Figures/easy-pcb-o

Easy–PCB Solder Reflow Oven

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Features

- **Insulated aluminum frame with XxYxZ interior chamber**
- **XXX Watt heating element with solid state relay control**
- **120 VAC power supply with surge and short protection**
- **Forced convection fan driven by bipolar stepper motor with speed control**
- **Type X thermocouple for temperature feedback loop**
- **PIC18F14K50 based control**
- **Convenient 7–segment display and pushbutton user interface**

Introduction

Easy–PCB is a small, desktop convection oven for DIY reflow soldering at home.

As integrated circuits continue to become smaller and faster, many μControllers, FPGAs, and other ICs are no longer available in DIP form for breadboard prototyping or iron soldering. Similar to the shift away from PC parallel ports in the early 2000s, the shift away from DIPs means modern electronics hobbyists need more complicated equipment than their predessesors.

Currently, commercial solder reflow stations are available for soldering fine pitch, SMD, and BGA componenets. More recently, several hackers have created open source designs for inexpensive reflow ovens, using converted kitchen toaster ovens.

Easy–PCB is better because it is a convection oven; controlled air flow prevents parts from being blown out of position and convection heating obviates the uneven heat absorbtion seen in infrared radiation based systems. Furthermore, *Easy–PCB* was designed from the ground up for soldering, so the heating elements and oven frame were optimized alongside the temperature controller for a typical solder reflow profile.

Figures/control-system.pdf

The *Easy–PCB* Control System: not just a controller bolted onto a disjoint oven.

Easy–PCB allows hobbyists to produce reflow temperature profiles with a high degree of accuracy and repeatability. Alongside freely available PCB design programs like Eagle and low-quantity fabrication services like OSH Park, *Easy–PCB* makes modern integrated components, such as digital CMOS cameras, within the design space of hobbyists and hackers.

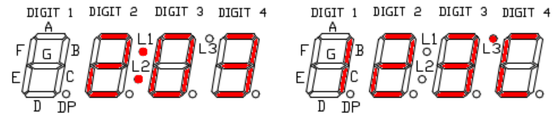
Figures/control-results.pdf

Faithful Temperature Profile Control

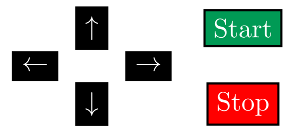
Contents

1 User Interface

Easy–PCB presents temperature and time information on a four digit LED display. After pressing the green 'start' button, the current temperature and process runtime are alternately displayed every second.

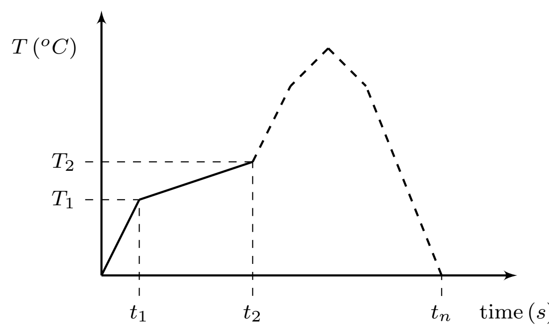


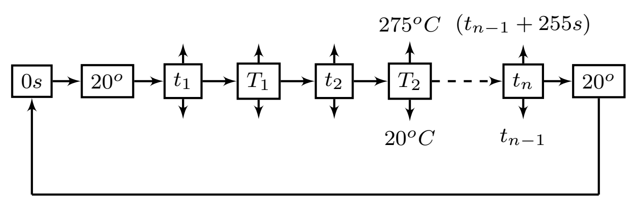
The red 'stop' button can be pressed at anytime to quit the current process or reset the microcontroller.



Pushbutton Interface

Set point programming with the 4 nav keys is used to enter a time–temperature profile. Use the 'left' and 'right' keys to move between set points and the 'up' and 'down' keys to edit each set point value.





