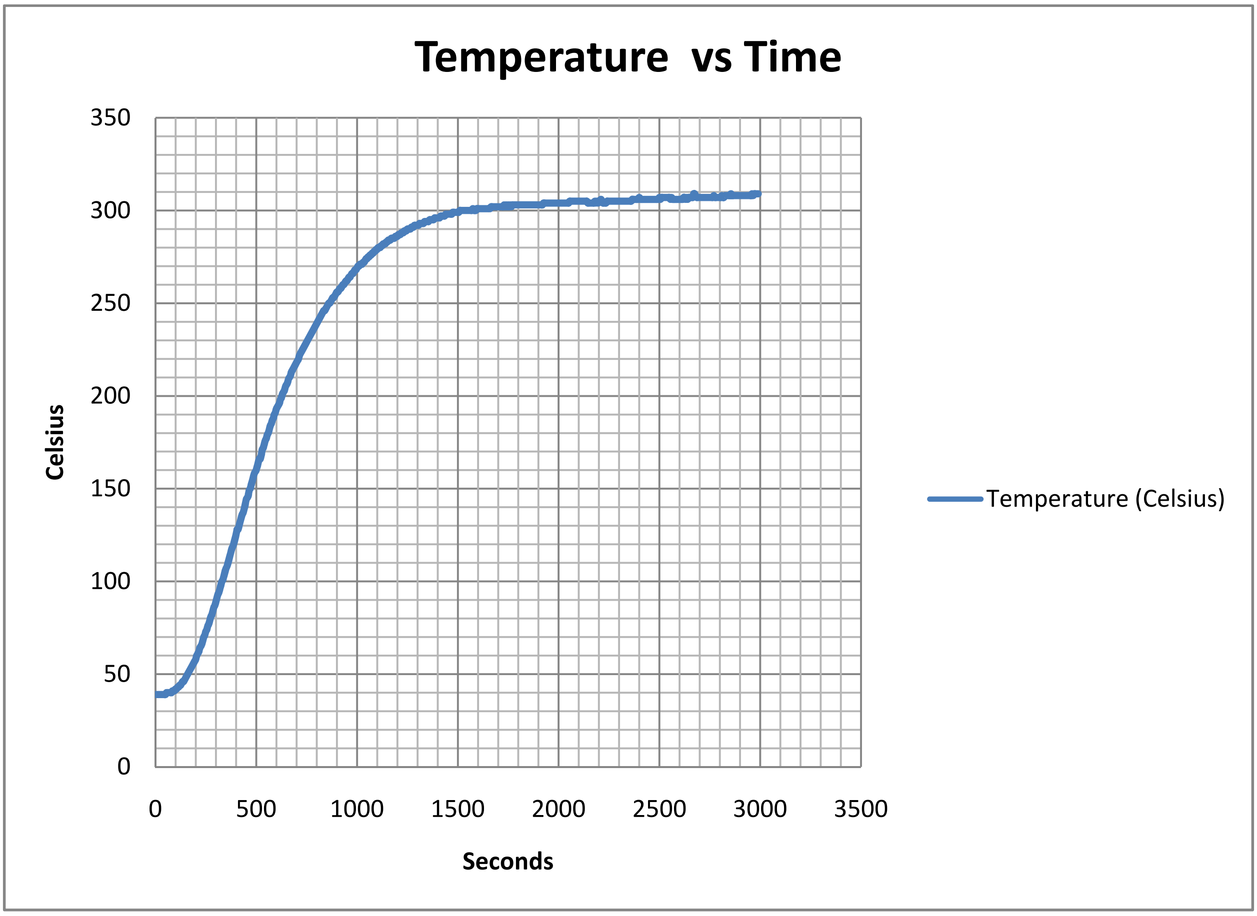


Figure 3.2 Open loop response of another oven

Time passed until the oven temperature to reach at 183°C degree that is the melting point of the SnPb alloy is roughly 560 seconds. Required time for the oven temperature to reach at 215°C, that is the recommended minimum peak temperature for SnPb alloy according to NXP application note "Surface mount reflow soldering description" is 700 seconds. Even if the performance of this oven is better than the first one, it also does not satisfy IPC/JEDEC standard of 25°C to peak temperature in 6 minutes.

When a simple on/off control algorithm was used, and a step input of 193°C was applied to this oven, temperature curve below was obtained. Firstly, temperature makes a large overshoot of approximately 27°C, and then it makes constant oscillations around the set point with amplitude of nearly +/-17°C and with a period of approximately 650 seconds.

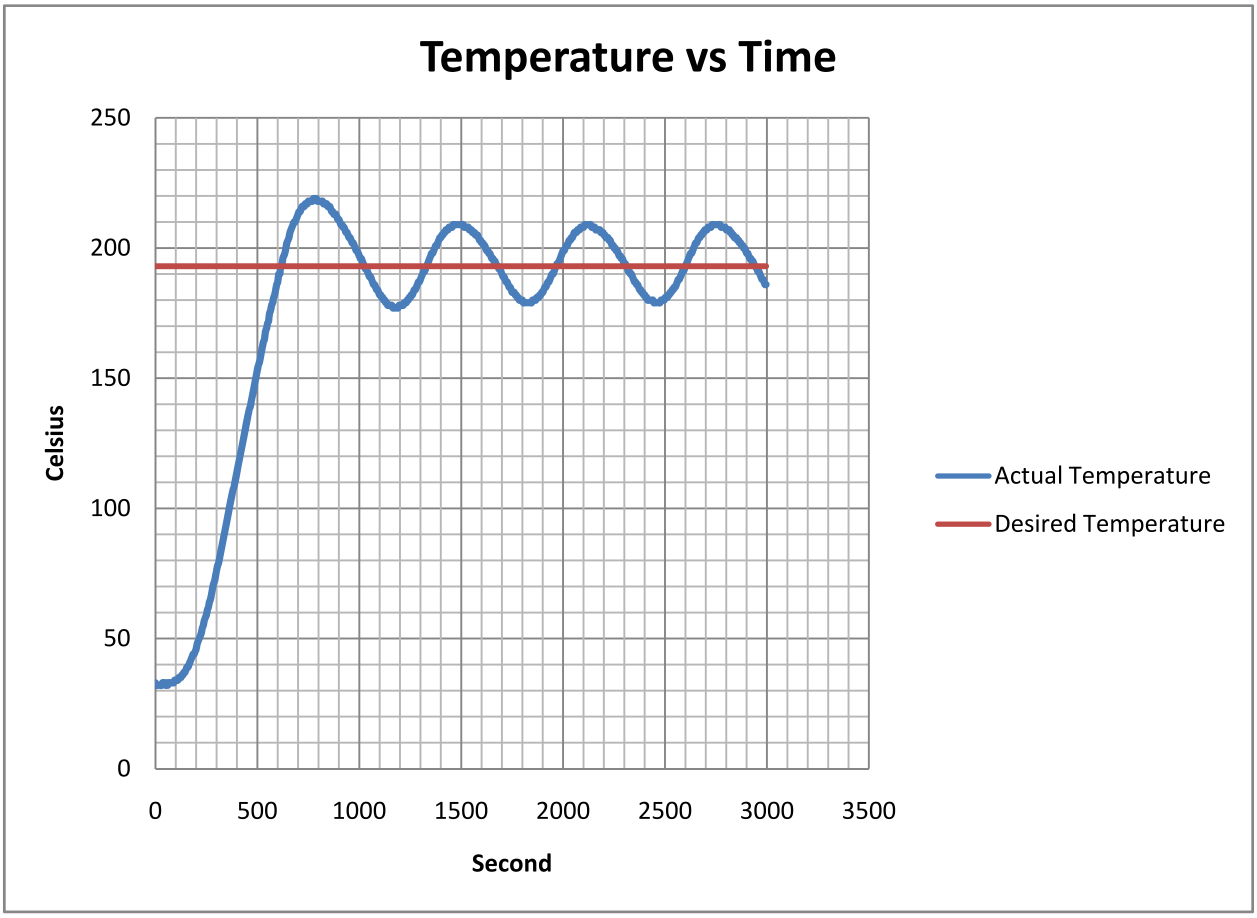


Figure 3.3 Step response - On/Off control

When a proportional control was applied with a proportional gain of 5, step response overshoot decreased to about 7°C and oscillations showed an underdamped characteristics. A steady state error of about 10°C is noted.

When the proportional gain was increased to the 10, overshoot increased as expected. Oscillations showed underdamped characteristics again, but attenuation of oscillations and steady state error decreased.

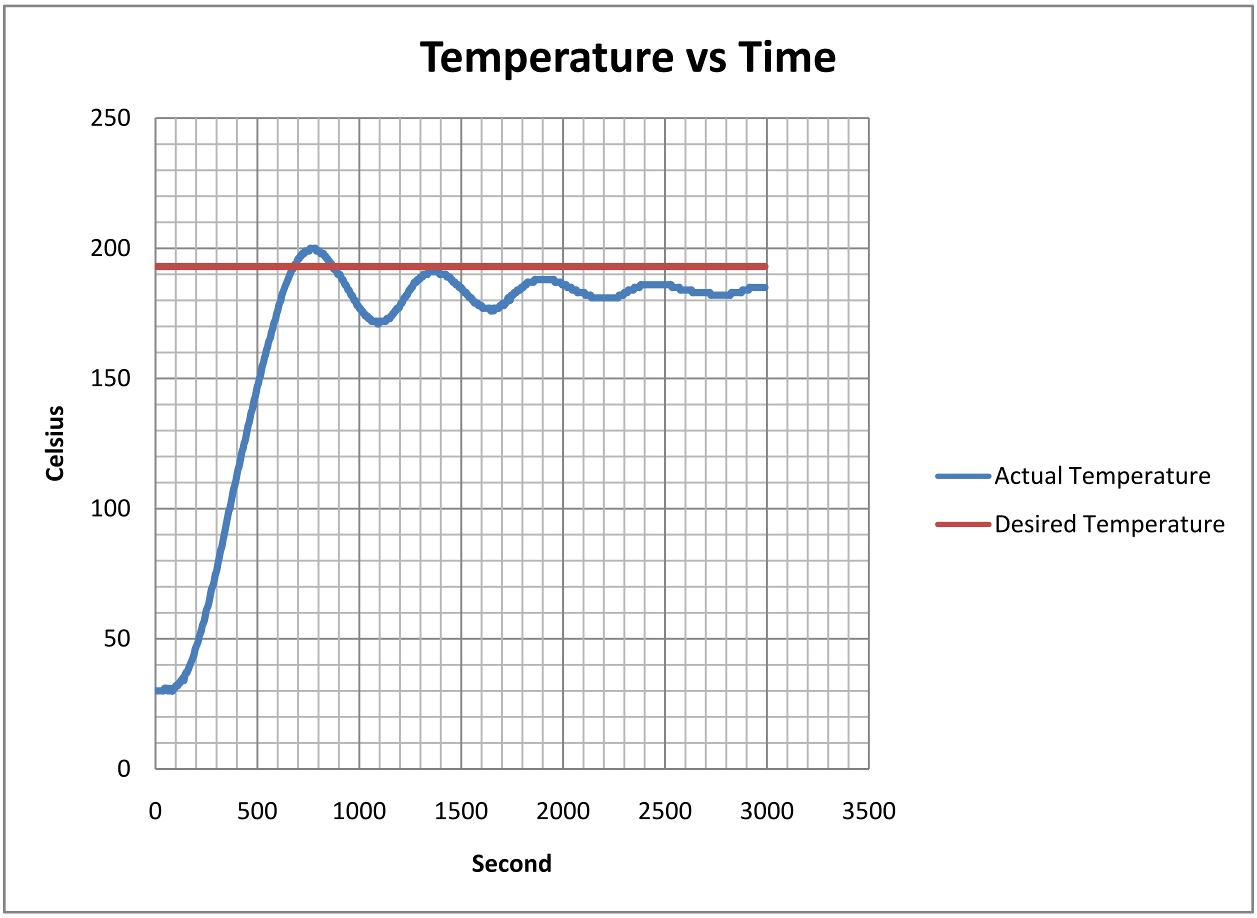


Figure 3.4 Step response - Proportional control with gain 5

When the proportional gain was increased to the 20, sustained oscillations were obtained as in the *Figure 3.6 Step response - Proportional control with gain 20*. Overshoot increased and temperature reached a peak level of about 215°C, on the other hand steady state error further decreased in comparison to its value in proportional control with gain 10.

