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Addressing Safety Concerns Regarding a Silicon Furnace

Alyssa Hope Mun
Worcester Polytechnic Institute

Addressing Safety Concerns Regarding a Silicon Furnace

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Project Advisor: Alexander Emanuel, WPI Professor

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Alyssa Mun

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Abstract

This work addresses the safety features design of a GT Advanced Technologies silicon furnace. An over temperature relay, over pressure relay, silicon spill relay, chamber brake and emergency stop were created to prevent possible accidents from occurring. For each of these safety requirements the electric circuits and the processes that correspond to each safety feature were analyzed. The relays were then integrated into the existing furnace and each feature was tested. A Pspice simulation demonstrates the reliability of the protection system proposed.

Executive Summary

The project discussed in this document involved designing and implementing safety features into a research and design silicon furnace created by GT Advanced Technologies. For each of the safety features, I designed the circuits and processes that make up both the hardware and software portions of the relays. The safety features that were incorporated into the furnace will help to avoid possible hazards from occurring. Two silicon spill wires were incorporated into the design to alert the operators of the occurrence of a silicon spill. When a spill occurs the silicon will melt through the copper spill wire which will cause an open circuit. Due to the fact that silicon is a conductor when solid and an insulator when in its molten form the spill wire relay couldn't rely purely on the silicon cutting through the wire. For this reason the silicon spill relay checks for a change in the current through the spill wire. An over temperature safety relay was designed using two thermocouples which will inform the operators when the temperature within the furnace has exceeded a preset temperature of 1560^{o}C. Similarly an over pressure relay was created so that if the pressure within the chamber exceeds a preset value the pressure flap located on the top of the furnace will open and the operator will be alerted. An emergency stop pull switch is located on the front of the control cabinet for the furnace. If an emergency were to occur or the operator needed to stop the furnace immediately the emergency stop could be pulled. The final safety feature was a chamber brake which ensures that the chamber cannot open or close unintentionally. With the incorporation of these features the furnace continued to operate properly, but now has safety features which will help to prevent hazards from occurring. Without these features there is potential for employees and operators being burned by the molten silicon if a spill were to

occur. There will also be a large loss of time if any of these dangers were to occur. When a spill occurs the building must be evacuated and the spill must be cleared by the fire department, this can take between 30 minutes and an hour. Also if the temperature or pressure within the chamber exceeds what is necessary the silicon will crack and you will lose that grow cycle. By implementing these safety features into the furnace I have helped to prevent possible accidents from occurring as well as helping them to be as efficient as possible.

1.0 Introduction

GT Advanced Technologies focuses their efforts on polysilicon production technology as well as silicon and sapphire crystal growth. Research and design ensures that companies are enhancing and redesigning their products to remain competitive within their particular field. For my major qualifying project I worked with GT Advanced Technologies to upgrade the safety within an existing research and design polysilicon furnace. This included integrating both hardware and software features into the furnace. The polysilicon furnace is used to convert raw silicon into pure polysilicon wafers. This process requires large machinery and high temperatures which, if not carefully monitored can be potentially dangerous. To prevent dangerous incidents from occurring and to make it as safe as possible if an incident were to occur a number of safety relays were incorporated into the polysilicon furnace design. If the safety features discussed in this report were not implemented into the furnace a number of accidents could occur. This report will discuss the process of converting raw silicon material into pure silicon wafers, the safety guidelines that needed to be followed when upgrading the furnace as well as the changes that were made to incorporate these features.

2.0 Description of System

The purpose of the furnace is to facilitate polysilicon production. To produce polysilicon wafers, a pure form of silicon must be created. This is done by placing the raw form of silicon, silicon dioxide or quartzite gravel, into a furnace where a carbon arc is applied. When the arc is applied, the oxygen within the raw material is released. After all inlet gasses are introduced, the furnace goes into vacuum mode. During the vacuum mode, the inlet gas valves are closed and the roughing valve is opened, thus allowing the chamber to be pumped to low pressure.

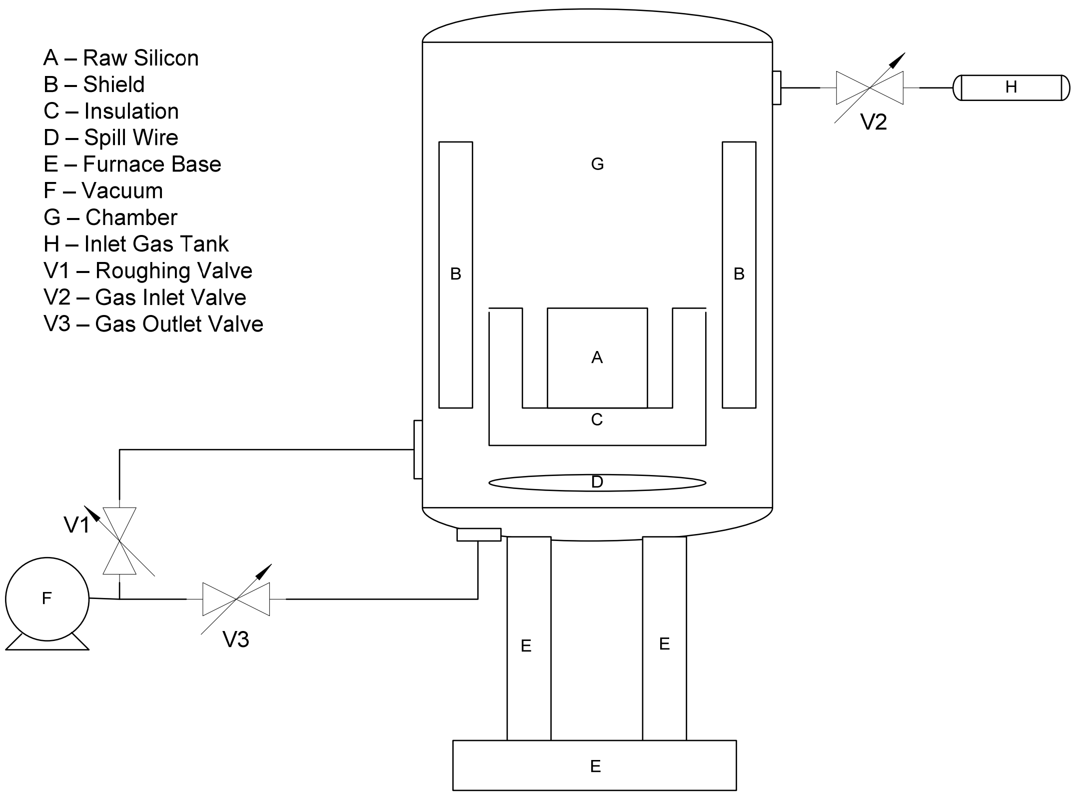

Figure 1 - Silicon Furnace

The next step in purifying silicon is doping the raw material with either phosphorous or boron. If n-type silicon is being created then the raw material must be doped with phosphorous. To create p-type silicon the raw material must be doped with boron. To dope the raw silicon a small amount of either material, either boron or phosphorous, is introduced during the Czochralski process.