Set Point Programming

A total of 128 set points can be entered. The first set point is always ($0s$, 20^oC), and the process will terminate at the next occurance of 20^o in a point. Temperatures can take any value in the range $20^oC < T < 275^oC = 527^oF$. The time between two points must be between $0 <= t < 255$ seconds.

2 Plant Design

2.1 Temperature Objectives

A typical solder reflow profile is shown in figure 1. The optimal shape and peak temperature depend on the components and, more significantly, on the use of

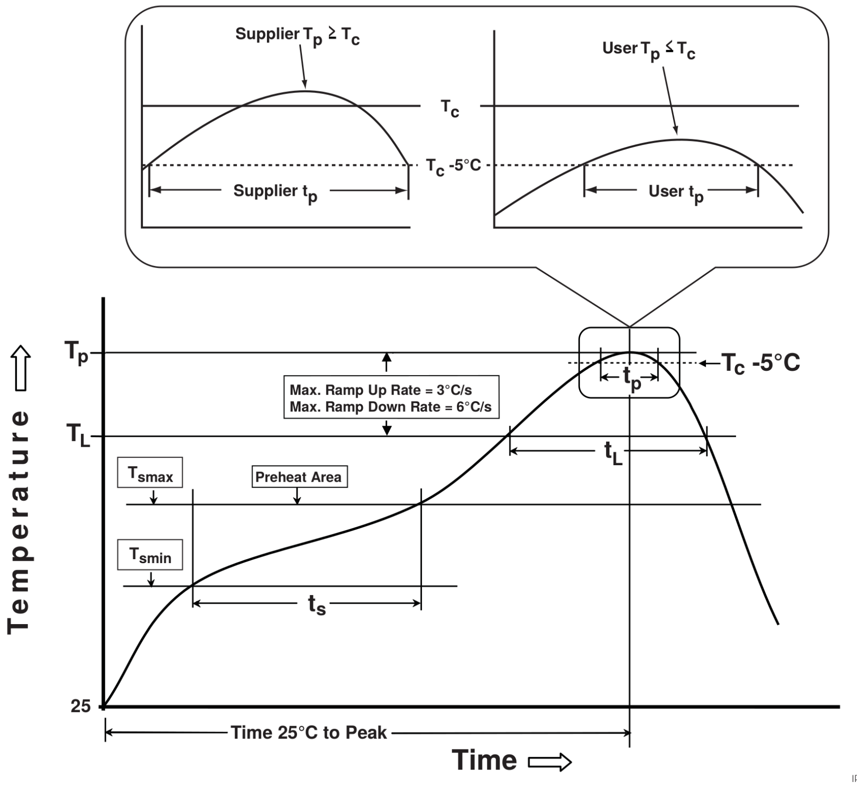


Figure 1: Standard Solder Reflow Profile, per IPC/JEDEC STD-1-020D.1

leaded solder.

$$T_p \approx T_c = \begin{cases} 220-235^oC & \text{Leaded solder} \\ 245-260^oC & \text{Pb–free} \end{cases}$$

$$t_p = \begin{cases} 20s & \text{Leaded solder} \\ 30s & \text{Pb–free} \end{cases}$$

Easy–PCB was designed from the ground up for faithfully producing these reflow profiles. This design process for the thermodynamic system is detailed below.

2.2 Thermodynamics Theory

Heat is everyone's least favorite form of energy because it tends to dissipate everywhere and is difficult to transform into useful work. Nevertheless, it is a form of energy so it is measured in joules.

$$Q := \text{Heat}\,[\text{Joules}]$$

From a microscopic view, heat is the kinetic energy of gas molecules or the vibrational energy of bonds in solids. In both cases, summed over every molecule, every bond, and every vibrational mode in the system.

