Sous-Vide Final Project

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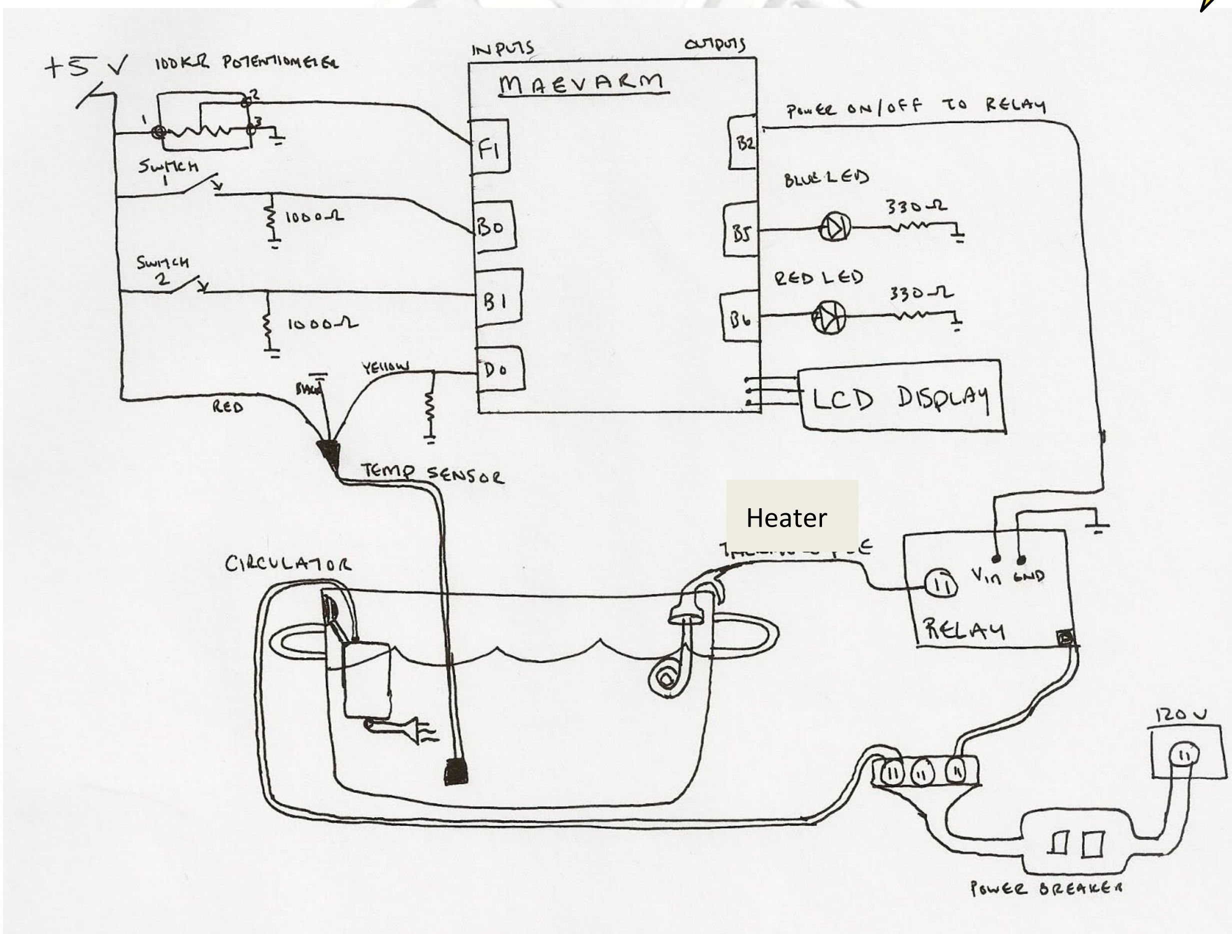
1) Introduction

The world of culinary arts is a creative and inspiring platform for chefs and scientists alike to share a love for food. This final design project details a careful marriage of these two brilliant art forms in the creation of a multidisciplinary cooking apparatus. In the culinary world there has been a recent shift towards experimenting with scientific approaches to cooking. This manner of food preparation in known as molecular gastronomy and is characterized by use of technical innovations from the scientific disciplines. One of the most popular techniques used in this style is known as sous-vide which is French for “under vacuum.” In this final design project, a thermal immersion circulator is created for the purpose of sous-vide cooking. Below is an image of sous-vide cooking in action taken from the famous *Modernist Cuisine*, a best seller on molecular gastronomy.