A simple empirical method for determining PID controller gains is the Ziegler-Nichols method. In this method, derivative and integral gains are made zero and proportional gain is tuned alone first. Tuning is started with a small proportional gain, and the gain is gradually increased to a level where the sustained oscillations are observed in the steady state response of the system. Proportional gain at this point is noted as the ultimate gain or critical gain. Final period of steady state oscillations are noted also. Then by using critical gain and critical oscillation period noted before, gains are calculated as in the *Table 3.1 Ziegler-Nichols recommended gains*.

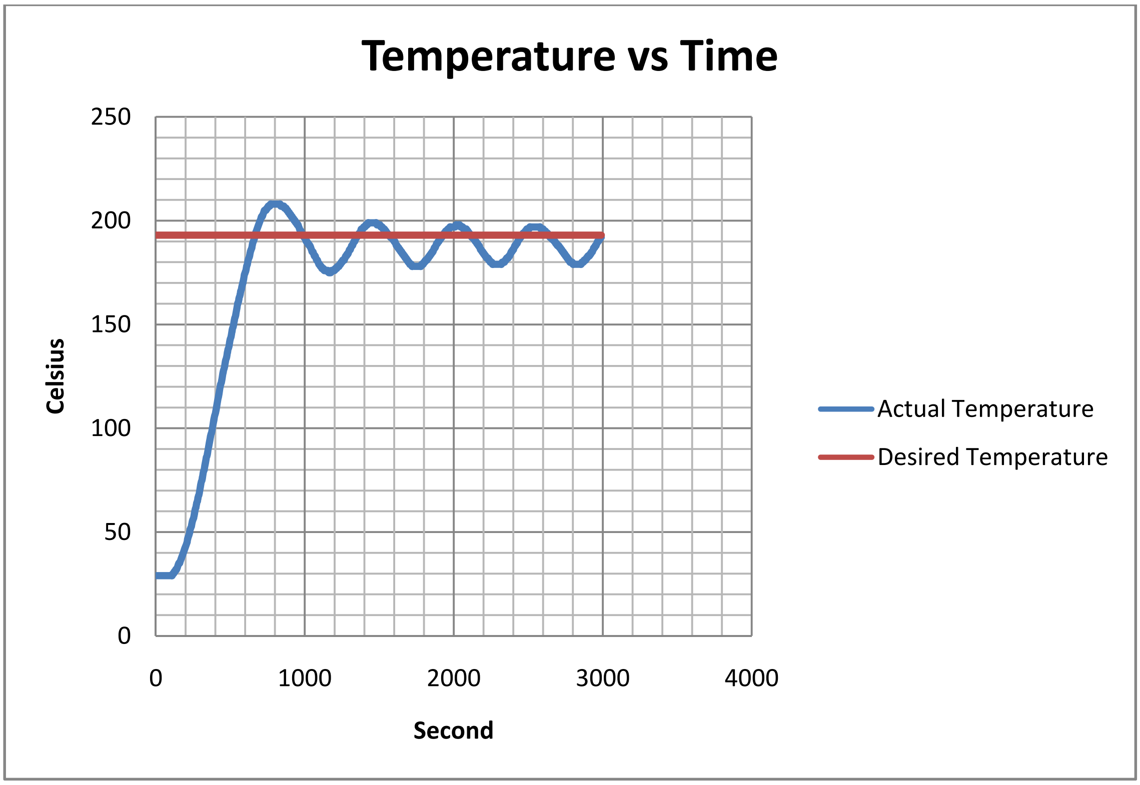


Figure 3.5 Step response - Proportional control with gain 10

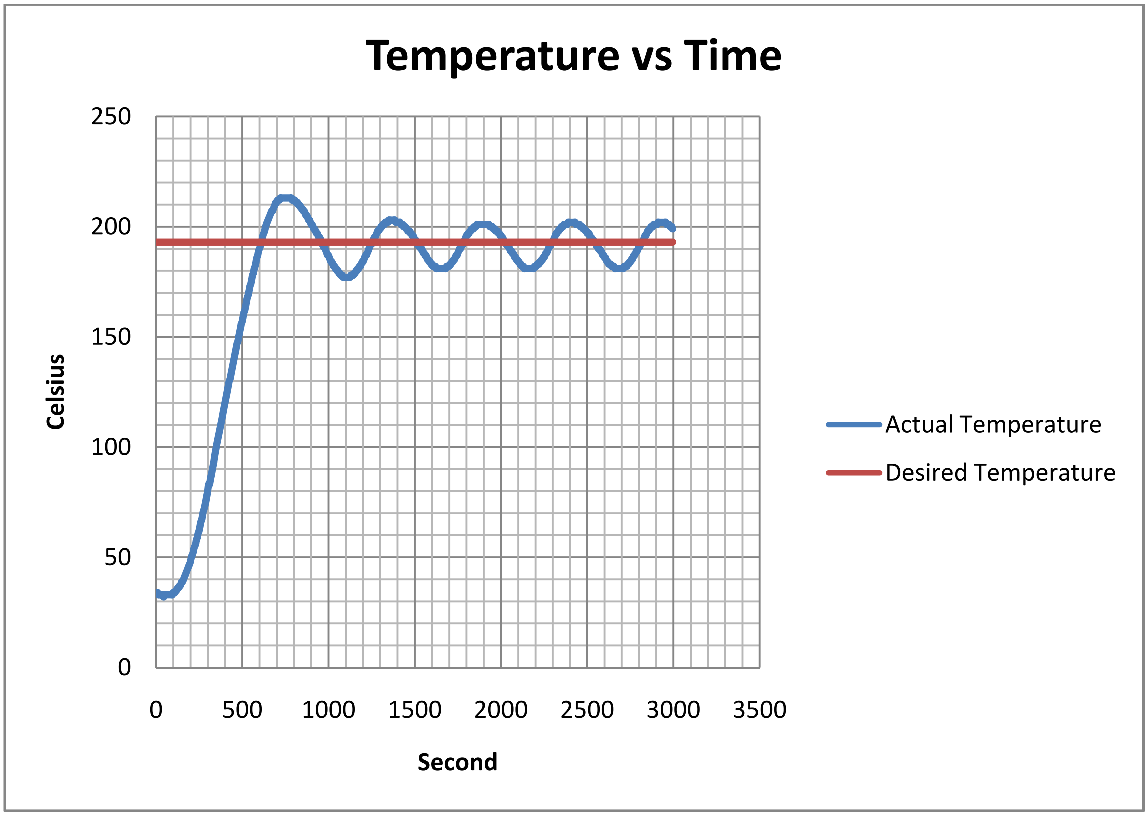


Figure 3.6 Step response - Proportional control with gain 20

Table 3.1 Ziegler-Nichols recommended gains

Controller	K_p	K_i	K_d
P	$0.5\ K_{cr}$	0	0
PI	$0.45\ K_{cr}$	$1.2\ K_p/P_{cr}$	0
PID	$0.6\ K_{cr}$	$2\ K_p/P_{cr}$	$K_pP_{cr}/8$

In the oven used in this study, sustained oscillations are observed at a proportional gain of 20. So, critical gain for this system is noted as 20. Critical period is measured as 530 seconds as seen in the figure below.

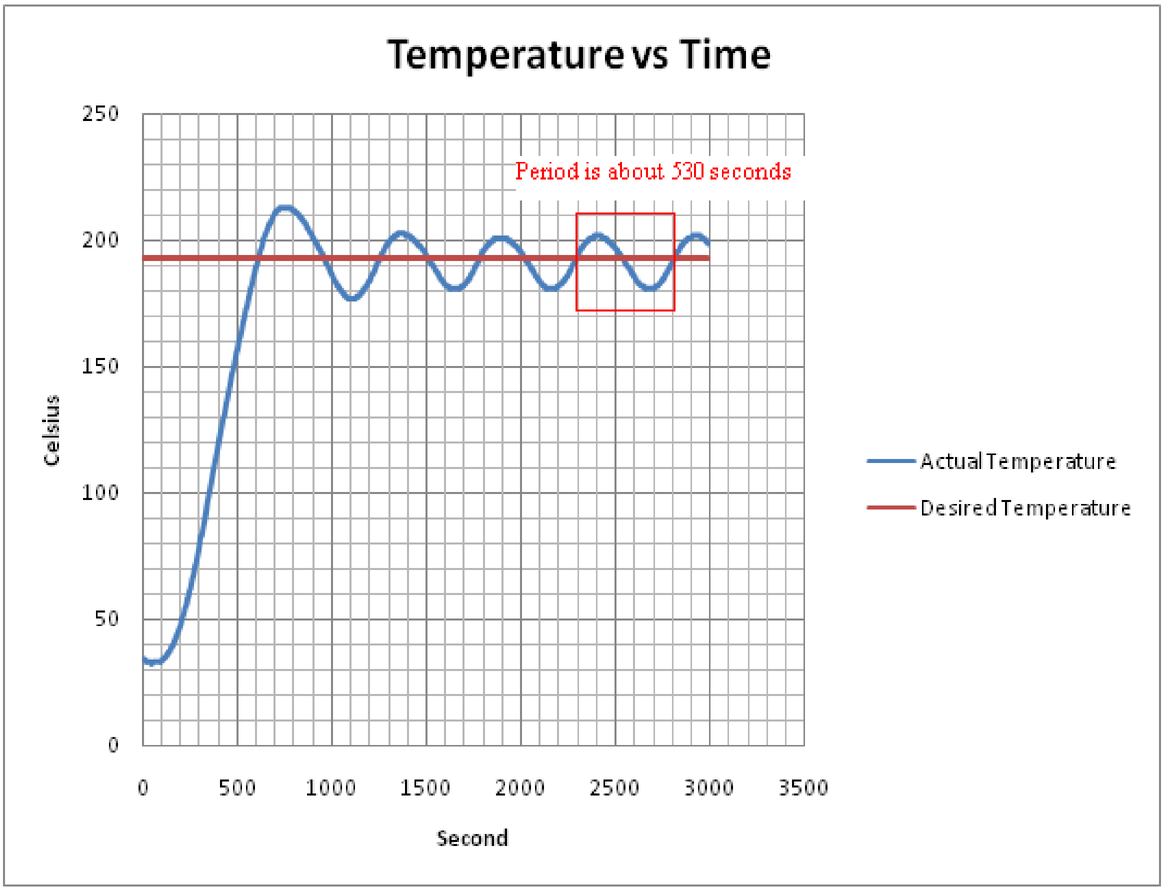


Figure 3.7 Critical Period

By using the table above, Ziegler-Nichols recommended gains can be calculated as follow:

$$K_p = 0.6\ K_{cr} = 0.6 \times 20 = 12$$

$$K_i = 2\ K_p/P_{cr} = 2 \times 12 / 530 \approx 0.045$$

$$K_d = K_pP_{cr}/8 = 12 \times 530 / 8 = 795$$

Figure below shows the temperature response when the gains are chosen according to Ziegler-Nichols method. Temperature goes far more beyond the set point. Main reason for this behavior is the relatively large integral gain.