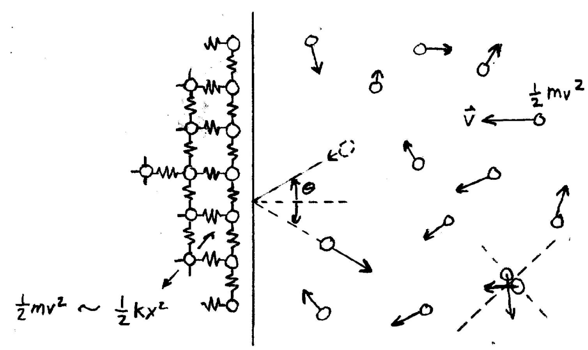


Figure 2: Heat Energy on a Molecular Scale

Temperature is a potential field that measures an objects tendancy to give up or absorb heat. On average, heat always flows from regions of hotter temperature temperature to lower temperature. Temperature is usually measured in Kelvin or Celsius, which are related by

$$T_{\text{Celsius}} = T_{\text{Kelvin}} + 273.16.$$

Another way to think of temperature is a measure of heat density that also incorporates the types of bonds (or lack thereof) in which heat energy is stored.

For example, a glacier contains more heat than a pot of boiling water, but has a much lower heat density.

The relationship between temperature and heat stored in an object is given by

$$dQ = mc_p dT, \tag{1}$$

where c_p is the specific heat of the material with units $\left[\frac{kJ}{kg*K}\right]$.

So heat flows spontaneously to reduce temperature gradients, but how does heat flow and at what rate? There are three mechanisms of heat transfer: *conduction*, *convection*, and *radiation*.

Conduction of heat is caused by molecular interactions, such as the push–pull of nearby atomic bonds in solids or elastic collisions between molecules of air.

The empirical relation for conduction is Fourier's Law, which says the rate of heat transfer due to conduction is proportional to both the difference in temperature and the media:

$$\vec{q} = k\vec{\nabla}T$$

where $\vec{q}$ is the rate of heat transfer per unit surface area and k is the thermal conductivity of the medium with units $\left[\frac{W}{m*K}\right]$.

In integral form, Fourier's Law is

$$\frac{\delta Q}{\delta t} = k \oint_S \vec{\nabla}T * d\vec{A}.$$

And, in the one dimensional case,

$$\frac{\delta Q}{\delta t} = -kA\frac{\delta T}{\delta x}. \tag{2}$$

Convection is the second mechanism of heat transfer, involving the bulk movement of particles driven by diffusion.

Every air molecule is moving in a random direction with random kinetic energy, but a region of air with higher average kinetic energy (temperature) will see more molecules leaving than entering on average, because those leaving are moving faster than those entering.

Note that in convection, no molecules gain or lose energy; molecules of different energy simply trade places.

If a fan is used to apply work to a gas, the rate of convection increases and then Newtons' Law of Cooling can predict the rate of convection in gas near a solid surface of different temperature.

$$\frac{dQ}{dt} = hA\Delta T \tag{3}$$

where h is the heat transfer coefficient with units $\left[\frac{W}{m^2*K}\right]$.

Radiation, the third mechanism of heat transfer, is more familiar to electrical engineers. In any material, electrons have discrete amounts of energy based on the wave patterns that can exist for the atomic geometry. When an electron spontaneously falls to a less energetic patter, that energy is emitted as a photon of light.

The classic, physics–history example is black body radiation, when a metal is heated to high temperature and glows. A more modern examle is the LED.

The empirical relation for radiation is the Stefan–Boltzmann Law, which says that the total energy radiated, over all wavelengths and per unit surface area, is proportional to the fourth power of the body's temperature.

$$j^* = \sigma T^4 \tag{4}$$

where σ is a proportionality constant derived from other constants of nature.

Mechanisms & Media Usually one mechanism of heat transfer is dominant in a particular medium, so much so that we can ignore the other two. Typically this means conduction in solids, convection in fluids or gas, and radiation in space. However, sometimes the picture is more complicated including two cases in an oven:

1. At the boundary of metal and air, where conduction and convection are both significant.

2. In a thermocouple loop, where thermal diffusion (convection) of electrons is useful despite conduction still being dominant.