During the Czochralski process a seed crystal of raw silicon is dipped into nearly molten polycrystalline silicon. The seed crystal is then rotated and withdrawn and a cylindrical ingot of silicon is produced. This form of silicon is considered pure because any impurities within the silicon remain in the nearly molten silicon.

The raw silicon is then placed within a silicon furnace and the material is heated to slightly below the melting point. The temperature within the furnace is raised by controlling the power going to the heaters. This is done under vacuum, low pressure, until the furnace reaches its crossover temperature. This is the temperature at which the furnace switches from power control to temperature control. The reason for the control changing at this particular point is because the pyrometer used cannot accurately measure the thermal radiation until around 1150^{o}C. Once the cross over point has been reached, the furnace will then go into melt in mode. The melting point of silicon is 1410^{o}C. To track the rate that the silicon is melting at, a quartz rod of about a ½'' diameter is pushed into the melting silicon until it hits a piece of solid silicon. That point is then marked on the rod and the depth of the melt is measured. Once the material has gotten to the appropriate temperature and depth phosphorous gas is introduced. The atoms of the phosphorous then combine with the silicon. The reason for adding the phosphorous gas just before the melting point is because the silicon is more porous and more likely to combine with the gas.

After the gas has been introduced, the temperature is increased until the silicon is completely molten. At this point the pressure within the furnace is kept at a constant 600mBar. Argon gas is then injected over the crucible, this helps to carry away any impurities and keep the view portal clear.

Once melted, the temperature is dropped slowly, beginning the growth cycle. During this cycle the silicon begins to grow from the bottom up. The depth of the growth is checked with a ½'' quartz rod, in the same way as the depth is checked during the melt cycle. Once the silicon completes the growth cycle and becomes solid the anneal cycle begins. During the anneal cycle, the furnace is brought down to a predetermined temperature. Once at this temperature the internal temperature of the furnace is kept at this value for approximately three hours. By keeping the silicon at this temperature for this period of time it anneals out any stresses in the ingot. Once the ingot is annealed it is brought to the cross over temperature again where it switches back to power control and the furnace goes into cool down mode. It often times takes about two days to complete the cool down cycle. If it is cooled too quickly then the silicon will crack and if the silicon cracks then wafer cannot be used.

The research and design furnace has two different modes that it must be in at all times, manual or automatic. When the furnace is in automatic mode, nothing on the furnace can be moved manually by the controller. The furnace is commonly in automatic mode. Any time that a part of the machine is moved or controlled without the user manually moving that part the furnace is in automatic mode. The manual movement of any parts of the furnace can only be achieved if the furnace were in manual mode. An example of what could be done if the furnace were in manual mode would be for the operator to open the chamber manually. The most common situation where manual mode would be valuable would be if an emergency occurred and the automatic motions of the furnace were not able to work properly.

To create a viable silicon crystal the pressure within the furnace needs to remain at the correct levels. There are seven valves which are controlled by the user to ensure that the pressure within the chamber is ideal for the silicon growth. If the pressure or heat within the chamber is not correct, then the silicon will crack and that particular crystal will not be viable. The valves can left completely open or closed or strategically opened by a specific percentage.

3.0 Safety Features

A number of safety features were incorporated into the silicon furnace to ensure the safety of the employees. The breakdown of each of these safety features is discussed below and represented through the use of flow charts.

3.1 Over Pressure

If an over pressure was to occur a large amount of time would be lost. An over pressure would cause the silicon to crack and to no longer be pure. That particular silicon grow would then have to be disposed of and the furnace would need to be cooled down completely before another grow could begin. The cool down period for the furnace could take anywhere between six and eight hours to cool completely. The figure shown below depicts what would occur if the over pressure flap on the machine was open. The over pressure flap is located on the top of the furnace and has a contact sensor which senses whether the flap is open or closed at all time. When the pressure within the chamber gets to be too high, the air within the furnace will push its way out through the pressure valve, causing it to open and trigger an over pressure. If the pressure flap was open, the siren and the red tower light would turn on, and the heaters would turn off automatically.

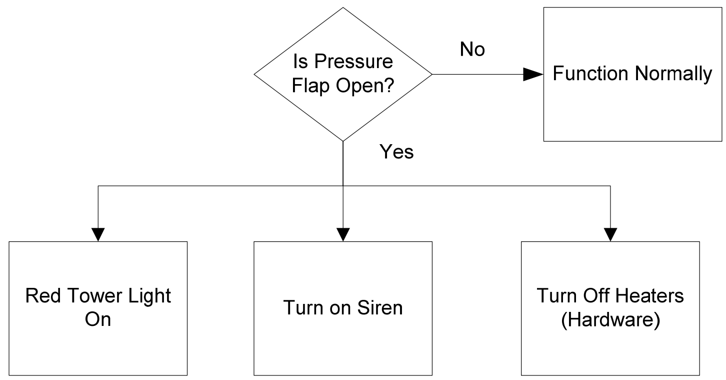

Figure 2 - Over Pressure Flow Chart

3.2 Over Temperature

If an over temperature were to occur the company involved would incur a loss of time similar to that of an over pressure. With an over temperature the silicon grown will crack and the furnace will need to be cooled completely before another grow could be started. Figure 3 shown below represents the flow chart depicting what would occur if the temperature within the furnace went above its maximum temperature preset of 1560^{o}C. This particular safety feature was not only a hardware upgrade, but also a software upgrade. In order to ensure that the over temperature feature will trigger at the correct temperature we added a section of code which set the maximum temperature to 1560^{o}C. By doing this we created a loop which constantly checked the actual temperature read by the thermocouples and compared it to the maximum temperature. If the current temperature was below the maximum, then the furnace could continue to function normally. There are three thermocouples located in different locations within the furnace, each of which is used to monitor the internal temperature of the furnace. If any of the three were to read an internal temperature of 1560^{o}C or more then the system will check if the furnace is in automatic mode.