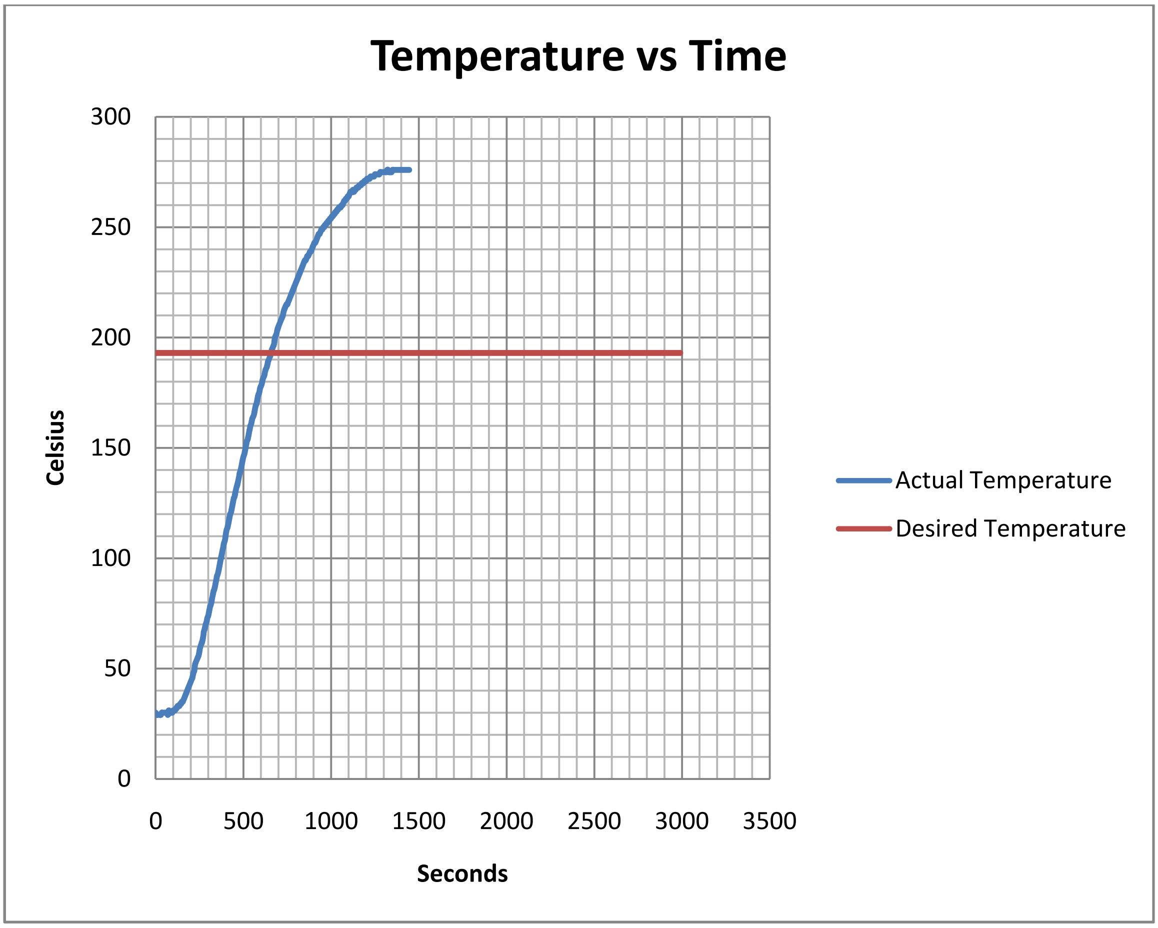


Figure 3.8 Step response - Gains with Ziegler-Nichols method

Figure 3.9 Step response - Output value, sum of P, I, and D terms shows also the output value which is the sum of proportional, integral and derivative terms. Until the 400th second, integral term dominates the output and makes it increase. After that point, contribution of proportional gain begins to dominate the output and makes it decrease. Instantaneous fluctuations on the output corresponds to the derivative term and occurs at the moments at which the temperature changes.

When a kind of electrical grill is used instead of an oven, faster responses and smaller oscillations are obtained. When simple on/off control algorithm is applied, response curve in *Figure 3.10 Step response - On/Off control of grill* is obtained. Temperature firstly makes an overshoot of about 15°C, and then fluctuates around the set point.

Figure 3.11 On/Off control of grill - Steady state, shows the steady state characteristic of the grill when on/off control was applied in a closer look. Temperature constantly oscillates around the set point with amplitude of +/-1°C.

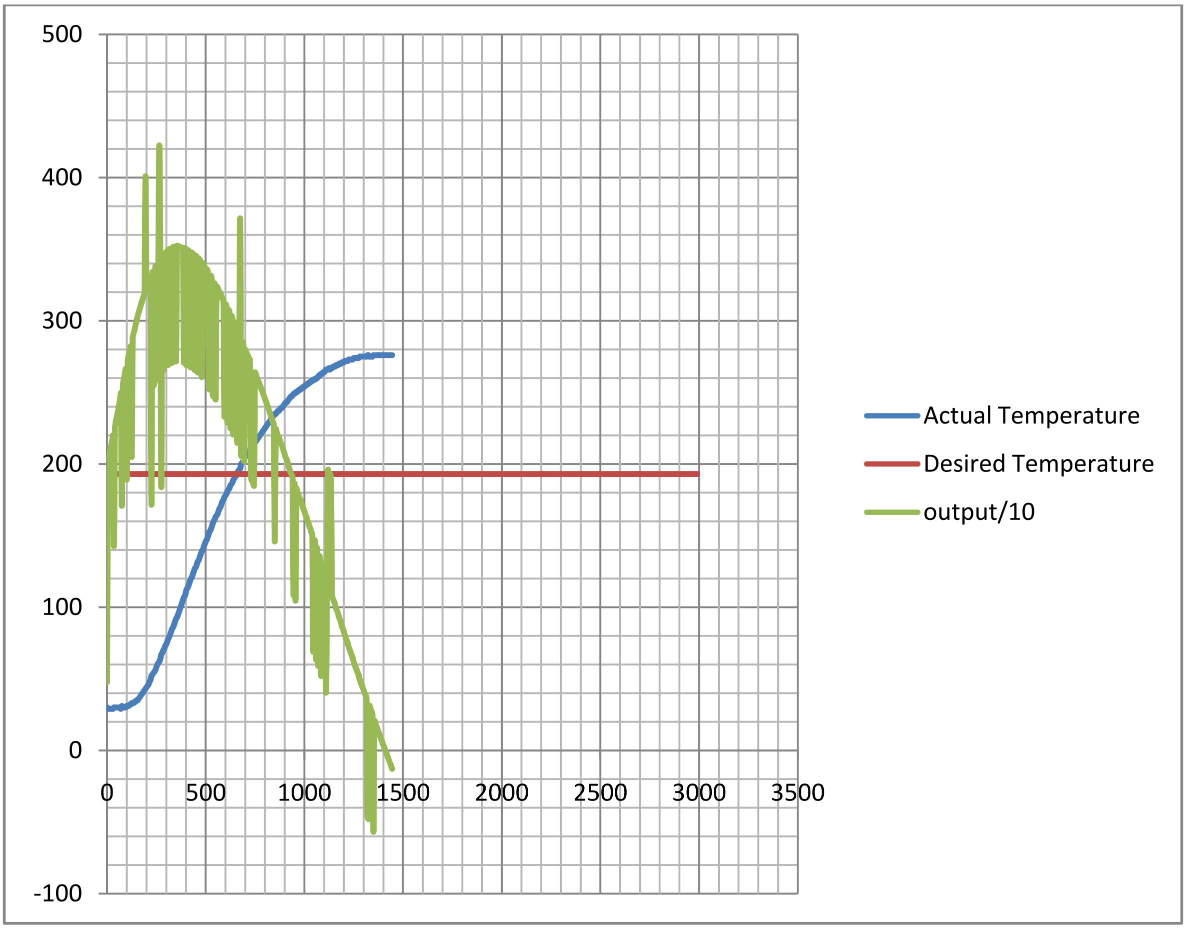


Figure 3.9 Step response - Output value, sum of P, I, and D terms

When proportional only control was applied and the gain was set to 5, *Figure 3.12 Step response of grill - Proportional control with gain 5* was obtained. Steady state error is about 6°C, and the overshoot is about 14°C.