2) Circuit Documentation:

a) Figure 1: Circuit Diagram



b) Description of Circuit:

There are four inputs and four outputs connected to the JHURSAEB/ Maevarm. There is a 100KΩ potentiometer connected to pin F1 that we use analog to digital conversion on to set our values for desired temperature for cooking and desired time for the timer. There are two switches connected to pins B0 and B1 with 1000Ω pull down resistors connected to ground. These buttons were used to navigate the menu and select temperature mode, control mode, and other settings. There is a temperature sensor that uses a 5V voltage supply, and sends and receives data through pin D0. The thermometer itself is submerged in water inside of our pot. There are two LEDs connected to pins B5 and B6 and in series with a 330Ω resistor in order to get a desired current of .1A **. The red LED (B6) turns on when the heating element is on and the blue LED (B5) turns on when the sous vide is in PID mode. There is an LCD display connected to the JHURSAEB in order to output our menu and temperature information. The last output (B2) is the relay power signal which controls the heating element.

We used a relay to switch a heater on and off depending on the reading of the temperature sensor. The relay is connected to a power breaker which is connected to a 120V wall plug. The signal input comes from pin B2, the other pin is grounded. The heating element is submerged in water inside of a pot. There is also a circulator pump in the pot that circulates the water so the temperature is the same everywhere in the pot.
** $(5V - 1.7V)/.1A = 330\Omega\ Resistor$

c) Engineering Analysis

The sous vide has two settings: Thermostat mode and PID mode. In Thermostat mode, the heater turns on whenever the temperature drops below the target, and turns off whenever the temperature rises above the target. This is crude but effective, and results in a sawtooth temperature profile, as the system overshoots and undershoots repeatedly (Figure 2).

PID mode uses Pulse-Width Modulation (PWM) and Proportional-Integral-Derivative (PID) feedback control to maintain the desired temperature more precisely. PWM quickly turns the heater on and off over a short period of time (Figure 3). The ratio of 'time on' to 'period' is known as the duty cycle, and takes a value between 0 and 1. If the duty cycle is low, the heater will be on for less time, maintaining a lower temperature in the pot.

PID feedback control uses the current state of the system as well as the history of the system to achieve the desired temperature as quickly and accurately as possible (Figure 4). The Proportional term adjusts the duty cycle in proportion with the error, or the difference between the actual and desired temperatures. The Integral term keeps a running sum of the error, and adjusts the duty cycle to minimize long-term error. The Derivative term looks at the dynamics of the system. For example, if the system is approaching the desired temperature too quickly, the D-term will adjust the duty cycle to prevent overshoot. Together, these terms help the system approach the target as quickly and accurately as possible.

Figure 5 demonstrates that our PID control worked as expected, adjusting the duty cycle as the temperature changed. Because this particular trial is quite short, the Integral term did not have time to achieve zero error. However, in longer trials, we saw that the system would quickly settle to a small error (as in Figure 4), and then a slow, consistent increase in duty cycle would eventually cancel out the error to achieve exact temperature control.

PWM: System heats when $k=1$ and cools when $k=0$

$$\frac{dT}{dt} = kH + (1-k)C$$

Simple model of temperature change
(derived in class)

$$\frac{dT}{dt} = -\alpha(T - T_{room}) + kQ_{in}$$

Heating: $k=1$

$$H = -\alpha(T - T_{room}) + Q_{in}$$

Cooling: $k=0$

$$C = -\alpha(T - T_{room})$$

Thermostat mode:

$T = 92\,F$

$T_{room} = 70F$

$H = .028\ F/s$

$C = -.014\ F/s$

$$C = -\alpha(92F - 70F) = -.014\ F/s$$

$$\alpha = 6.36e{-4}\ \tfrac{1}{s}$$

$$H = -\alpha(92F - 70F) + Q_{in} = C + Q_{in} = .028\ F/s$$

$$Q_{in} = .042\ F/s$$

$$\frac{dT}{dt} = kH + (1-k)C$$

Δt = duty cycle period
n = time on
$u(t)$ = duty cycle

$$T(t+\Delta t) - T(t) = \int_t^{t+\Delta t} kH + (1-k)C\,dt$$

$$= \int_t^{t+n} H\,dt + \int_{t+n}^{t+\Delta t} C\,dt$$

$$= Hn + C(\Delta t - n)$$

$$= (H - C)n + C\Delta t$$

$$\frac{T(t+\Delta t) - T(t)}{\Delta t} \doteq (H - C)u(t) + C$$

plug in H and C

$$\dot{T} = Q_{in}u(t) - \alpha(T - T_r)$$

$$\dot{T} + \alpha T = Q_{in} \cdot u(t) + \alpha T_r$$

plug in values

$$\dot{T} + (6.36e{-4})T = .042\, u(t) + .04452$$

To maintain a constant $T = T_{desired}$ $\quad (\dot{T} = 0)$

$$u(t) = \frac{\alpha}{Q_{in}}(T_{desired} - T_{room})$$

$$u(t) = .01514(T_{desired} - 70)$$

$$\dot{T} + \alpha T = Q_{in}\, u(t) + \alpha T_r$$

$$\Big\downarrow \mathcal{L}\text{aplace}$$

$$s\tilde{T}(s) + \alpha \tilde{T}(s) = Q_{in}\tilde{U}(s) + \frac{\alpha T_r}{s}$$

$$\tilde{T}(s) = \frac{Q_{in}}{s+\alpha}\tilde{U}(s) + \frac{\alpha T_r}{s(s+\alpha)}$$

A rough approximation of the transfer function may be $\frac{\tilde{T}(s)}{\tilde{U}(s)} = \frac{Q_{in}}{s+\alpha} \Rightarrow \mathcal{L}^{-1} \Rightarrow \frac{T(t)}{u(t)} = Q_{in} e^{-\alpha t}$

Step response: $\tilde{U}(s) = \frac{1}{s}$

$$\tilde{T}(s) = \frac{Q_{in}}{s+\alpha}\cdot\frac{1}{s} + \frac{\alpha T_r}{s(s+\alpha)}$$

$$\tilde{T}(s) = \frac{Q_{in} + \alpha T_r}{s(s+\alpha)}$$

$$\tilde{T}(s) = (Q_{in} + \alpha T_r)\left[\frac{1/\alpha}{s} - \frac{1/\alpha}{s+\alpha}\right]$$

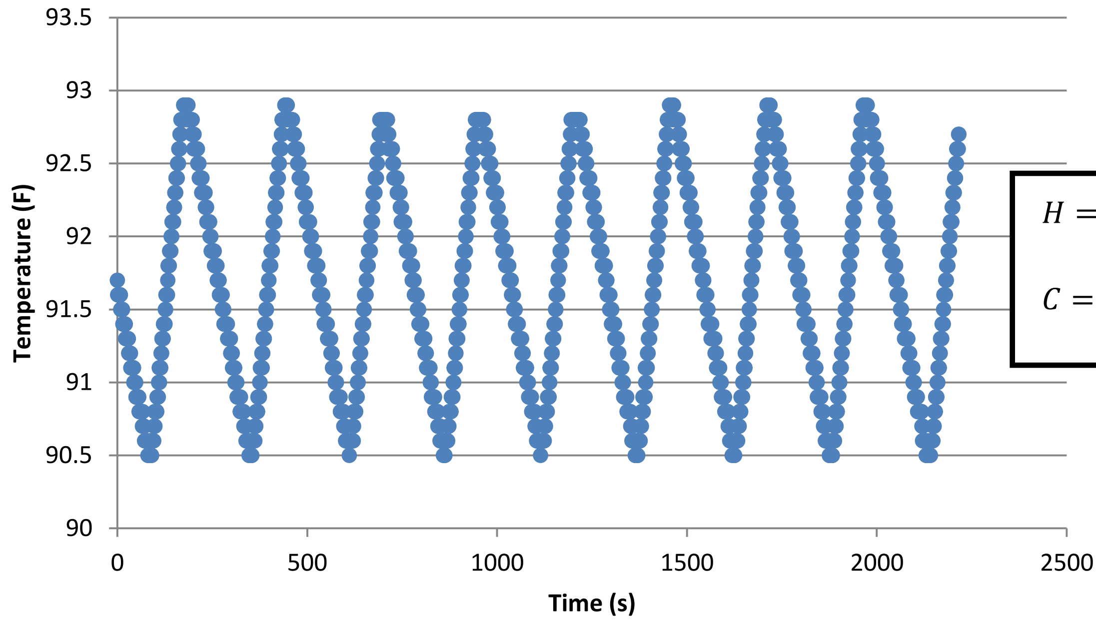
$$\tilde{T}(s) = \left(\frac{Q_{in}}{\alpha} + T_r\right)\left[\frac{1}{s} - \frac{1}{s+\alpha}\right]$$