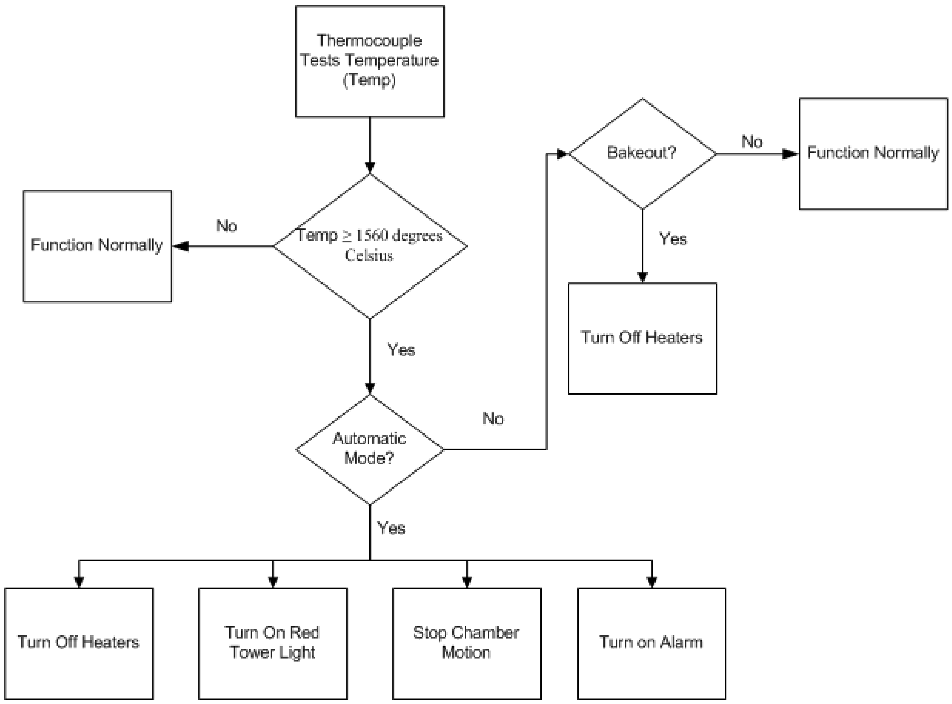

Figure 3 - Over Temperature Flow Chart

If the furnace is in automatic mode then a number of things will be triggered. If all of the above requirements are true, then the heaters will be turned off, the red tower light will be turned on, all motion within the chamber will be stopped and an alarm will sound. If the temperature were to get above 1560°C but not be in automatic mode, then the system will check if it is in bakeout, which refers to the time when the furnace is baking the silicon. If the furnace is in manual mode and in bakeout then the heaters will turn off and the furnace will go into automatic cool down.

3.3 Silicon Spill

There are multiple safety concerns associated with a silicon spill. Silicon becomes molten at around 1500 °C which would cause serious burns if an operator or employee were to come in contact with it. There is also the danger of a fire starting if the molten silicon were to come in contact with something flammable. Not only is there physical dangers associated with a silicon spill, but a large amount of time is lost by the entire building if a silicon spill occurs. When a spill occurs, the entire building must be evacuated and the fire department must clear the area before people can enter the building again, on most occasions it takes at least forty-five minutes for the spill to be cleared. If a spill were to occur, meaning if the spill wire was melted by a silicon spill and the furnace was in automatic mode then all emergency stop functions would be triggered as well as turning on the red tower light, turning on the strobe light and finally turning on the spill horn.

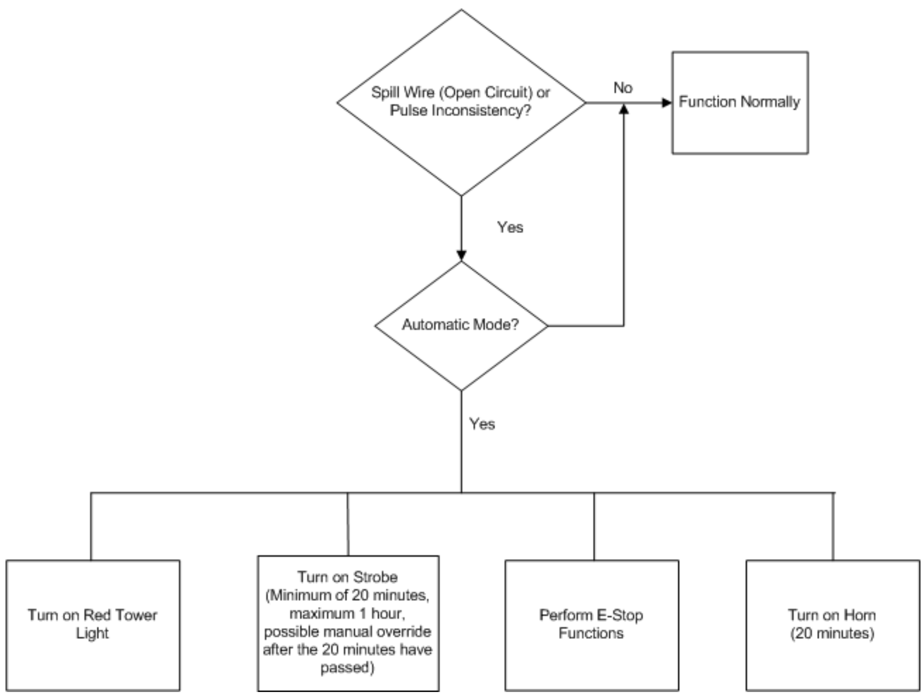

Figure 4 - Silicon Spill Flow Chart

The amount of time that the strobe and horn are on for are important to ensure that the severity of a silicon spill are recognized. If a spill occurs then the strobe will be turned on for a minimum of 20 minutes, meaning that before 20 minutes have passed there is no manual shut off. After the 20 minutes have passed a controller can manually turn off the strobe light and after an hour has passed the strobe will turn off automatically. Similarly to the strobe, the spill horn is automatically turned on if a spill occurs. After 20 minutes have passed the spill horn will turn off automatically.

3.4 Chamber Open

If the chamber were unintentionally open, operators could be in danger of burns caused by the heat coming out of the opening in the furnace. There is also danger that an employee could get caught in the furnace if the chamber were unintentionally open. To mitigate these possible problems, I incorporated a design such that if the chamber of the silicon furnace is opened then the heaters are automatically shut off. If the chamber is closed then normal operation can continue. The chamber can only be opened if the temperature within the chamber is below 400^{o}C.