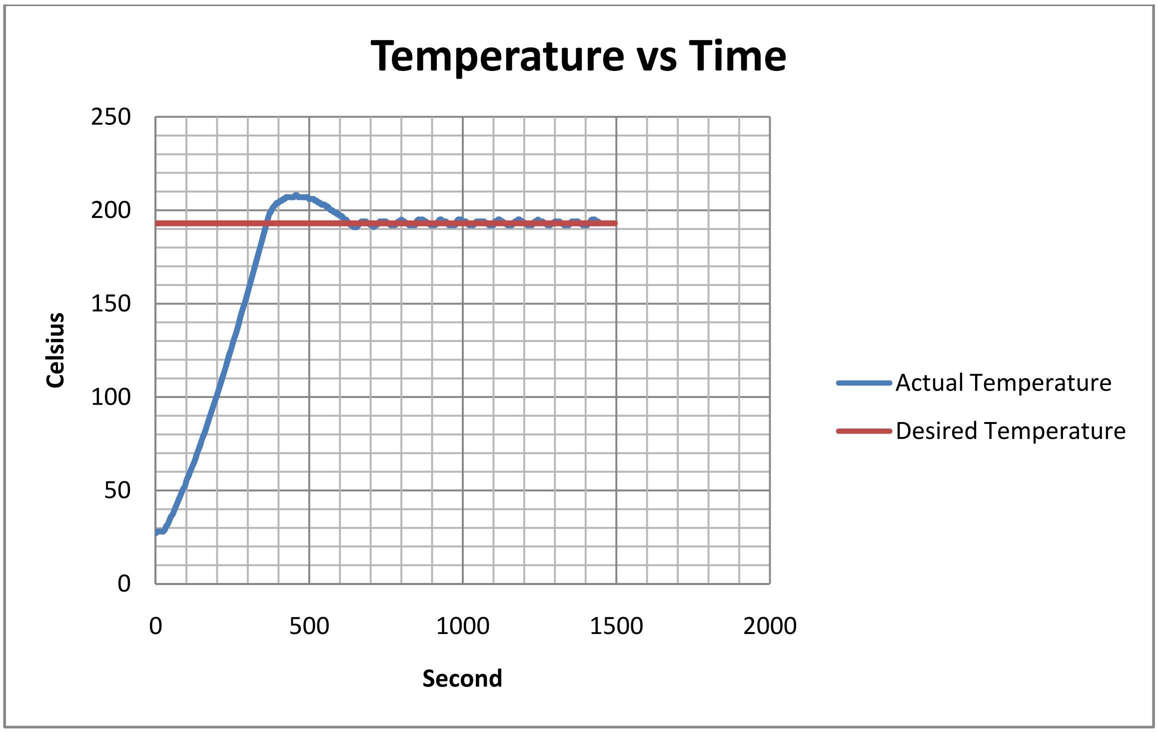


Figure 3.10 Step response - On/Off control of grill

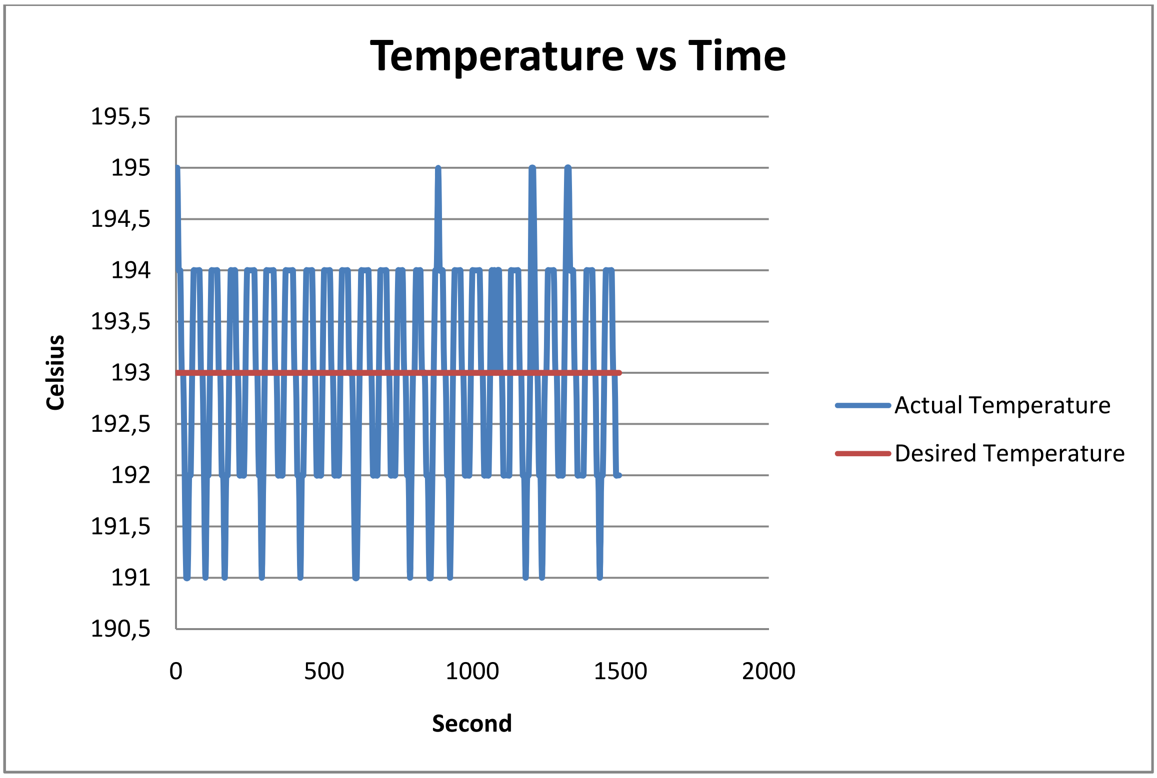


Figure 3.11 On/Off control of grill - Steady state

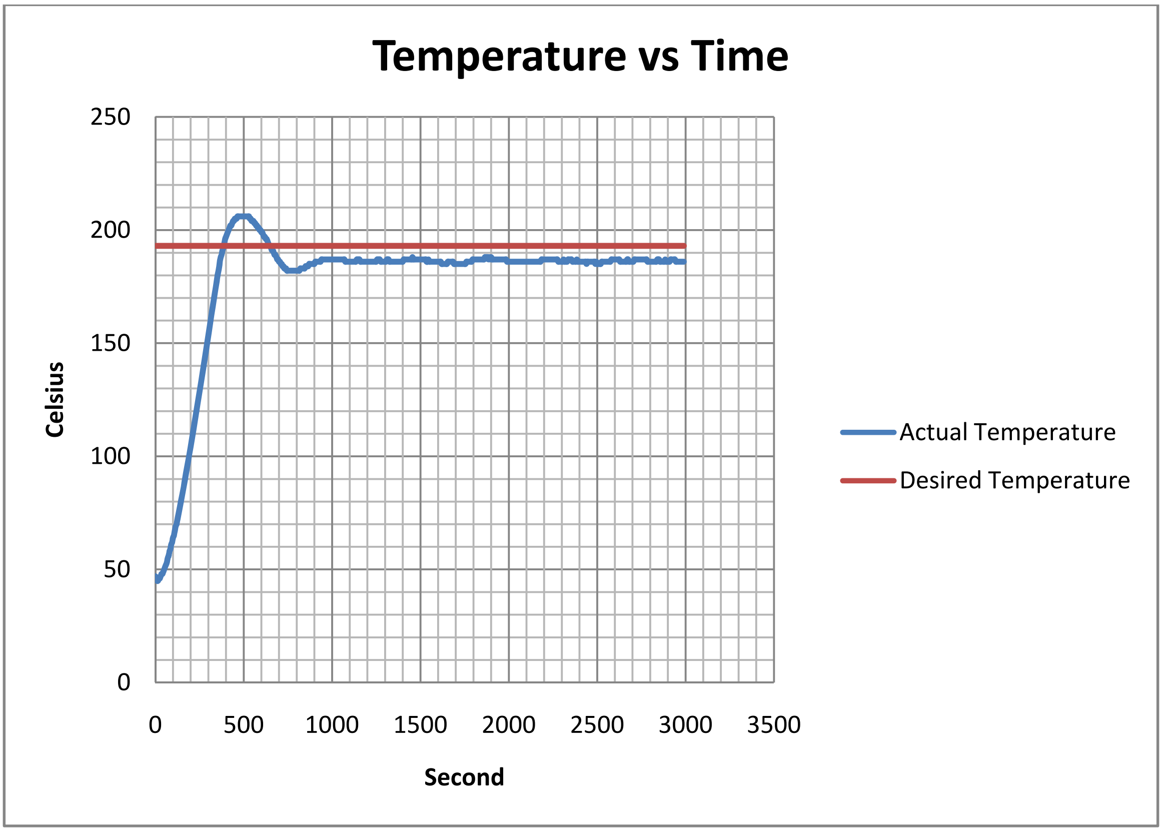


Figure 3.12 Step response of grill - Proportional control with gain 5

When the proportional gain was increased to 10, overshoot increased and the steady state error decreased as expected. Overshoot in this gain was nearly 17°C, and the steady state error was nearly 4°C. Figure *3.13* Step response of grill - Proportional control with gain 10 shows the temperature response in this gain.

When the proportional gain was increased to 20, overshoot increased to 20°C. If the steady state part in this gain is zoomed, it is seen that irregular fluctuations occur as shown in *Figure 3.15 Step response of grill - Proportional control with gain 20, steady state*. Overall temperature response can be seen in Figure *3.14* Step response of grill - Proportional control with gain 20.