$$\Big\downarrow \mathcal{L}^{-1}$$

$$T(t) = \left(\frac{Q_{in}}{\alpha} + T_r\right)\left[1 - e^{-\alpha t}\right]$$

d) Plots

Figure 2: Thermostat Control of Sous-Vide



$H = .028\frac{F}{s}$

$C = -.014\frac{F}{s}$

Figure 3:

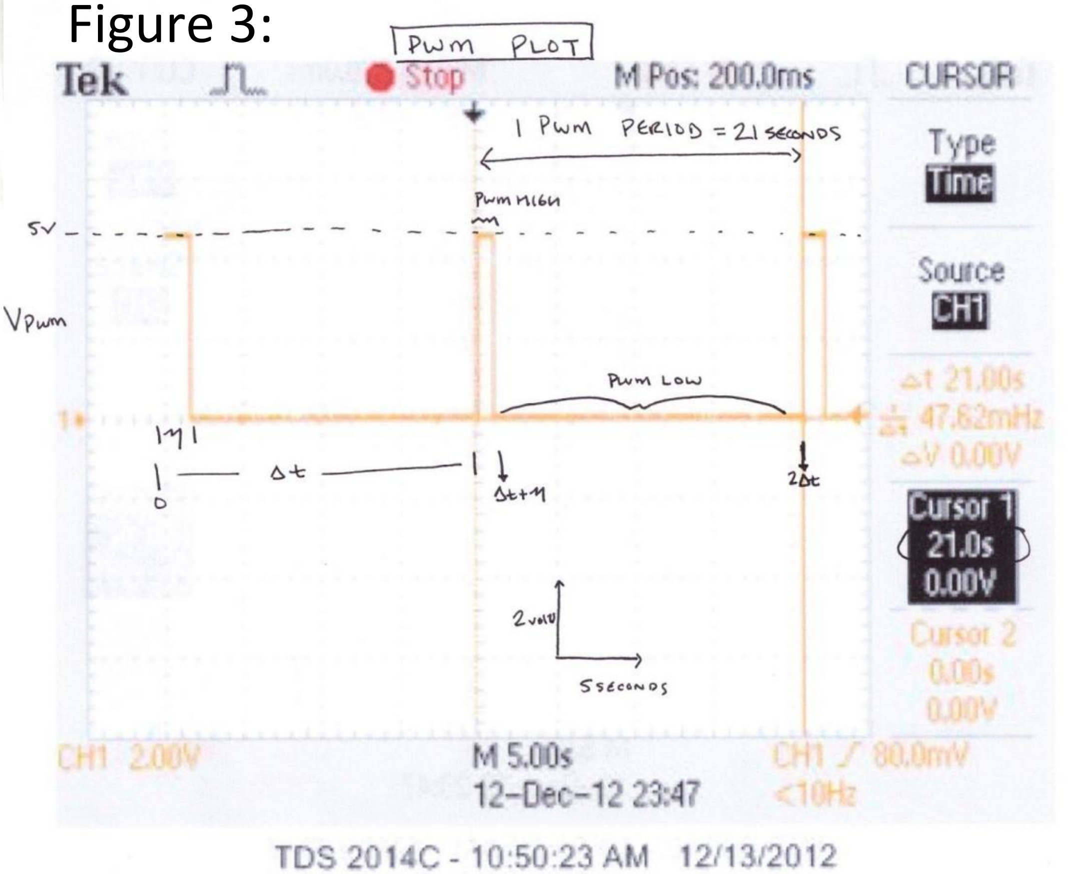


Figure 4: Step Response

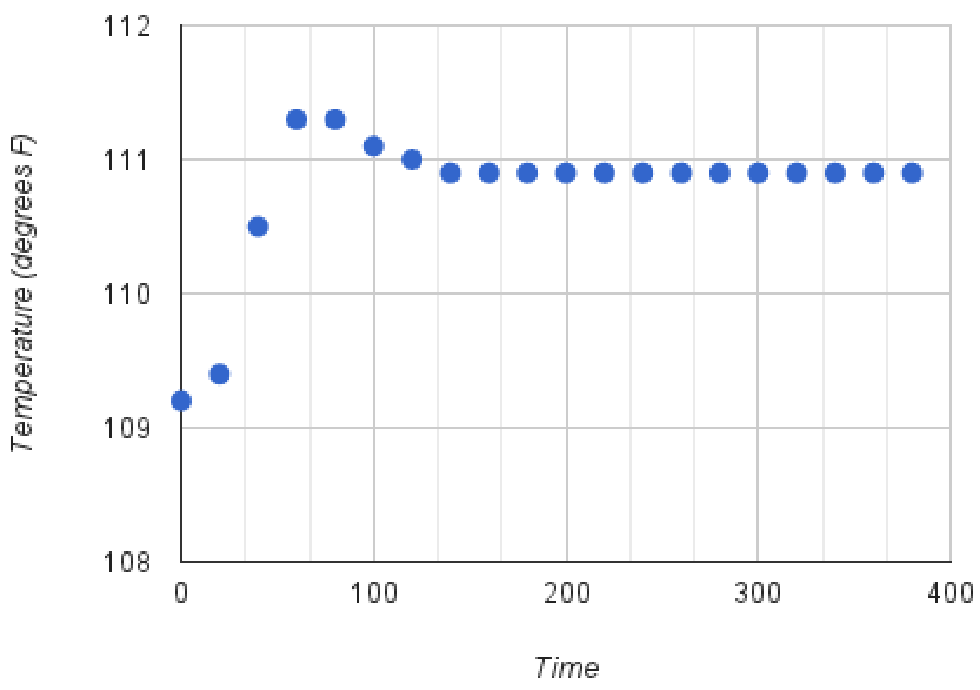
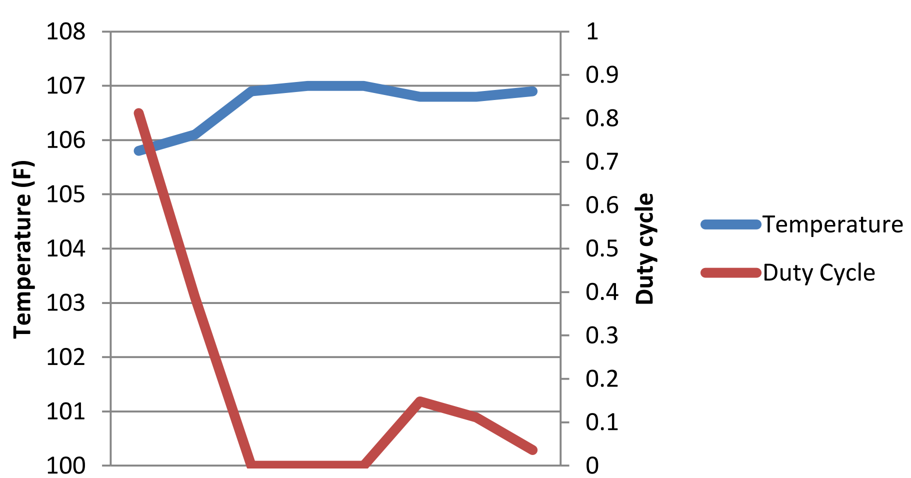


Figure 5: Temperature and Duty Cycle



Code Description:

Our Code starts off by initializing the I/O, then the USART for the LCD display. Then we set up the ADC and set our derivative, integral, duty cycle, difference, and old difference variables to zero for PID control. In our main code, after initializing all of the settings, we enter a menu. One of our buttons allows the user to switch between submenus, and the other button or potentiometer lets the user set values within each submenu. The menus are as follow:

1. Temperature menu - you can set Celsius or Fahrenheit
2. Control menu - you can set PID or thermostat mode
3. Timer menu - you can choose to turn on a timer
    3a. Timer submenu - you set the length of the timer
4. Desired temperature menu - you can set the desired temp using the potentiometer.