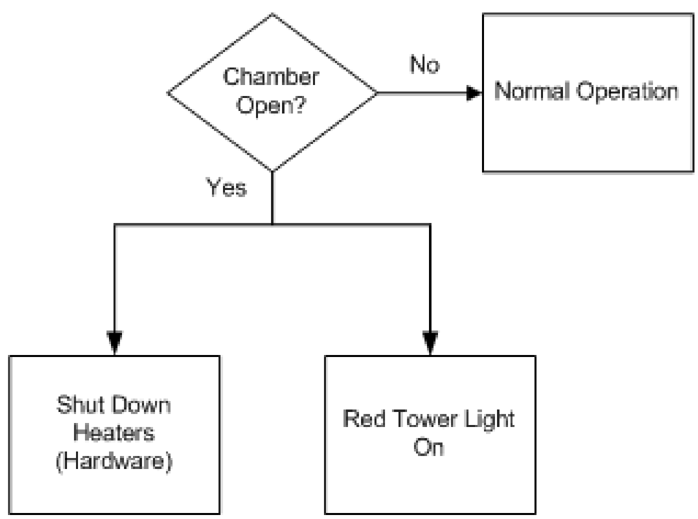

Figure 5 - Chamber Open Flow Chart

3.5 Emergency Stop

The emergency stop features is meant to be used if the operator feels that the furnace is not operating properly. If an emergency occurs then the operator can pull the emergency stop switch. When the emergency stop switch is pulled, the processes in figure 6 occur. The emergency stop switch is located above the user interface for ease of access. If the emergency stop switch (e-stop) is pulled then the heaters will turn off, the red tower light will turn on and the chamber motion will stop.

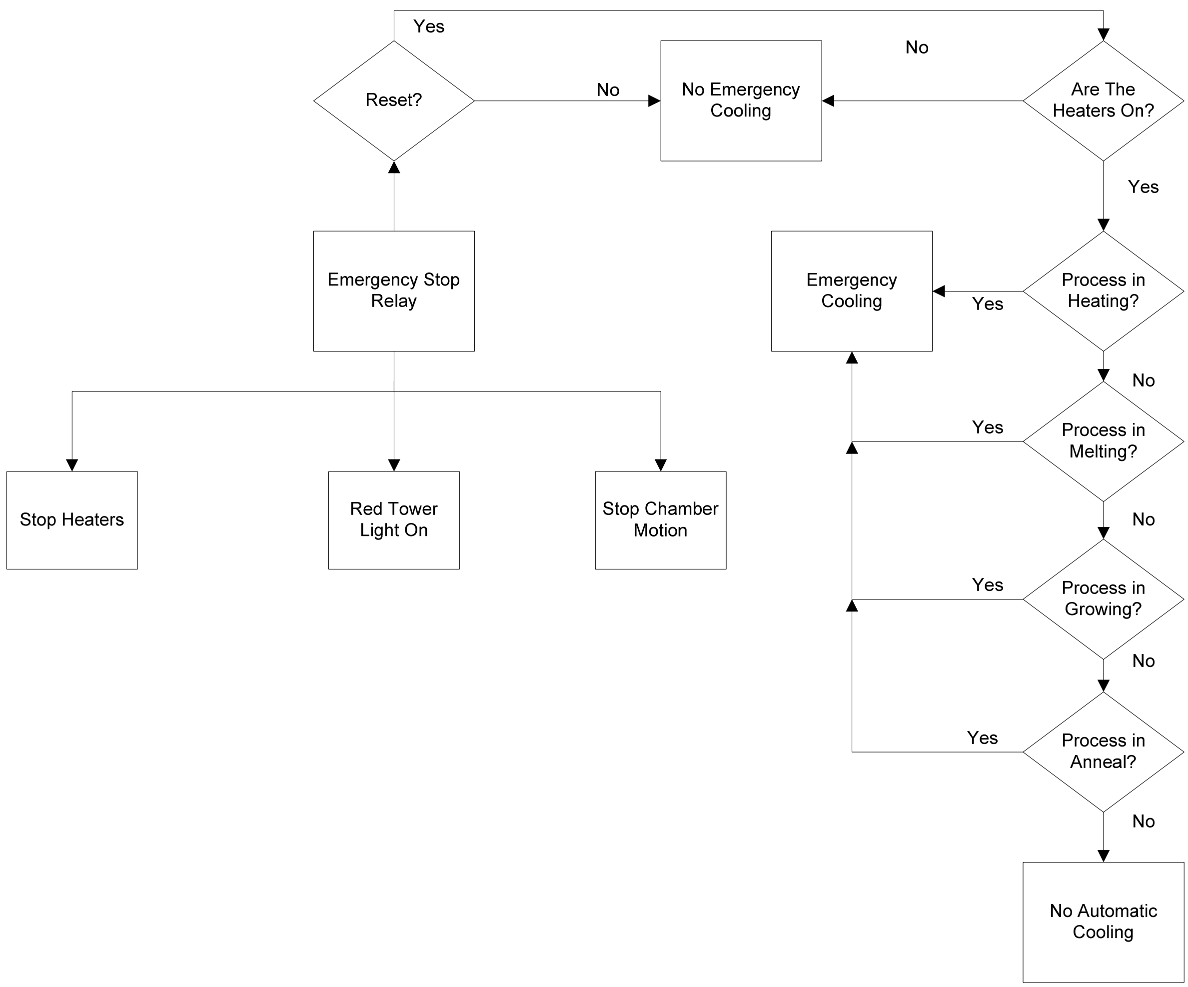

Figure 6 - Emergency Stop Flow Chart

After the e-stop is pulled, for the furnace to be run again, the reset button needs to be pressed. If the reset button is pressed then the system will check if the heaters are on. If the heaters are on then the system checks if the furnace is in the heating cycle, the melting cycle, the growth cycle or the anneal cycle. If the system is in any of the listed cycles, then the furnace will go into emergency cooling which will cool the furnace as quickly as possible.

4.0 Circuit Design

When integrating safety features into an existing furnace it is important to ensure that the new features properly integrate with the existing ones. This required consulting with existing schematics and determining which wires in the existing design would need to be connected to the inputs and outputs of the new design.

4.1 Chamber Lift Brake

In figure 7 below, the chamber lift brake circuitry is represented. As the circuit shows, a switch is connected to the chamber lift brake. When the wire labeled 213 is high, the switch will close which will allow the 90 volts of power to trigger the brake. When the brake is triggered the chamber lift feature will stop at the location it is currently at when the switch closes.

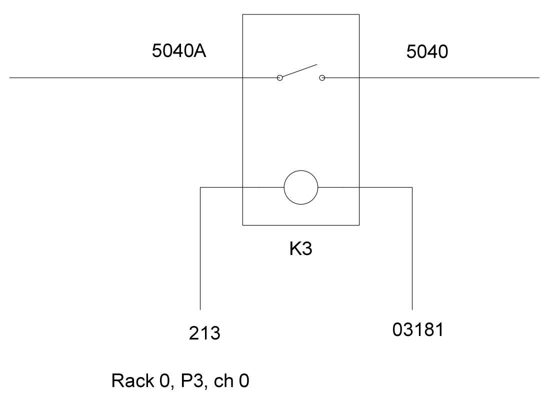

Figure 7 - Chamber Lift Brake Circuitry

4.2 Over Temperature

Figure 8 shown below depicts the over temperature circuitry. There are two over temperature sensors to ensure that if one of the thermocouples is not working properly or is broken there will be a way to observe and certify that the temperature within the chamber is correct. Over temperature 1 and 2 are wired in parallel to ensure that if one were to fail, then the safety feature would still work. The temperature reset buttons on both over temperature 1 (OT 1) and over temperature 2 (OT 2) are interconnected to ensure that if either reset button is pushed, everything will reset simultaneously. The two thermocouples were installed onto the front side of the furnace's cabinet so that the two temperatures can be easily compared and monitored.