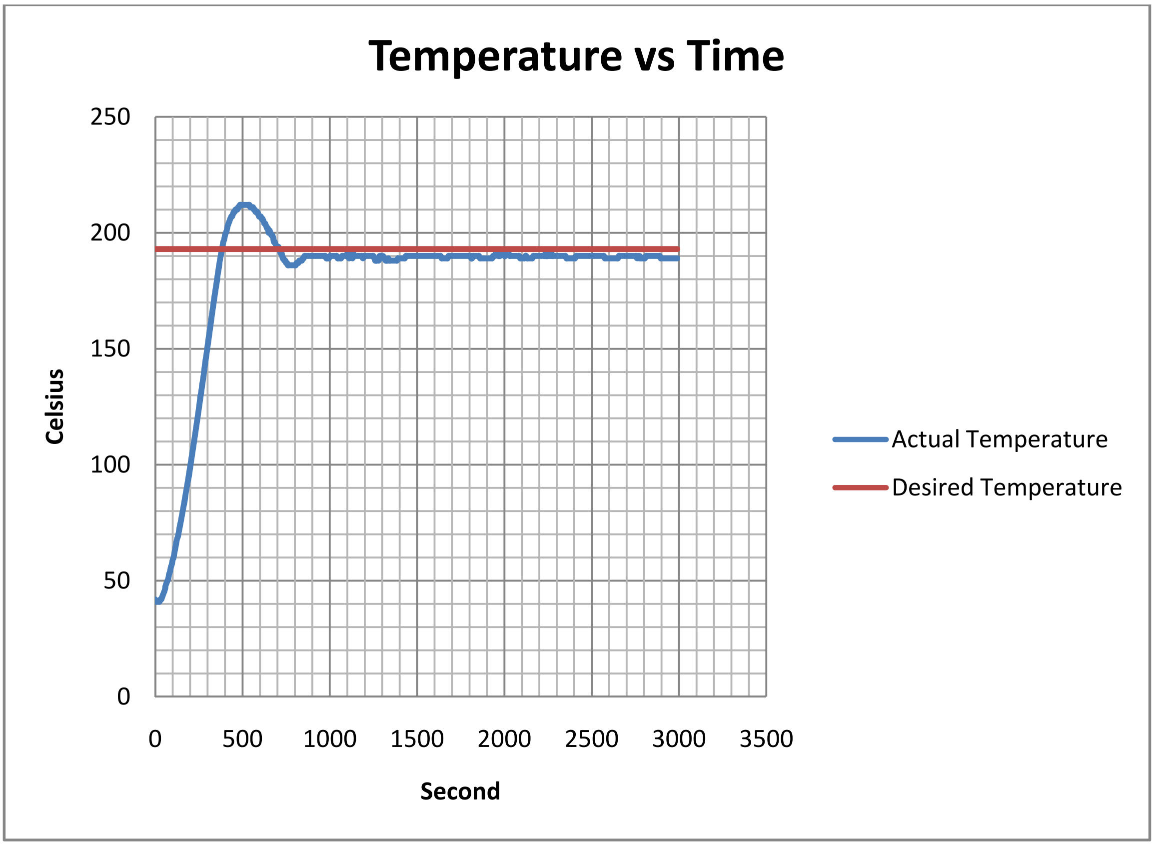


Figure 3.13 Step response of grill - Proportional control with gain 10

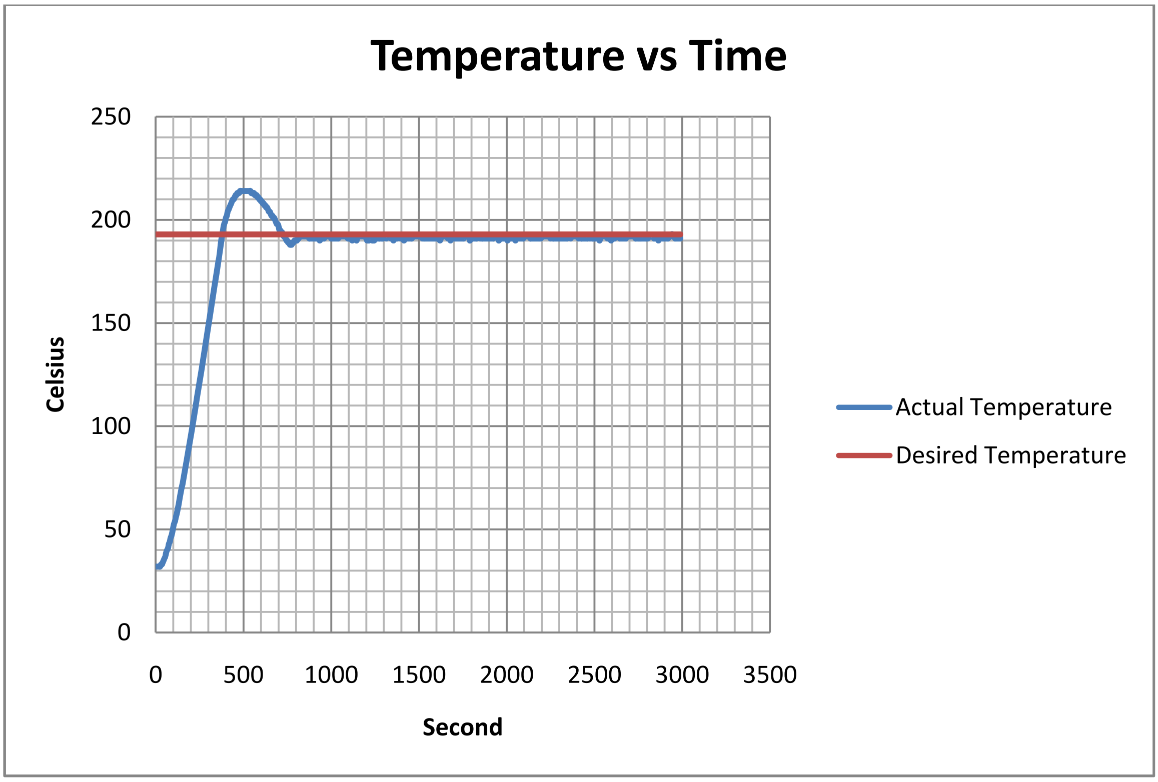


Figure 3.14 Step response of grill - Proportional control with gain 20

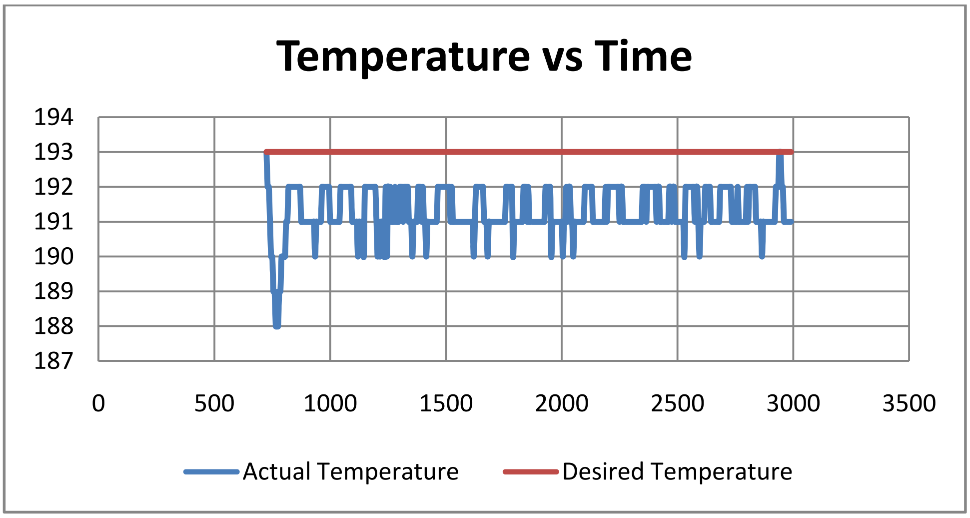


Figure 3.15 Step response of grill - Proportional control with gain 20, steady state

When another grill with the same type and same brand is used for measurements graphs below were obtained. First graph shows the temperature response for proportional gain of 20. Steady state error is 2°C and the overshoot is about 10°C. Temperature graph for proportional gain of 33 is also present below.

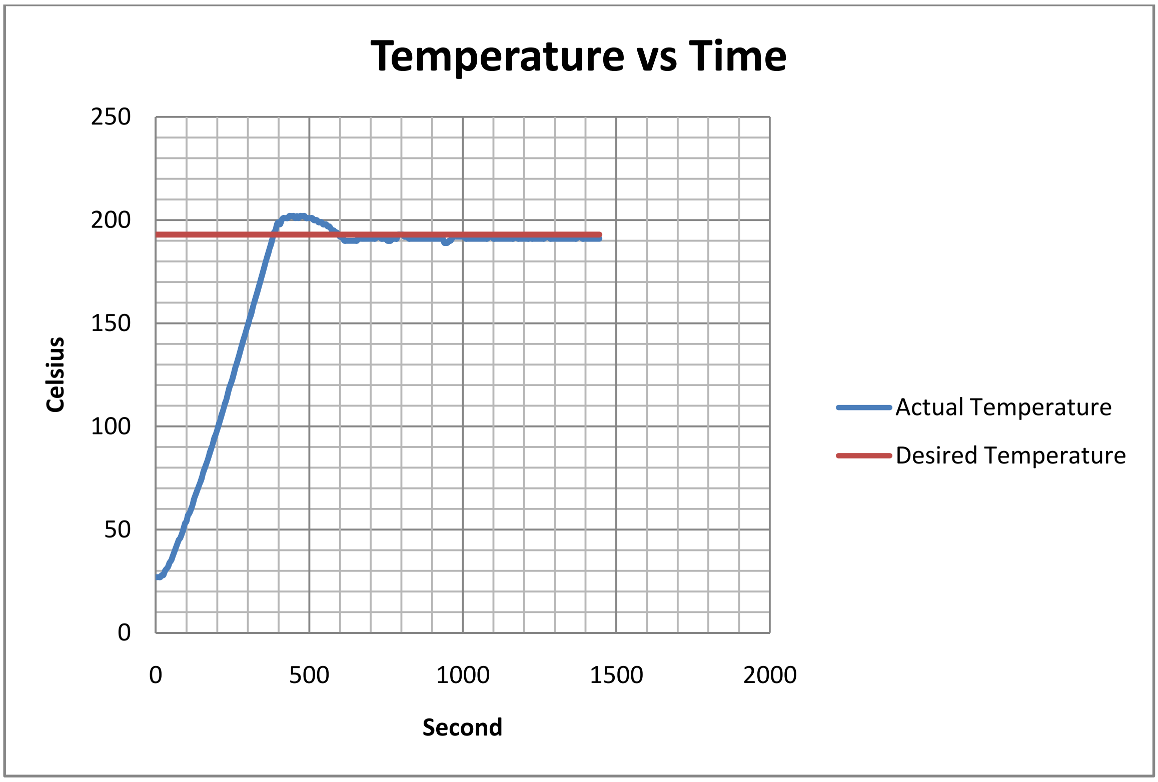


Figure 3.16 Step response of the second grill - Proportional control with gain 20

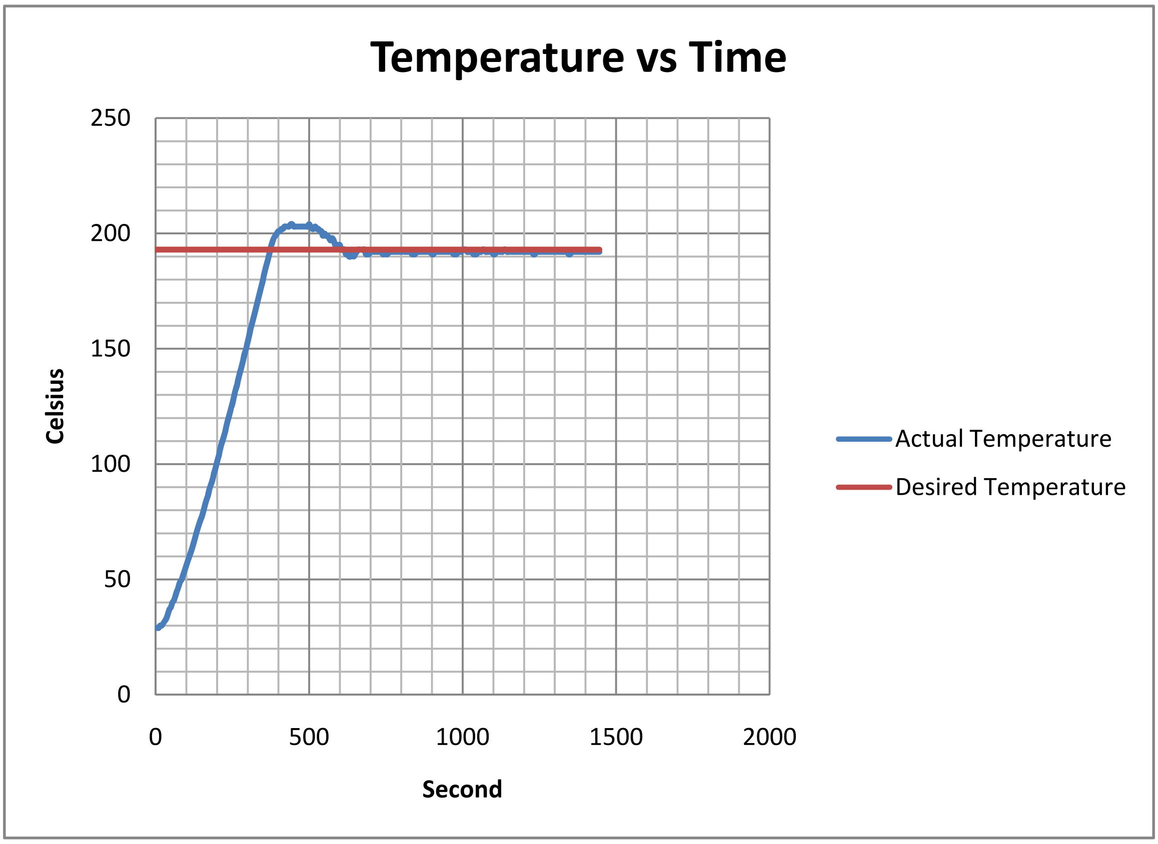


Figure 3.17 Step response of the second grill - Proportional control with gain 33

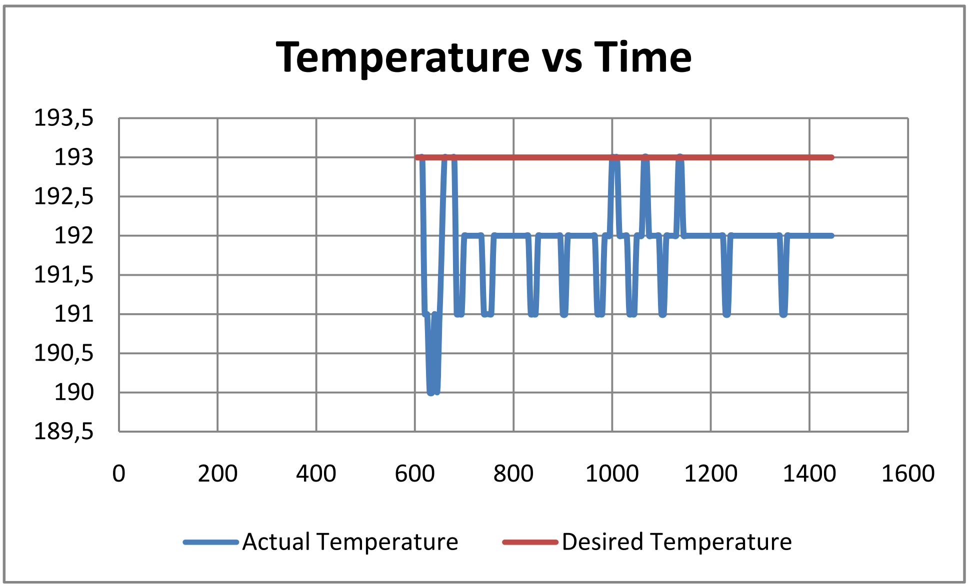


Figure 3.18 Step response of the second grill - Proportional control with gain 33, steady state

When proportional control increased to 40, sustained oscillations are observed. So, 40 can be used as critical or ultimate gain for Ziegler-Nichols method.