2.3 Thermodynamic Design

Most microwaves draw between 600 and 1200 Watts of power. An IR toaster oven may draw 1500 Watts into its lamps. How much power does *Easy-PCB* need to produce the required temperature profiles?

Our approach for answering this question is to browse available parts on McMaster.com, imagine how they would be assembled into an oven, and then model their thermodynamic response using SPICE.

A first conceptual design of *Easy–PCB* is shown in figure 3.

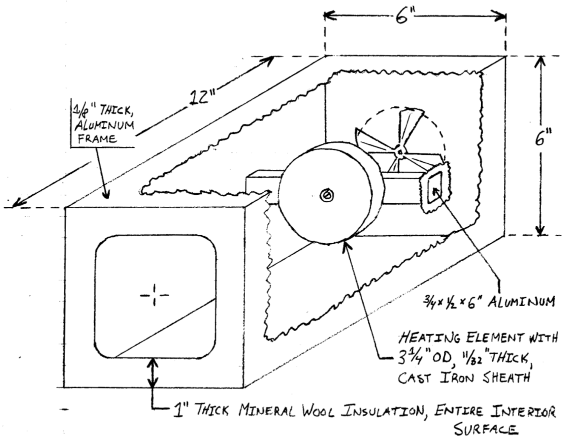


Figure 3: Concept for Thermodynamic System

Conduction through Metals & Insulation

In the concept, the oven chamber is isolated from the outside with walls of mineral wool insulation and aluminum. If the wall is relatively thin compared to the square root of its surface area, then its heat transfer can be modeled as a 1–D transmission line, like shown in figure 4.

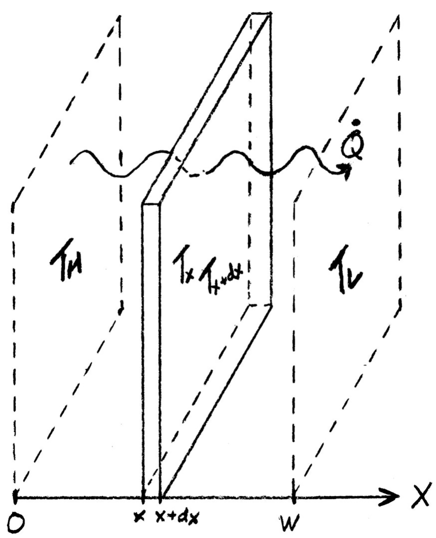


Figure 4: Heat Conduction in 1–D

Assuming conduction is the dominant mechanism of heat transfer and using Fourier's Law in 1–D, (equation 2) the rate of heat passing through a thin slice is

$$\frac{\delta Q}{\delta t} = -kA\frac{\delta T}{\delta x}$$

And, from equation 1, the heat capacity of a thin slice of the metal sheath is

$$dQ = (\rho A dx)c_p dT$$

Rewriting these equations to look like current-voltage relationships gives

$$\delta T = R_x\frac{\delta Q}{\delta t}, \quad R_x = \frac{\delta x}{kA} \tag{5}$$

and

$$\frac{\delta Q}{\delta t} = C_x\frac{\delta T}{\delta t}, \quad C_x = \rho A c_p * \delta x \tag{6}$$

Values for thermal conductivity k, specific heat capacity c_p, and density ρ of different materials are listed in table 1.

Long metal bars and rods can also be modeled with equations 5 and 6 if the heat loss along the length of the bar is assumed to be negligible compared to heat transfered at the end faces.