The design of the two over temperature circuits is the same; the only difference between the two is that they have different input and output wire numbers. The label "Orange AWG18" represents that an 18 gauge orange wire should be used in those specific locations. The reason for that particular gauge is to ensure that the wire can carry the amount of current and voltage that will be traveling through those wires safely.

As it is shown in figure 9, positions 98 and 99 are power inputs. The wires labeled 9002 and 9003 connect via terminal blocks to other portions of the safety circuitry. Positions S1 and R1 are positions designated for the thermocouple. This allows for the temperature detected by the thermocouple to be displayed on the temperature display.

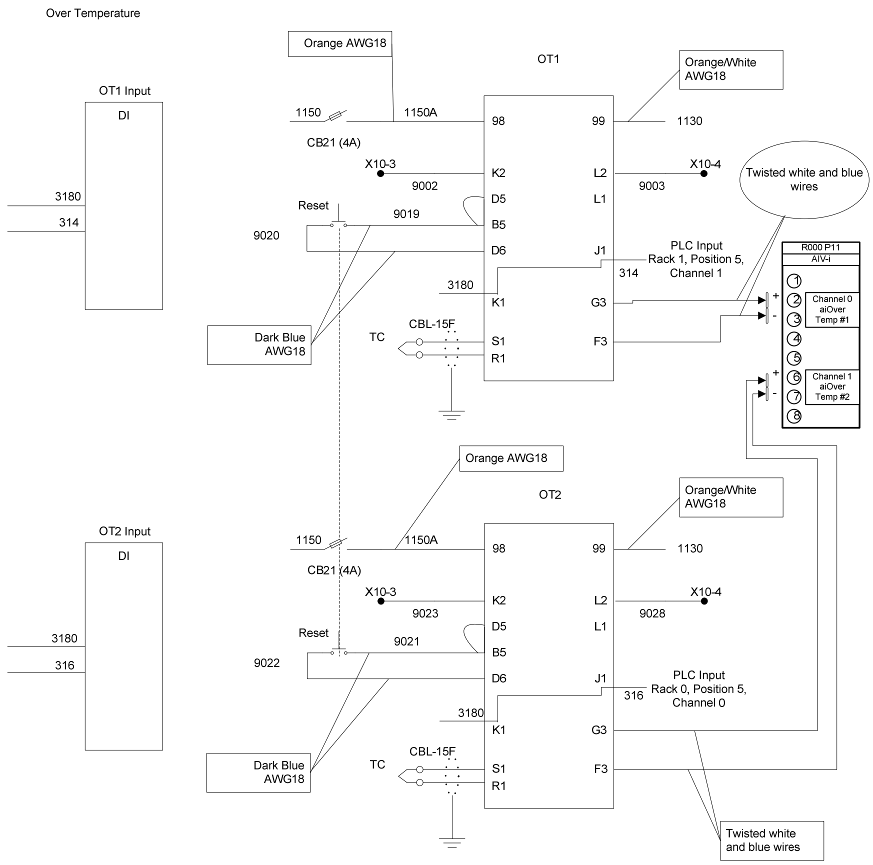

Figure 8 - Over Temperature Circuitry

Terminal Definitions

Slot C		Terminal Function	Model
98 99		power input: ac or dc+ power input: ac or dc-	PM _(C)_ _ _ - AAAAB _ _
L1 K1	L2 K2	normally open common	Solid-State Relay 0.5 A, Form A output 1: PM _(C)_ K _ - _ AAAB _ _ output 2: PM _(C)_ _ K - _ AAAB _ _

Figure 9 - Watlow Temperature Display

4.3 Over Pressure

If the pressure within the chamber of the silicon furnace is above the pressure programmed into the machine then the circuit shown in figure 10 will trigger. In the over pressure circuit, terminal blocks are labeled as X10-4, X10-5 and X10-9. The terminal blocks were used to easily move and change the wires connecting different portions of the circuitry within the furnace's cabinet. When the over pressure circuit is triggered, an alert will appear on the user interfacing screen to inform the user that an over pressure has occurred. This alert is shown as DI 308 on figure 9 below.

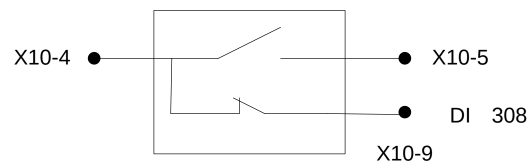

Figure 10 - Over Pressure Circuitry

4.4 Silicon Spill

In figure 10 below the circuitry for the spill relay safety feature is shown. In the circuit there are two spill wires which are used to ensure that if a spill were to occur that the safety feature would trigger properly. If a spill occurs the molten silicon will melt through the wire creating an open circuit which will cause the spill relay to trigger and the emergency features shown in the flow charts above will occur.