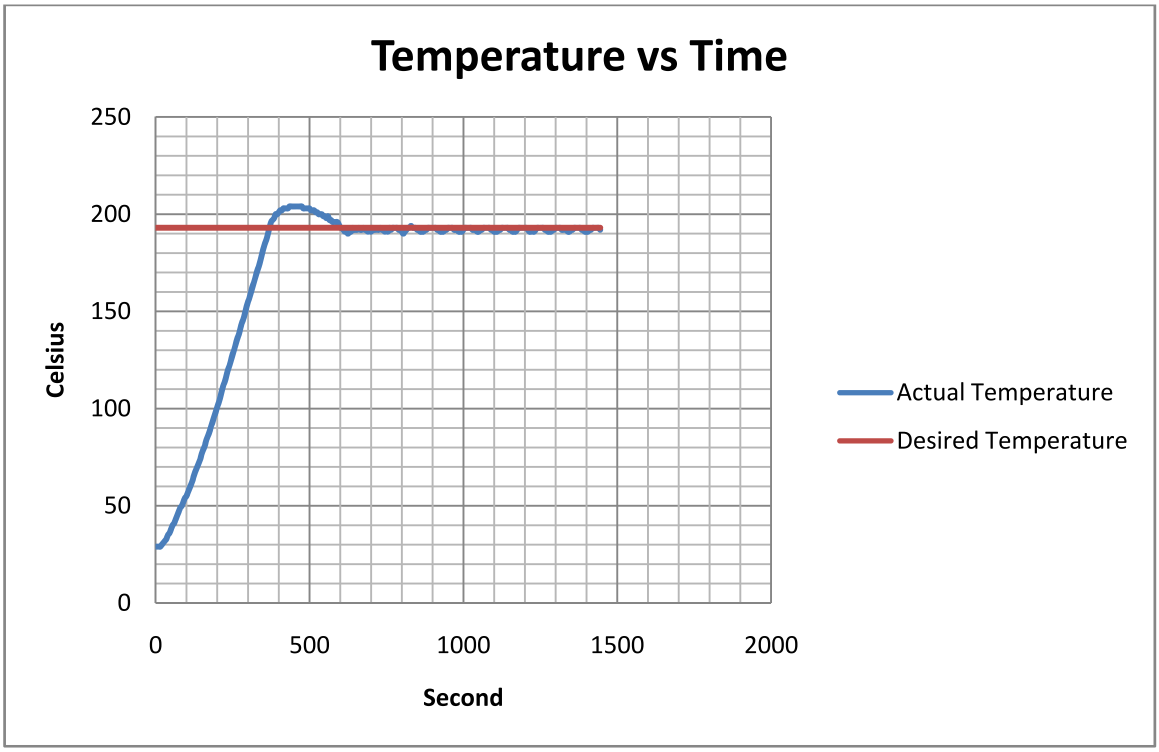


Figure 3.19 Step response of the second grill - Proportional control with gain 40

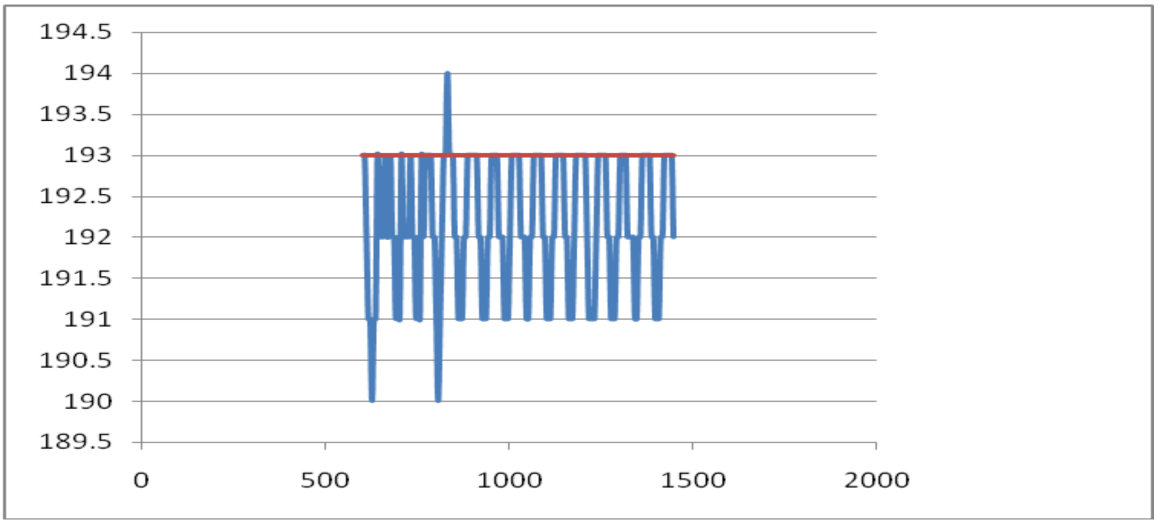


Figure 3.20 Step response of the second grill - Proportional control with gain 40, steady state

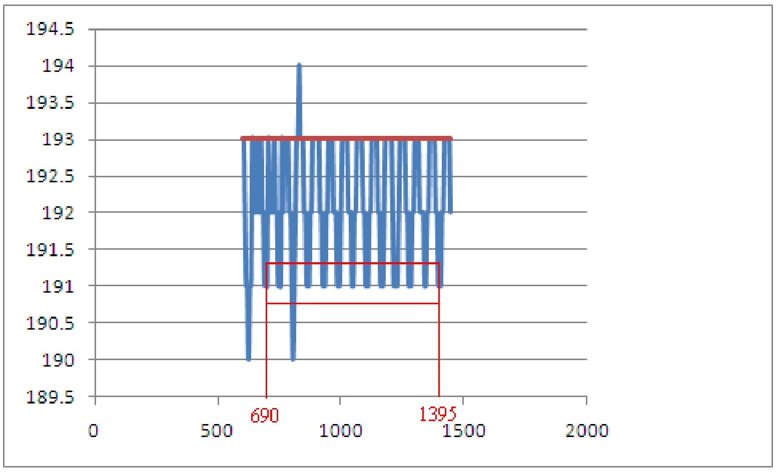


Figure 3.21 Critical period or ultimate period

Period of oscillation is: (1395 – 690) / 12 = 58.75 seconds. Where 12 is the number of oscillation periods between the seconds 690 and 1395. Ziegler-Nichols recommended gains can be calculated as follows:

$K_{cr} = 40$

$P_{cr} = 58.75$

$K_p = 0.6\ K_{cr} = 0.6 \times 40 = 24$

$K_i = 2\ K_p/P_{cr} = 2 \times 24 / 58.75 \approx 0.82$

$K_d = K_pP_{cr}/8 = 24 \times 58.75 / 8 = 176.25$

When these gain values were applied, temperature graph below was obtained. Temperature goes beyond the allowed range of ADC, that is about 300°C and the ADC goes into saturation. Resulting graph is not as expected. Temperature wildly rises even if it exceeds the set point. This is because of the high integral gain value obtained by Ziegler-Nichols method.

Figure *3.23* Step response - K_p=20, K_i=0.001, K_d=0 was obtained for the values K_p=20, K_i=0.001 K_d=0. Note that, steady state error is zero even with an integral gain of 0.001.

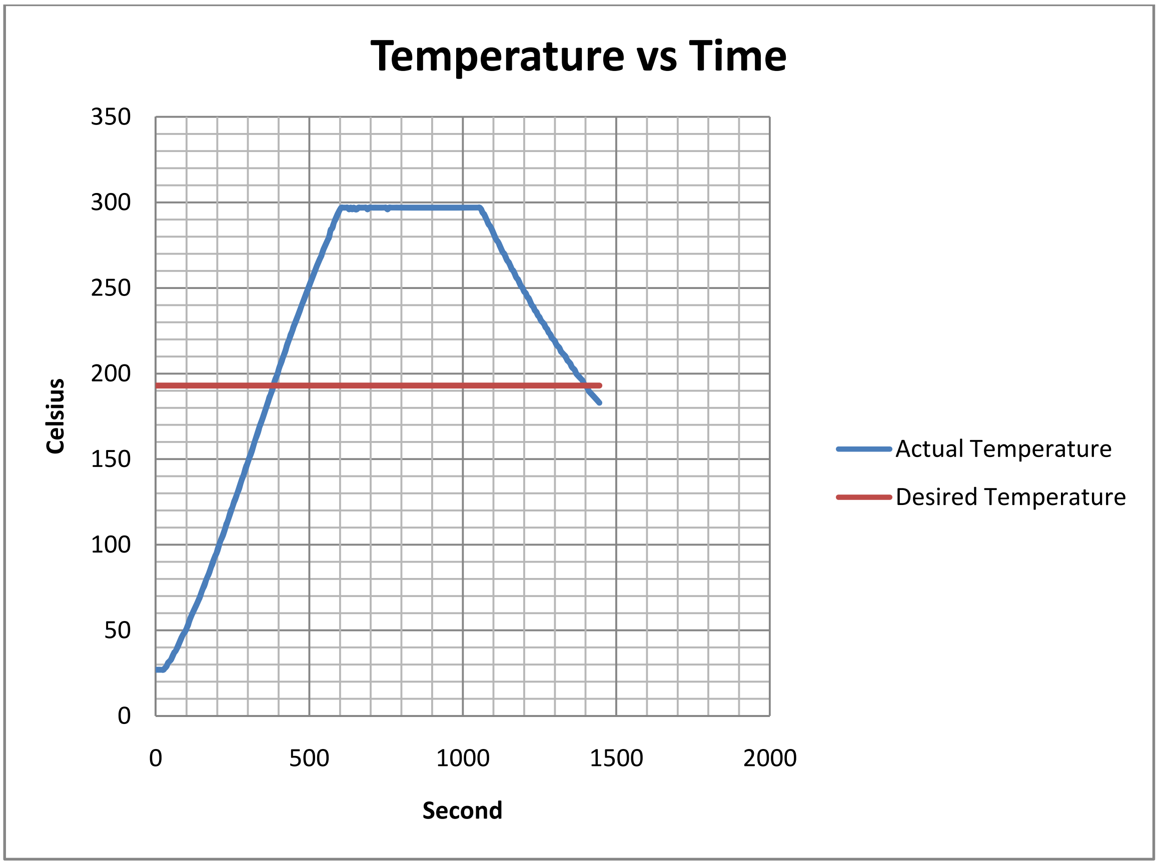


Figure 3.22 Step response - K_p=24, K_i=0.82, K_d=176.25

Since an integral gain of 0.001 seems enough for eliminating steady state error, it was used with the Ziegler-Nichols calculated proportional and derivative gains. Resulting response is shown in the Figure 3.25 Step response - K_p=24, K_i=0.001, K_d=176.25.