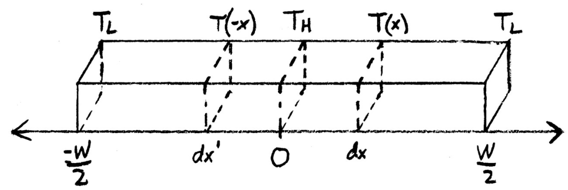


Figure 5: 1–D Conduction in Both Directions

For metal components where heat is injected at the center of the part and dissipates symmetrically in either direction, such as the support bar shown in figure 5 or the metal sheath encasing the heating element, the surface area can be doubled so that the transmission line only needs to be integraded in the positive direction.

$$\begin{cases} R_x & \Rightarrow & R_x/2 \\ C_x & \Rightarrow & 2C_x \\ \{x \mid -\frac{w}{2} \le x \le \frac{w}{2}\} & \Rightarrow & \{x \mid 0 \le x \le \frac{w}{2}\} \end{cases} \tag{7}$$

Conductivity of Metal–Air Interface

In the bulk volume of air, convection is the dominant form of heat transfer and collisions are relatively rare. However, where the air meets a solid surface, the net convection must go to zero because there can be no net movement of air molecules into the solid. Furthermore, every air molecule that reaches the surface experiences a collision so there is 100% conduction at the surface.

For some distance away from the surface, there is a larger than normal chance of head–on collisions and slower rates of diffusion due to the nearby wall. In this region, both conduction and convection may be

Table 1: Thermal Conductivity, Specific Heat, and Density of Selected Materials

Material	Linear Region (K–K)	k $\left(\frac{W}{m*K}\right)$	c_p $\left(\frac{kJ}{kg*K}\right)$	ρ (kg/m^3)

significant. To analyze this transition region, we will start at the surface where there is 100% conduction because that is the mechanism we have equations for.

From the first law of thermodynamics, the rate of heat being stored in a differential volume is equal to the rate of heat entering less the rate of heat leaving the volume element.

$$\frac{\delta Q_{\text{stored}}}{\delta t} = \frac{\delta Q_{\text{in}}}{\delta t} - \frac{\delta Q_{\text{out}}}{\delta t}$$

Looking back at figure 4, the differential volume element is a plane, so

$$\frac{\delta Q_{\text{stored}}}{\delta t} = \frac{\delta Q_{x}}{\delta t} - \frac{\delta Q_{x+\delta x}}{\delta t}.$$

Substituting in equation 1 for stored heat capacity and equation 2 for conduction through the element yields a transport equation.

$$mc_p\frac{\delta T}{\delta t} = kA\frac{\delta T}{\delta x} \tag{8}$$

This cannot be solved analytically unless space and time are independent. Sorry Albert.

$$T(x\,,t) = T_x(x) * T_t(t) \tag{9}$$

Applying the chain rule to equation 8

$$mc_p\frac{\delta T_t(t)}{\delta t}T_x(x) = kA\frac{\delta T_x(x)}{\delta x}T_t(t)$$

and separating variables gives

$$mc_p\frac{\delta T_t(t)}{\delta t} * \frac{1}{T_t(t)} = kA\frac{\delta T_x(x)}{\delta x} * \frac{1}{T_x(x)}.$$

The only way for the equality to be true for all space and time is if both sides are equal to a common constant.

$$\alpha = mc_p\frac{\delta T_t(t)}{\delta t} * \frac{1}{T_t(t)}$$

$$\alpha = kA\frac{\delta T_x(x)}{\delta x} * \frac{1}{T_x(x)}$$

Each of these can be solved by separation of variables.

$$\frac{\alpha}{kA}\delta x = \frac{\delta T_x(x)}{T_x(x)}$$

$$\frac{\alpha}{kA}\int \delta x = \int \frac{1}{T_x(x)} * \delta T_x(x)$$

$$\frac{\alpha x}{kA} = ln\left(T_x(x)\right) + \beta_1$$

$$T_x(x) = \beta_1^{'} e^{\alpha x/kA}$$

Similarly for time,

$$T_t(t) = \beta_2^{'} e^{\alpha t/mc_p}.$$

Recombining the independent components gives

$$\Delta T(x\,,t) = \beta_1^{'}\beta_2^{'} e^{\alpha x/kA + \alpha t/mc_p}$$

The boundary conditions are that at $t = 0$ and $x = 0$, the temperature difference is the initial temperature difference, and at $t \to \infty$ and $x \to \infty$, the temperature difference dissipates to zero.