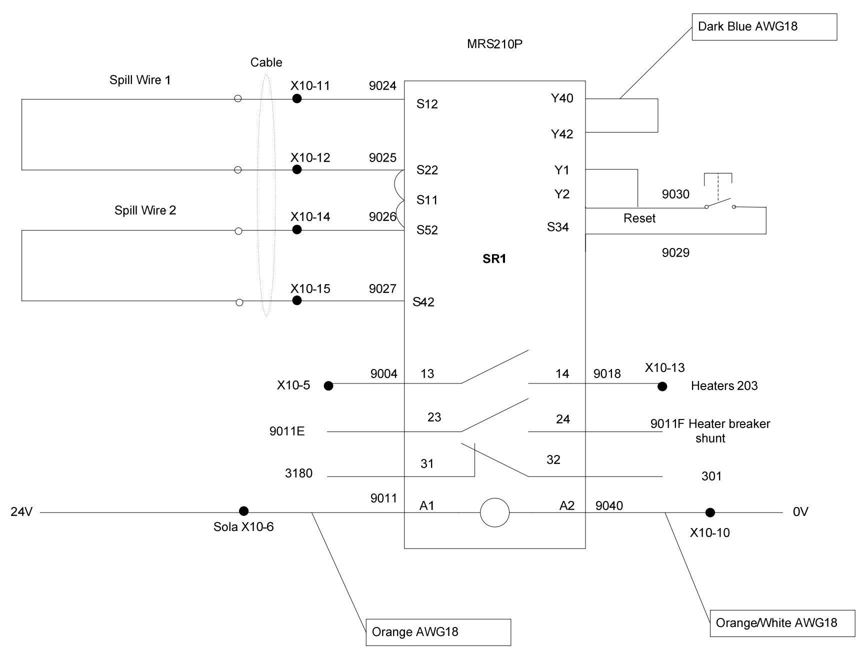

Figure 11 - Spill Relay Circuitry

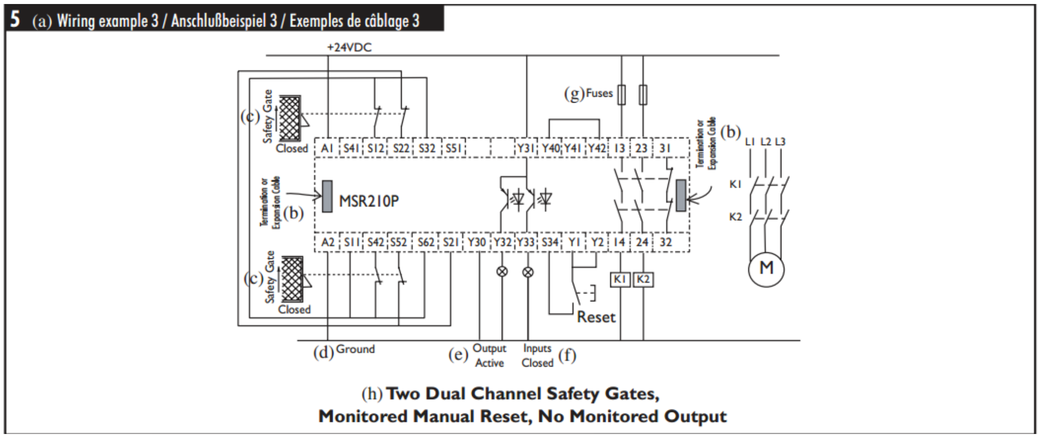

Figure 12 - MSR210P

The configuration of the spill relay shown in figure 11 incorporates the MSR210P that's configuration is shown in figure 12 above. This product creates a safety control system which has two inputs which can be wired in multiple ways. This product has the ability to have up to three normally closed connections. For this particular safety relay the circuit was built with one normally closed input. A1 is connected to a 24 volt SOLA power supply which, when powered, will trigger the three output switches. The result will be the shutting down of the furnace's heaters, the heater shunt (shown in figure 15) and the digital output 301. The digital output will alert the user on the interfacing screen that a spill has occurred.

4.5 Emergency Stop

In figure 16 the emergency stop (e-stop) circuitry is shown. This feature is triggered when a button type switch is pulled.

The emergency stop switch needed to be changed due to a safety regulation. The previous emergency stop was a push button which can be a hazard due to the fact that it can be triggered accidently which creates a violation of The Electrical Standard of Machines. To correct this error a twist and pull button type switch was mounted on the front of the control panel. This ensures that the emergency stop feature is not unintentionally activated because two actions need to occur to trigger the feature. Another violation that needed to be corrected was the coloring of the emergency stop button and its background colors. By NFPA 79, section 10.7.3 in The Electrical Standard of Machines, the emergency stop button must be colored red with a yellow background.

10.7.3 Emergency Stop Actuators. Actuators of emergency stop devices shall be colored RED. The background immediately around pushbuttons and disconnect switch actuators used as emergency stop devices shall be colored YELLOW. The actuator of a pushbutton-operated device shall be of the palm or mushroom-head type and shall effect an emergency stop when depressed. The RED/YELLOW color combination shall be reserved exclusively for emergency stop applications.

Figure 13 - 10.7.3

10.2.2.3 Emergency Stop. RED shall be used for emergency stop actuators in accordance with 10.7.3.

Figure 14 - 10.2.2.3

The MSR127TP safety relay is used in the emergency stop circuit. Figure 15 represents the circuitry within each relay. This product has three switches that can be configured with either one or two normally closed connections. In the design that was implemented into the emergency stop circuitry, only one normally closed configuration was used and the remaining two switches are normally open. The MSR127TP has the ability to have either an automatic or manual reset depending on the wiring configuration. The emergency stop was designed to have a manual reset which was wired with a normally open switch which will only trigger if the reset button is pressed.

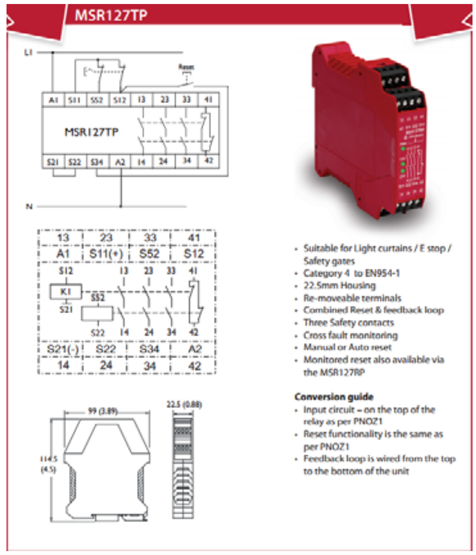

Figure 15 - MSR127TP

When A1 is high each of the output switches in the emergency stop circuitry will trigger. When this occurs the chamber motion will stop and the heaters will turn off. When the switch at position 33 and 34 closes, the shield and insulation motion within the furnace will stop.