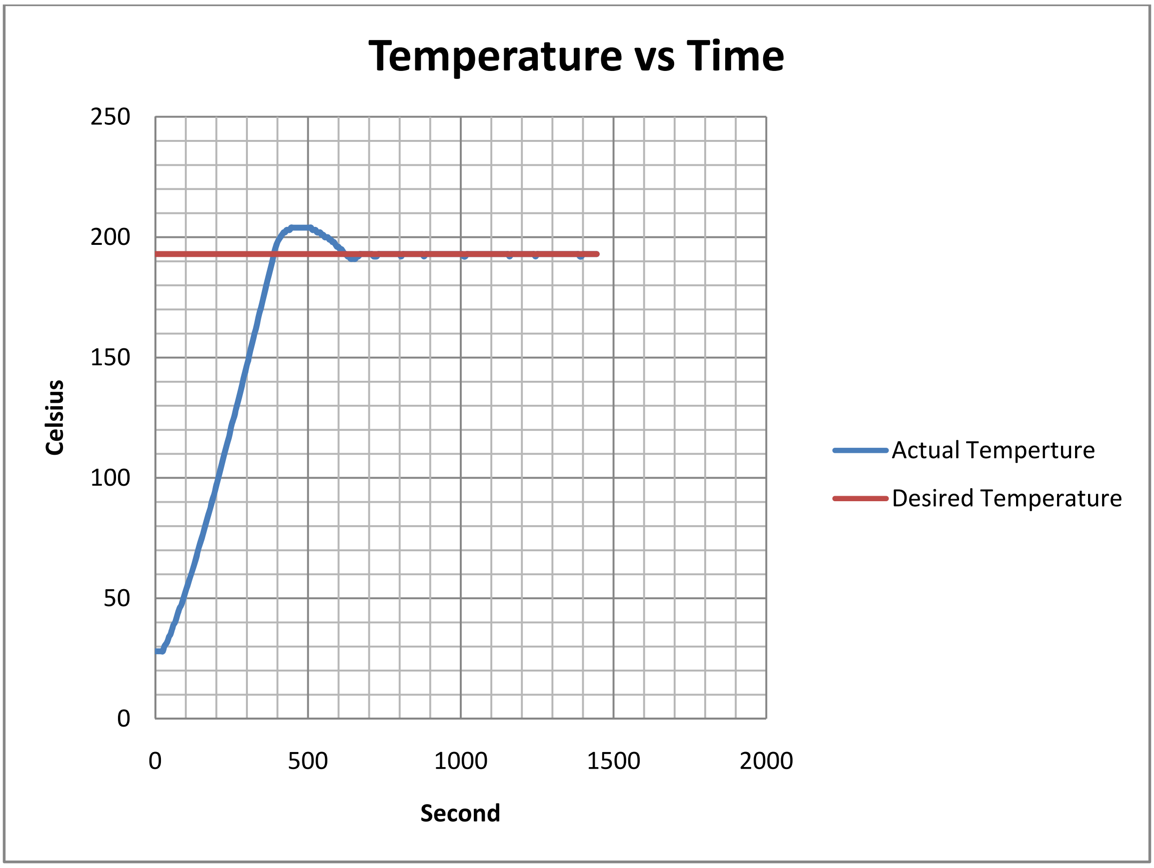


Figure 3.23 Step response - K_p=20, K_i=0.001, K_d=0

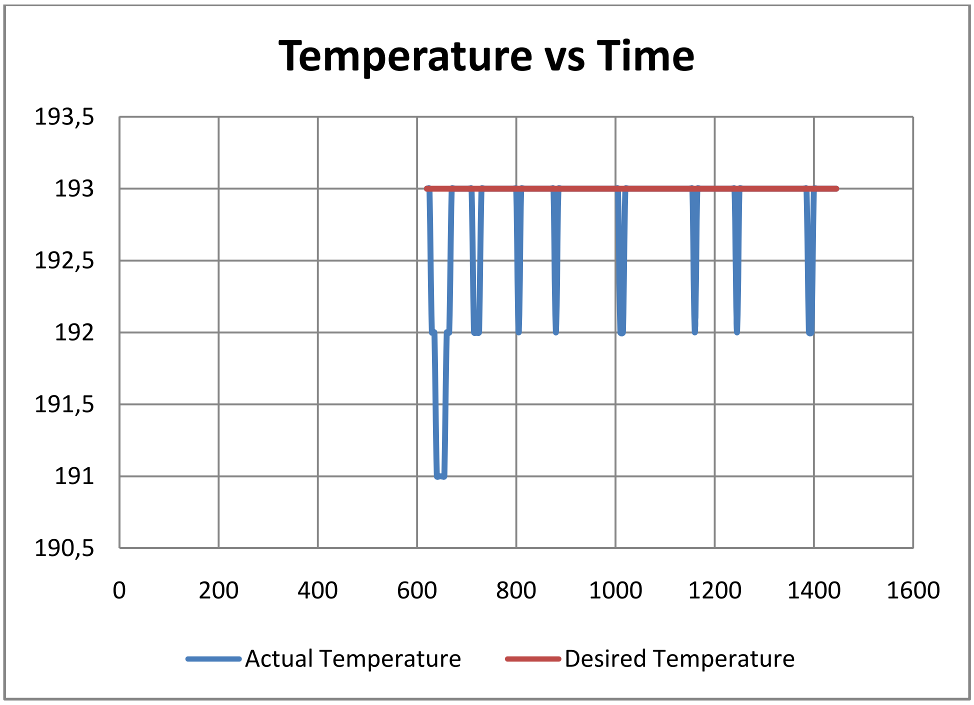


Figure 3.24 Step response - K_p=20, K_i=0.001, K_d=0, steady state

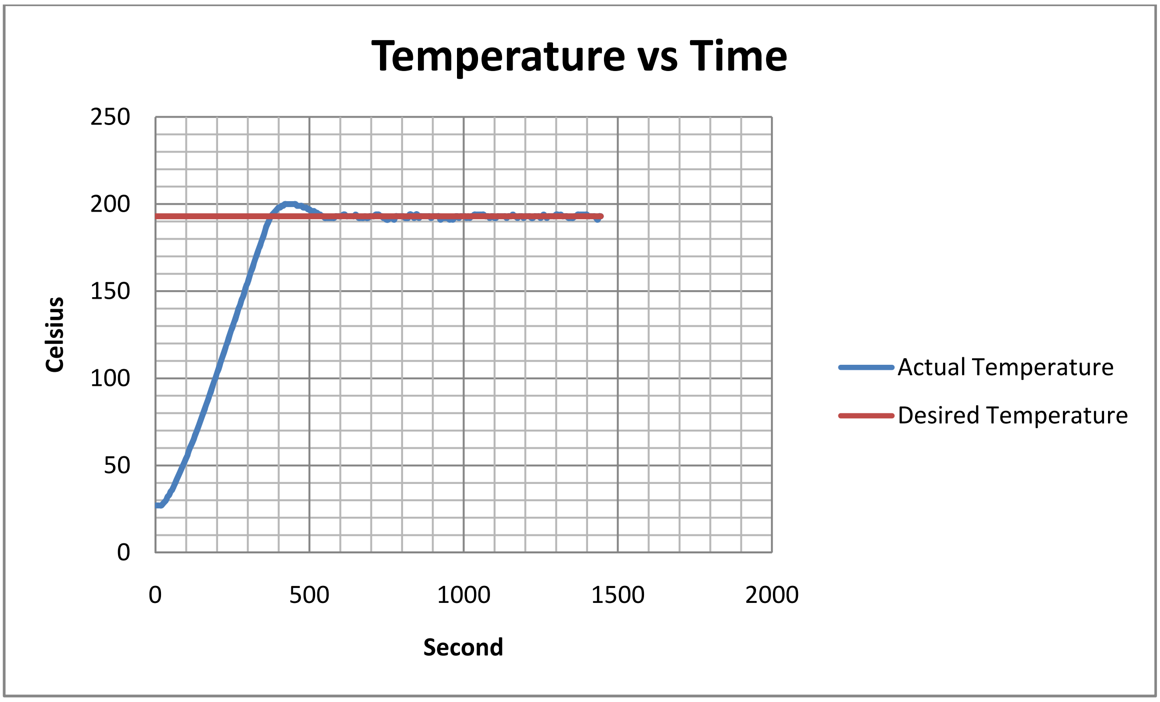


Figure 3.25 Step response - K_p=24, K_i=0.001, K_d=176.25

By looking at the steady state response closer, it is seen that the steady state error is zero although there are some fluctuations around set point.

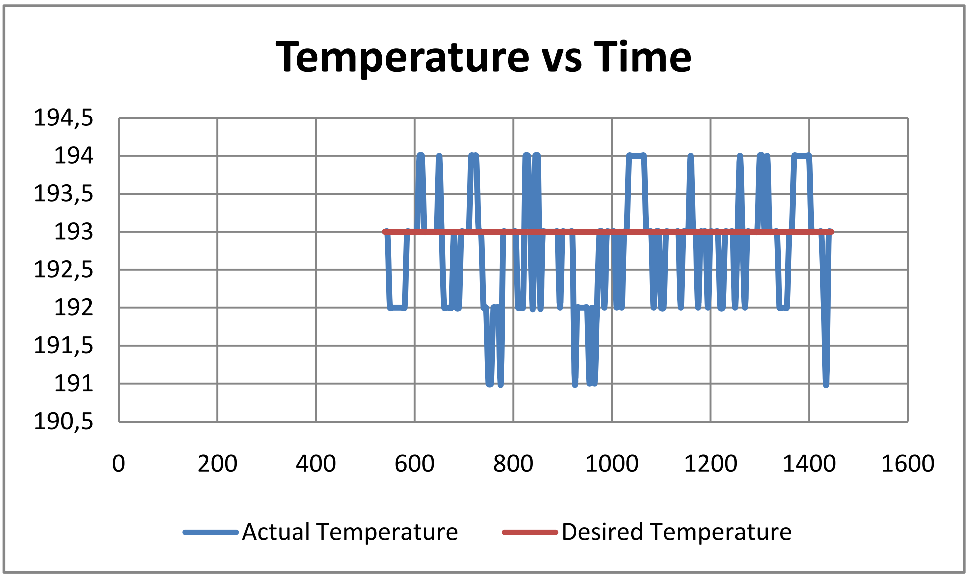


Figure 3.26 Step response - K_p=24, K_i=0.001, K_d=176.25, steady state

Figure below, shows the temperature response of the oven for the Pb-Free soldering with the above gains (K_p=24, K_i=0.001, K_d=176.25). In this setting, time within the preheat area, that is time required for temperature go from 150°C to 200°C for Pb-Free solder alloys, was set to its allowed minimum value of 60 seconds in order to satisfy maximum time for 25°C to peak temperature of 8 minutes. Temperature reached 150°C at nearly 260th seconds, and entered into the soak zone or preheats area. Temperature reached at 200°C at nearly 340th second and so it exits the preheat area. Time spent in preheat area is:

$$340 - 260 = 80 \text{ seconds.}$$

This value satisfies the IPC/JEDEC standard of 60-120 seconds. Liquidous temperature of Pb-Free solder alloy of 217°C was reached at nearly 380th second, and a peak temperature of nearly 240°C was obtained at nearly 440th second. This value is below the maximum time of 8 minutes 25°C to peak temperature according to IPC/JEDEC standards. Ramp up rate in preheat area and in the region above the liquidous temperature is nearly 0.5°C/second, and these values are also satisfies the maximum allowed values of 3°C/second and 6°C/second respectively. On the other hand, requirement for time above liquidous temperature is stated as 60-150 seconds in the standard, but it is read as about 230 seconds in the graph below.

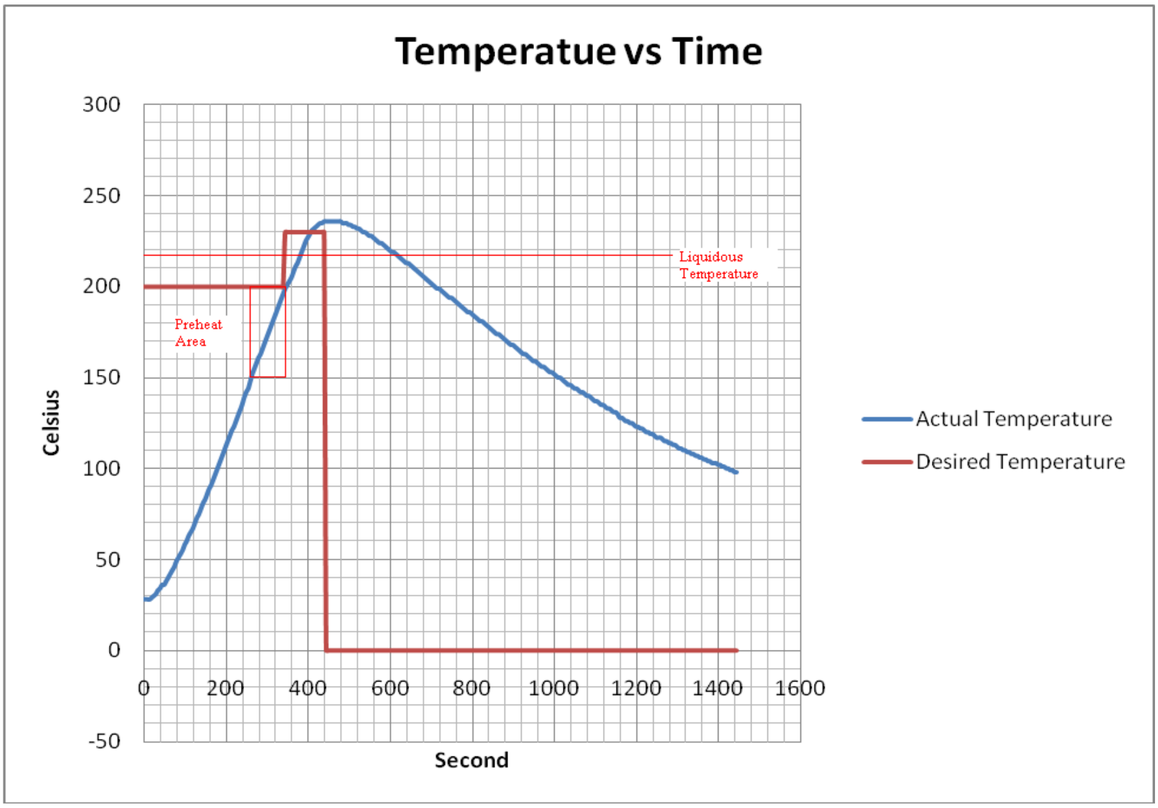


Figure 3.27 Temperature response for Pb-Free soldering - K_p=24, K_i=0.001, K_d=176.25

4. CONCLUSIONS

In this study, a reflow oven for soldering SMD components is designed from the system level to the end of its circuit design and implementation. IPC/JEDEC industry standards are adopted as base requirements, but several other sources from industry are also used as guidelines.