For Celsius mode, the range of available temperatures is 25-98 degrees.
For Fahrenheit mode, the range of available temperatures is 70-210 degrees.
For timer mode, the range of available times is 0-180 minutes.
All of these values are found using analog to digital conversion. We multiply the ADC count value (1023 steps corresponding to 0-5V) by a scaling number depending on the range of values we want to be possible.

When you press the "go" button after setting the desired temperature we go into the main while loop of the program. We get the current temperature, convert to Fahrenheit if necessary, and print out the current and desired values. We then calculate the difference between the two temperatures, save the old difference and calculate the derivative and integral terms for PID control.

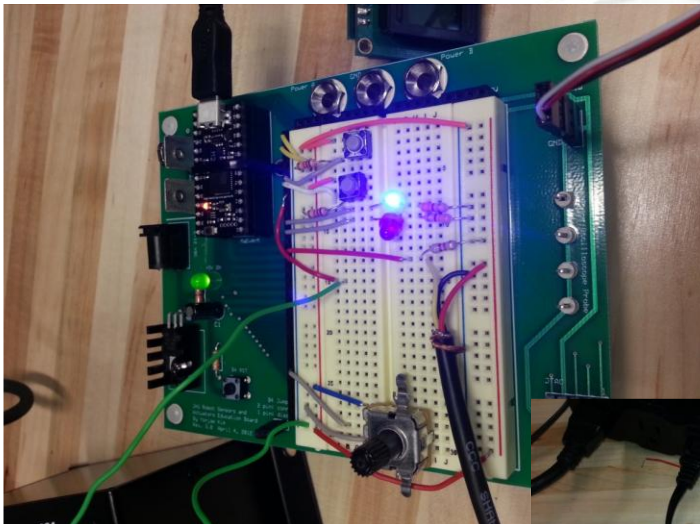
If we are in thermostat mode, we turn on the power if we are under the desired temp and turn off the power if we are over the desired temp. The red LED always lights up when the heating element is on and the green LED lights up if we are within .5 degrees of the desired temperature.

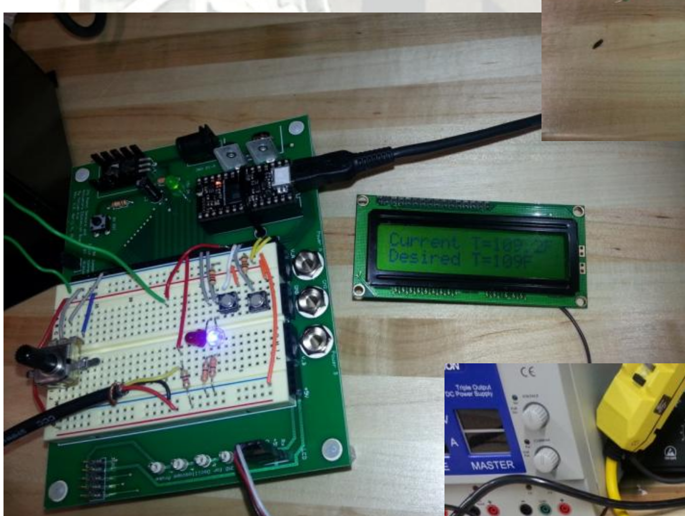
If we are in PID mode, we use thermostat mode until we are within 2 degrees of the desired temperature then turn on the PID control. We calculate the duty cycle by adding the difference, derivative, and integral all multiplied by their respective constants. If the duty comes out to more than 1 we set it to 1. If it is less than 0 we set it to zero. Then we output our PWM wave. We set the power high, delay for the duty cycle * period then set the power high and delay for 1-the duty cycle * the period.