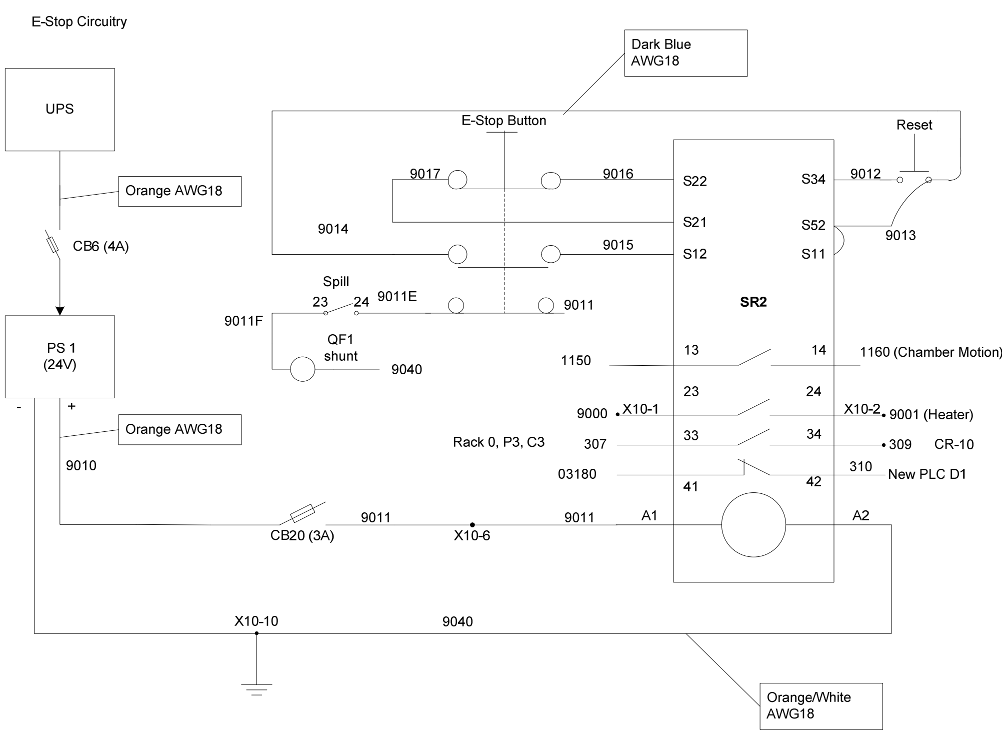

Figure 16 - Emergency Stop Circuitry

4.6 Reset

Figure 18 shows the circuitry created to incorporate a reset feature into the SI furnace. As the circuit shows, if the reset button is pushed down each of the safety features including emergency stop, over temperature one and two, digital inputs and the spill relay will have a completed circuits. This will cause each of the features to be reset concurrently.

The reset button is located next to the furnace for easy accessibility. In accordance with section 10.2.2.7 of NFPA 79 a blue reset button replaced the previous reset button which was colored green.

10.2.2.7 Reset. Reset pushbuttons shall be BLUE, BLACK, WHITE, or GRAY except when they also act as a stop or off button, in which case they shall be RED.

Figure 17 - 10.2.2.7

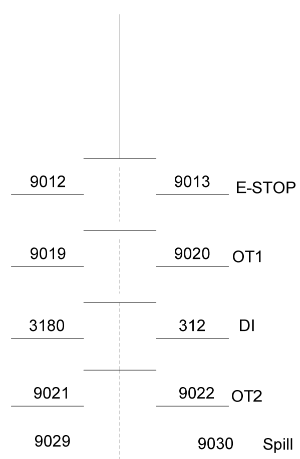

Figure 18 - Reset Circuitry

4.7 Spill Outputs

The circuitry for the digital outputs is shown in the figure below. If a spill occurs the spill horn, located on the top of the cabinet, will sound for twenty minutes. The horn, at 118 dB, is meant to alert all personnel in the area to leave the premises until the location has been cleared for reentry. A strobe will also begin to flash for a minimum of twenty minutes and a maximum of one hour. After the twenty minutes have passed the silicon furnace controller can override the strobe, but if the strobe is not overridden it will flash for another forty minutes and turn off automatically.

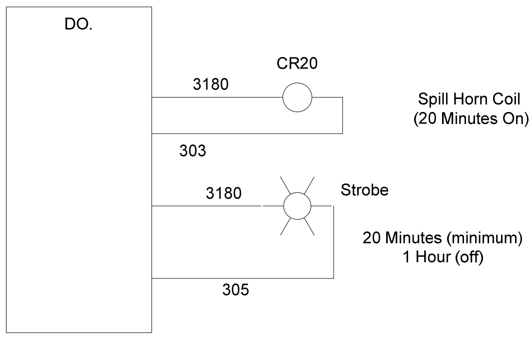

Figure 19 - Spill Outputs

4.8 Alert System

The alert system incorporates both light and sound to make employees aware of the state of the silicon furnace and to inform them that a problem has occurred. The system is made up of three different colored lights as well as two separate sound features.

4.8.1 Spill Horn

The circuitry for the spill horn is shown below. When 303, shown in figure 18, is low, switch CR20 closes. When closed the 24 volt supply from 3080 will flow through the circuit causing the horn to sound. The spill horn circuit is wired with an 18 gauge dark blue wire until switch CR20. A cable is used for the horn portion of the circuit which has been labeled as CBL-31.

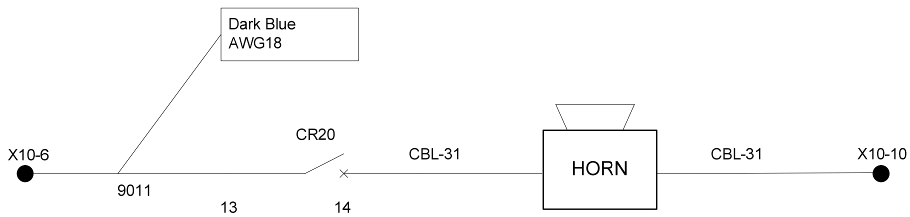

Figure 20 - Spill Horn Circuitry

4.8.2 Light Stack

In the figure shown below, the light stack circuitry is shown. This circuit shows a 24 volt power supply, wired directly into the light stack. In the light stack there are four possible functions that could be triggered. The red, yellow and green lights can be turned on individually, or if need be turned on at the same time, to alert to controller that there are multiple problems with different levels of concern. The alarm is triggered in most cases where either the red or yellow light is turned on. A testing feature was added to the program to allow the user to test the functionality of the red, yellow and green lights as well as the alarm. If the user would like to test to ensure that the light stack is working correctly they can click the part of the light stack that they would like to trigger, on the user interface, and the alert will occur for a very short period of time, so as not to give a false alarm.

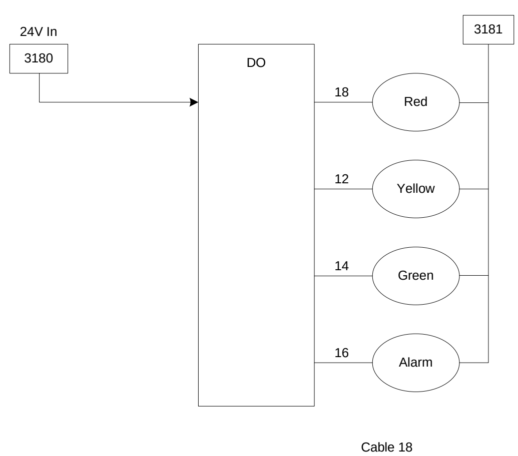

Figure 21 - Light Stack Circuitry

The previous light stack used with the silicon furnace was a single green light. In the NFPA 79 the color of the light represents the meaning of that particular light. With a single green light it can only be assumed that everything with the silicon furnace is normal and safe. In order to alert the furnace controller three lights were used. The red light, located at the top of the color stack, signifies danger or an emergency that needs immediate attention. The amber light signifies a warning or a potential problem with the furnace that needs to be inspected. The green light located at the bottom of the tower indicates that the furnace is currently in use and is working correctly.