In the system level design, blocks needed for the study are determined. Several alternatives that are available for use in these blocks are compared whenever possible, and the best suited choice for the purpose of this study is adopted.

As temperature sensors, thermocouples are chosen. Use of thermocouples is more complicated than other available temperature sensors because of their need of reference junction compensation. Either one of the junctions of the thermocouple, that is called as reference junction, must be held in a reference temperature such as in a ice-water bath so that its temperature is known to be at nearly 0°C, or another temperature sensor that can measure the absolute temperature must be used to measure and compensate reference junction temperature. Sensitivity is another concern about thermocouples. Approximate sensitivity of a type J thermocouple is 0.054 mV/°C, where as this value decreases to 0.011 mV/°C for type S thermocouples. On the other hand, temperature range that can be measured by thermocouples is much wider than temperature range that can be measured by other temperature sensors. They are stated as most versatile temperature transducers [5].

Switching the oven turn on or off by the controller automatically requires an alternating current power switch controllable by electronic controller circuit. Power transistors are not suitable for switching alternating current sources. Using a relay was one of the alternatives. But relays work mechanically and so, they have long response time. Since PWM is used in this study for controlling the power delivered to the oven, long response time offered by relays makes them unsuitable for the purpose of this project. Another alternative was the use of triacs, which is based on a semiconductor technology, so having a very fast response time and it is chosen as the power switch to the oven. But some troubles were faced while using triac as the power switch. It was not switching the power on or off consistently. When the problem was examined, it turned out to be a overheating problem. Since triac conducts large amount of current to the oven through itself, and has a very small mass and volume, it gets hot as current flows through it. After a while, temperature of triac goes beyond the operating range of it and triac does not work as expected. To solve this problem, a heat sink was connected to triac by using thermal grease, and the heat sink was faced with a fan for efficient cooling.

Switching triac creates high frequency noises in the mains-line, and power signal amplitude during switching affects the amount of noises positively. So, in order to prevent this noise and its dispersion through the mains-line, a zero voltage crossing detector is used to trigger triac.

Temperature response of standard kitchen ovens was seen to be very slow in comparison to requirements specified by IPC/JEDEC standards. Most kitchen ovens available at the market have a power of 1000 watt or 1200 watt. Although 1300 watt ovens were chosen for the measurement in this study, even their temperature responses were seen to be insufficient. Maximum time allowed for temperature to reach at its peak value is specified as 6 minutes for SnPb solder alloy, and 8 minutes for Pb-Free solder alloy in IPC/JEDEC standards. Minimum recommended peak temperatures for SnPb and Pb-Free solder alloys are 215°C and 235°C respectively according to NXP application note "Surface mount reflow soldering description". Time required for the first oven used in this study to reach at these temperatures under open loop response were measured as 1280 seconds and more than 1500 seconds respectively. For the second oven, these values were measured as nearly 700 seconds and 800 seconds respectively. These values are far more beyond the recommended values by the IPC/JEDEC standards.

As a simple alternative to kitchen oven, a mussel grill is used. This grill has two symmetric parts assembled to each other, and opens like a mussel. Upper part contains the resistance in it, so it can efficiently heat up the board and components on the board.

Although response of the ovens is slow, when an on/off or proportional control algorithm was used and step response of the oven was examined, large fluctuations were observed. Amplitudes of these fluctuations are much slower when a mussel grill is used. A reason for these large fluctuations in ovens may be additional delay introduced by the full convectional heating used in the ovens. Since thermocouple used in this study has an important mass, it is possible for it to heat up more slowly than the oven atmosphere does. On the other hand, heating by radiation in the mussel grill can make thermocouple response faster, and can decrease amplitudes of fluctuations significantly.

When proportional, integral and derivative gains calculated by Ziegler-Nichols method were used, and step response of the system was examined, temperature response went far more beyond the set point. Reason for this unexpected behavior is the high integral gain obtained by Ziegler-Nichols method. High integral gain and high error at the beginning of the measurement makes integral term dominant. Since the temperature response is relatively slow, integral of the error becomes very large until the temperature reaches at the set point. With a relatively high integral term, a very high overshoot occurs. Error decreases as time goes on, and proportional term begins to dominate the total output. *Figure 3.9 Step response - Output value, sum of P, I, and D terms* is a good graph for analyzing temperature response and output relationship.

APPENDIX A: THERMOELECTRIC VOLTAGE AS A FUNCTION OF TEMPERATURE

Table A.1 Type J Thermocouples -- thermoelectric voltage as a function of temperature (°C) between 0°C and 310°C; reference junctions at 0 °C [12]

Thermoelectric Voltage in mV											
°C	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
0	0.000	0.050	0.101	0.151	0.202	0.253	0.303	0.354	0.405	0.456	0.507
10	0.507	0.558	0.609	0.660	0.711	0.762	0.814	0.865	0.916	0.968	1.019
20	1.019	1.071	1.122	1.174	1.226	1.277	1.329	1.381	1.433	1.485	1.537
30	1.537	1.589	1.641	1.693	1.745	1.797	1.849	1.902	1.954	2.006	2.059
40	2.059	2.111	2.164	2.216	2.269	2.322	2.374	2.427	2.480	2.532	2.585
50	2.585	2.638	2.691	2.744	2.797	2.850	2.903	2.956	3.009	3.062	3.116
60	3.116	3.169	3.222	3.275	3.329	3.382	3.436	3.489	3.543	3.596	3.650
70	3.650	3.703	3.757	3.810	3.864	3.918	3.971	4.025	4.079	4.133	4.187
80	4.187	4.240	4.294	4.348	4.402	4.456	4.510	4.564	4.618	4.672	4.726
90	4.726	4.781	4.835	4.889	4.943	4.997	5.052	5.106	5.160	5.215	5.269
100	5.269	5.323	5.378	5.432	5.487	5.541	5.595	5.650	5.705	5.759	5.814
110	5.814	5.868	5.923	5.977	6.032	6.087	6.141	6.196	6.251	6.306	6.360
120	6.360	6.415	6.470	6.525	6.579	6.634	6.689	6.744	6.799	6.854	6.909
130	6.909	6.964	7.019	7.074	7.129	7.184	7.239	7.294	7.349	7.404	7.459
140	7.459	7.514	7.569	7.624	7.679	7.734	7.789	7.844	7.900	7.955	8.010

Thermoelectric Voltage in mV											
°C	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
150	8.010	8.065	8.120	8.175	8.231	8.286	8.341	8.396	8.452	8.507	8.562
160	8.562	8.618	8.673	8.728	8.783	8.839	8.894	8.949	9.005	9.060	9.115
170	9.115	9.171	9.226	9.282	9.337	9.392	9.448	9.503	9.559	9.614	9.669
180	9.669	9.725	9.780	9.836	9.891	9.947	10.002	10.057	10.113	10.168	10.224
190	10.224	10.279	10.335	10.390	10.446	10.501	10.557	10.612	10.668	10.723	10.779
200	10.779	10.834	10.890	10.945	11.001	11.056	11.112	11.167	11.223	11.278	11.334
210	11.334	11.389	11.445	11.501	11.556	11.612	11.667	11.723	11.778	11.834	11.889
220	11.889	11.945	12.000	12.056	12.111	12.167	12.222	12.278	12.334	12.389	12.445
230	12.445	12.500	12.556	12.611	12.667	12.722	12.778	12.833	12.889	12.944	13.000
240	13.000	13.056	13.111	13.167	13.222	13.278	13.333	13.389	13.444	13.500	13.555
250	13.555	13.611	13.666	13.722	13.777	13.833	13.888	13.944	13.999	14.055	14.110
260	14.110	14.166	14.221	14.277	14.332	14.388	14.443	14.499	14.554	14.609	14.665
270	14.665	14.720	14.776	14.831	14.887	14.942	14.998	15.053	15.109	15.164	15.219
280	15.219	15.275	15.330	15.386	15.441	15.496	15.552	15.607	15.663	15.718	15.773
290	15.773	15.829	15.884	15.940	15.995	16.050	16.106	16.161	16.216	16.272	16.327
300	16.327	16.383	16.438	16.493	16.549	16.604	16.659	16.715	16.770	16.825	16.881
°C	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**

REFERENCES

1. Lee, N. C., *Reflow Soldering Processes and Troubleshooting: SMT, BGA, CSP and Flip Chip Technologies*, Newnes, 2002.

2. JEDEC Solid State Technology Association, IPC. (2008, March). *Moisture/Reflow Sensitivity Classification for Nonhermetic Solid State Surface Mount Devices.* JEDEC Global Standards for the Microelectronics Industry: http://www.jedec.org/sites/default/files/docs/JSTD020D-01.pdf. Retrieved 6 2010.

3. NXP Semiconductors. (2009, August 13). *AN10365 Surface mount reflow soldering description.* NXP Semiconductors: http://www.nxp.com/documents/mounting_and_soldering/AN10365.pdf. Retrieved 6 2010

4. Alciatore, D. G. and Histand, M. B., *Introduction to Mechatronics and Measurement Systems,* McGraw Hill, Singapore, 2007.

5. Omega Engineering, Inc. (n.d.). *Using Thermocouples.* Omega.com: http://www.omega.com/temperature/Z/pdf/z021-032.pdf. Retrieved 6 2010.

6. Texas Instruments. (2010, January). *MSP430x4xx Family User's Guide (Rev. J).* Texas Instruments: http://focus.ti.com.cn/cn/lit/ug/slau056j/slau056j.pdf. Retrieved 6 2010.

7. Burr-Brown Products from Texas Instruments. (2005, February). *Precision, Low Power Instrumentation Amplifiers (Rev. B).* Texas Instruments: http://focus.ti.com/lit/ds/symlink/ina128.pdf. Retrieved 6 2010.

8. The Ohio State University, Mechanical Engineering. (n.d.). *Electronic Components.* The Ohio State University: http://www.mecheng.osu.edu/book/export/html/187. Retrieved 6 2010

9. Bishop, O., *Understand Electronic Control Systems,* Newnes, Oxford, 2000.

10. Fairchild Semiconductor Corporation. (2009, September). *MOC3043-M. 6-Pin DIP 400V Zero Crossing Triac Driver Output Optocoupler.* Fairchild Semiconductor: http://www.fairchildsemi.com/ds/MO/MOC3043-M.pdf. Retrieved 6 2010.

11. Fairchild Semiconductor Corporation. (2002, 05 07). *AN-3004 Applications of Zero Voltage Crossing Optically Isolated Triac Drivers.* Fairchild Semiconductor: http://www.fairchildsemi.com/an/AN/AN-3004.pdf. Retrieved 6 2010.

12. National Institute of Standards and Technology. (1999, 12 21). *NIST Standard Reference Database 60, Version 2.0.* National Institute of Standards and Technology: http://srdata.nist.gov/its90/main/. Retrieved 6 2010.