$$\Delta T(x\,,t) = \Delta T_0 e^{-\alpha x/kA - \alpha t/mc_p}$$

Now, for the sake of physical intuition we can write

$$\Delta T(x\,,t) = \Delta T_0 e^{-(x/\delta + t/\tau)}, \tag{10}$$

where δ is a 'skin depth' over which the spacial gradient decays to $1/e$ its initial value and τ is a time constant related to the skin depth by

$$\tau = \frac{mc_p}{kA}\delta. \tag{11}$$

At any moment in time, we can plot the temperature of air as one moves away from the sheath surface. We see there is a certain distance, called the skin depth δ, over which the temperature gradient is nearly dissipaited and the bulk air begins.

PLOT with T0et/alpha and Tbulk on y axis and x on x axis

Forced convection from the fan causes the bulk air, uniform temperature region to be pushed closer to the sheath's surface. If the skin depth can be pushed sufficiently close to the surface, then the time constant shrinks due to the relation $\alpha = \frac{k}{\rho c_p}\delta$. Thus, for sufficiently strong circullation and close skin depth, the time constant becomes small enough that the system is effectively always in steady state, where

$$\frac{dT}{dt} \approx 0$$

From the first law of thermodynamics (conservation of energy), the difference between heat flowing in and out of a thin slice by all mechanisms is equal to the heat stored within that slice, for all t and x.

$$\frac{\delta Q_{\text{cap.}}}{\delta t} * \frac{1}{\delta x} = \frac{\delta Q_{\text{cond.}}}{\delta t} * \frac{1}{\delta x} + \frac{\delta Q_{\text{conv.}}}{\delta t} * \frac{1}{\delta x}$$

Substituting equation 6 for the heat capacity of a thin slice yields:

$$\rho A c_p \frac{\delta T}{\delta t} = \frac{\delta Q_{\text{cond.}}}{\delta t} * \frac{1}{\delta x} + \frac{\delta Q_{\text{conv.}}}{\delta t} * \frac{1}{\delta x}$$

But we have just argued that if the skin depth can be made very close by forced convection, then $\frac{dT}{dt} \to 0$.

$$\frac{\delta Q_{\text{conv.}}}{\delta t} * \frac{1}{\delta x} = -\frac{\delta Q_{\text{cond.}}}{\delta t} * \frac{1}{\delta x}$$

Integrating across x is easy.

$$\frac{dQ_{\text{conv.}}}{dt}(x) = C - \frac{dQ_{\text{cond.}}}{dt}(x)$$

At the surface of the sheath ($X = 0$), heat transfer in the air is 100% conduction because every air molecule at ($X = 0$) is colliding with metal and exchanging energy. Therefore

$$C = \frac{dQ_{\text{cond.}}}{dt}(X = 0)$$

Applying Fourier's Law to the temperature profile found in equation **??** give us equations for the rate of heat tranfer due to conduction, and finally this leads to

$$\dot{Q}_{\text{cond.}}(x) = Q_0 e^{-x/\delta}$$

and

$$\dot{Q}_{\text{conv.}}(x) = Q_0 \left(1 - e^{-x/\delta}\right)$$

where

$$Q_0 = \frac{kAT_0}{\delta} e^{-t/\alpha}$$

Finally, if we absorb $e^{-t/\alpha}$ into T_0 for steady state, then

$$Q_0 = \frac{kA}{\delta} T_0 \tag{12}$$

Heat Capacity of Chamber Air

2.4 Component Selection & SPICE Modeling

2.5 Transfer Model

3 Thermocouple Amplifier Design

3.1 Controller and Power Requirements

4 Motor Driver Design

4.1 Power Requirements

5 Power Circuit Design

6 Controller Design