If the timer is on, we beep twice every time we go thorough a PWM cycle (21 seconds) if the current time is over the previously set timer length.

If a button is pressed, we exit back to the main menu. If reset is pressed, we go back to the initialization of the sous vide settings.

3) Photographs





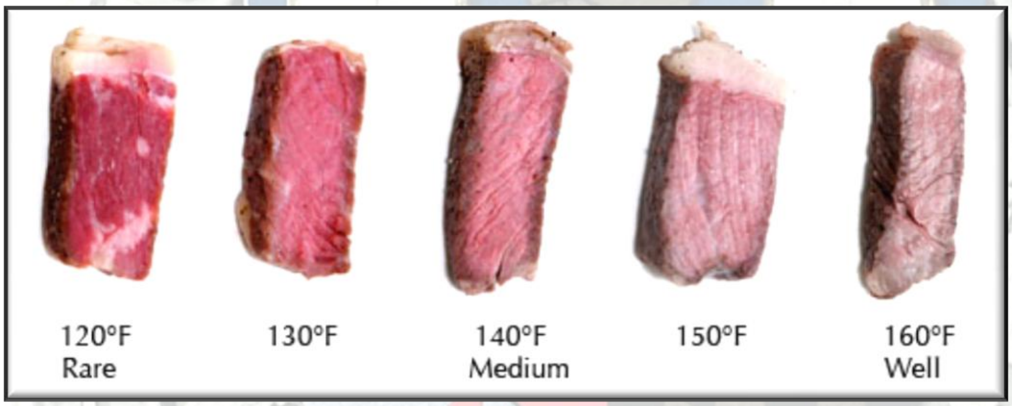
4) Food Summary

Recipe: http://www.seriouseats.com/2010/03/how-to-sous-vide-steak.html

http://www.seriouseats.com/2010/05/sous-vide-101-slow-cooked-eggs.html

Food Description:

During the demonstration day, we prepared a medium-rare flank steak. Earlier in the week we found quarter inch think steaks and seasoned them with salt and pepper. We then immediately pan seared them for about one minute on each side. During the last lab session we vacuum sealed the two steaks and promptly refrigerated them. On demonstration day we cooked the steaks at 133 degrees Fahrenheit for forty-five minutes. This produced a medium rare steak. Also, in a preliminary test, we cooked eggs using the sous-vide technique.



5) Acknowledgements

We would like to acknowledge Professor Cowan for giving us the opportunity to take part in a final design project that was as innovative and fun as this one. Once a class is over, often times we leave feeling as if we haven't actually learned why we are learning particular concepts. This final project changed that. We truly feel we have put our knowledge to great use and feel satisfied with a tangible result. We would also like to thank Chef Pellegrino for allowing us to visit his restaurant and taking the time to talk to us about the science of cooking. Last but not least, we would like to thank the TAs for keeping us safe during lab sessions and enduring our incessant questions.

6) Bill of materials:

	Part name	Manufacturer	Manufacturer Part Number	Vendor	Vendor Part Number	Part Quantity	Cost for 100	Unit cost (out of 100)
JHUSAERB with MaEvArM						1	4225.19	42.2519
Digital thermometer	Waterproof DS18B20 Digital temperature sensor + extras	Maxim Integrated	DS18B20	www.adafruit.com	ID: 381	1	$796	$7.96
Heater	Immersion Heater for Warming Liquids	NORPRO	559	amazon.com		1	$734	$7.34
Circulator pump	Maxi Jet 600	Marineland	ML90510	www.petmountain.com		1	$1,499	$14.99
LCD screen	Parallax 2x16 Serial LCD (Non-Backlit)	Parallax	27976	Parallax	27976	1	$2,519	$25.19
Potentiometer	100 K potentiometer	CTS Electrocomponents	296UD104B1N	Digi-Key	CT2268-ND	1	$102.56	$1.03
Buttons	Tactile switch	Omron Electronics Inc-EMC Div	B3F-6022 BY OMZ	Digi-Key	SW264CT-ND	2	$42.04	$0.42
Relay	AC1	Xantech		smarthome.com	81301	1	$7,855	$78.55
		Total						$178.15

7) Video

Link to video: http://www.youtube.com/watch?v=paehF1s2_S8