10.3.2* Colors. Indicator lights and icons of color graphic interface devices shall be color-coded with respect to the condition (status) of the machine in accordance with Table 10.3.2. Alternative purposes shall be permitted to indicate machine or process status.

Figure 22 - 10.3.2

At the top of the light stack, above the red light, is a black light that sounds an alarm at 85 dB. There is a silence button on the user screen that will temporarily silence the alarm for one minute at a time, but the alarm cannot be turned off completely until the error has been amended. Each of the alert lights will also remain lit until the error has been corrected.

Table 10.3.2 Machine Indicator Lights and Icons

Color	Purposes		
	Safety of Persons or Environment	Condition of Process	State of Equipment
RED	Danger	Emergency	Faulty
YELLOW (AMBER)	Warning/ Caution	Abnormal	Abnormal
GREEN	Safe	Normal	Normal
BLUE	Mandatory action		
CLEAR WHITE GRAY BLACK	No specific meaning assigned		

Table 1 - 10.3.2

The table shown below demonstrates the particular warning that will occur when the problems listed occur. The only problem that uses both the horn and strobe is a silicon spill. All other errors use either a colored alert or an alarm or both to alert employees that an error has occurred.

Alarm Name	***Yellow***	***Red***	***Alarm***	***Horn***	***Strobe***
Air Loss	*x*		*X*		
Argon Flow Deviation	*x*		*X*		
High Power Deviation	*x*		*X*		
High Pressure Deviation		*x*	*X*		
High Temperature Deviation	*x*		*X*		
Leak Failed	*x*				
Water Zone 1 Critical		*x*	*X*		
Water Zone 1 Warning	*x*		*X*		
Water Zone 10 Critical		*x*	*X*		
Water Zone 10 Warning	*x*		*X*		
Water Zone 2 Critical		*x*	*X*		
Water Zone 2 Warning	*x*		*X*		
Water Zone 3 Critical		*x*	*X*		
Water Zone 3 Warning	*x*		*X*		
Water Zone 4 Critical		*x*	*X*		
Water Zone 4 Warning	*x*		*X*		
Water Zone 5 Critical		*x*	*X*		
Water Zone 5 Warning	*x*		*X*		

Alarm Name	Yellow	Red	Alarm	Horn	Strobe
Water Zone 6 Critical		x	X		
Water Zone 6 Warning	x		X		
Water Zone 7 Critical		x	X		
Water Zone 7 Warning	x		X		
Water Zone 8 Critical		x	X		
Water Zone 8 Warning	x		X		
Water Zone 9 Critical		x	X		
Water Zone 9 Warning	x		X		
Low Power Deviation	x		X		
Low Pressure Deviation	x		X		
Low Temperature Deviation	x	x	X		
Max Power		x	X		
Max Pressure		x	X		
Max Temperature Allowed		x	X		
No Power Supply		x	X		
No Water		x	X		
Power Loss Occurred		x	X		
Spill		x		x	x

Table 2 - Alarm Alerts

4.9 Digital I/O's

The I/O's that were incorporated into the silicon furnace are placed within racks of the cabinet with specific positions and channels. The functions and their particular locations are shown in table 3 below.

Rack	Position	Channel	Function
0	0	0	Vacuum Pump Contactor
0	0	1	Solenoid Roughing Valve
0	0	2	Blower Contactor
0	0	3	Heater Breaker
0	2	0	Spill Horn Coil
0	2	1	Strobe
0	3	3	Motor Power Relay
0	4	0	Tower Red
0	4	1	Tower Yellow
0	4	2	Tower Green
0	4	3	Tower Alarm
0	5	0	Over Temperature #2
0	5	1	Spill
0	5	2	Reset
0	5	3	Spare
0	7	0	Water Temperature In
0	7	1	Water Temperature Out
0	11	1	Over Temperature #2
0	11	0	Over Temperature #1
1	4	3	Lower Chamber Lift Push Button
1	4	1	Heater Contactor On Sensor
1	5	0	Over Pressure
1	5	1	Over Temperature #1
1	5	2	Chamber Open
1	5	3	E-Stop
1	9	0	Thermocouple #3
1	9	1	Heater Thermocouple Type B
1	11	1	Melt Pyrometer

Table 3 - I/O Functions and Locations

5.0 Simulations

To represent the operation of the furnace I used a simulation tool called Pspice. The two diodes shown in figure 23 represent the carbon arc used to heat the chamber of the furnace. The voltage labeled V represents a 100 volt sinusoidal wave with a frequency of 60 Hz. The two ohm resistor labeled R_d is used simply to protect the circuit. Switch 2 which is labeled with node C is connected to the circuit shown in figure 27.

```
V 1 0 sin(0 100 60)
D1 1 2 Di
D2 3 2 Di
.model Di D(bv=40 rs=1m)
Rd 3 4 2
S2 4 0 C 0 SW
```

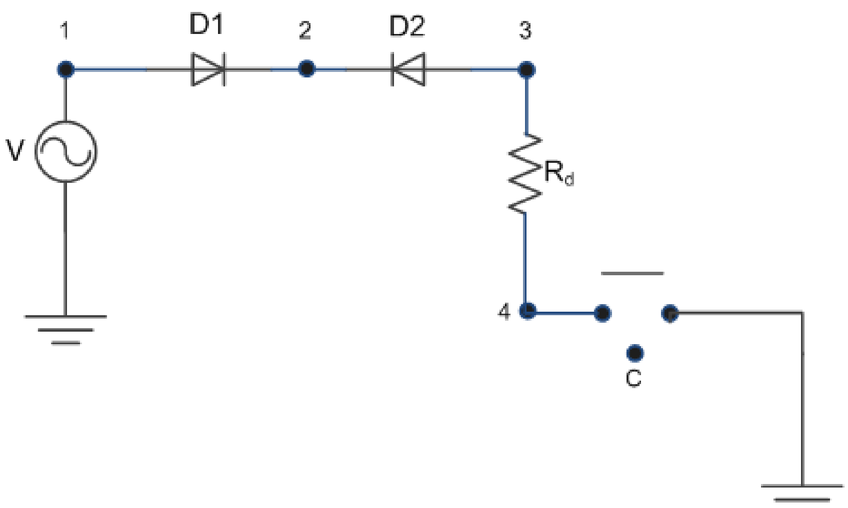

Figure 23 - Furnace Heating System

The graph represented in figure 24 shows the current through switch 2. The current through the switch is a constant sinusoidal waveform until the one second mark. At this point, a spill is simulated which causes the switch to open, when the switch opens the current shown in the graph drops to a constant zero.

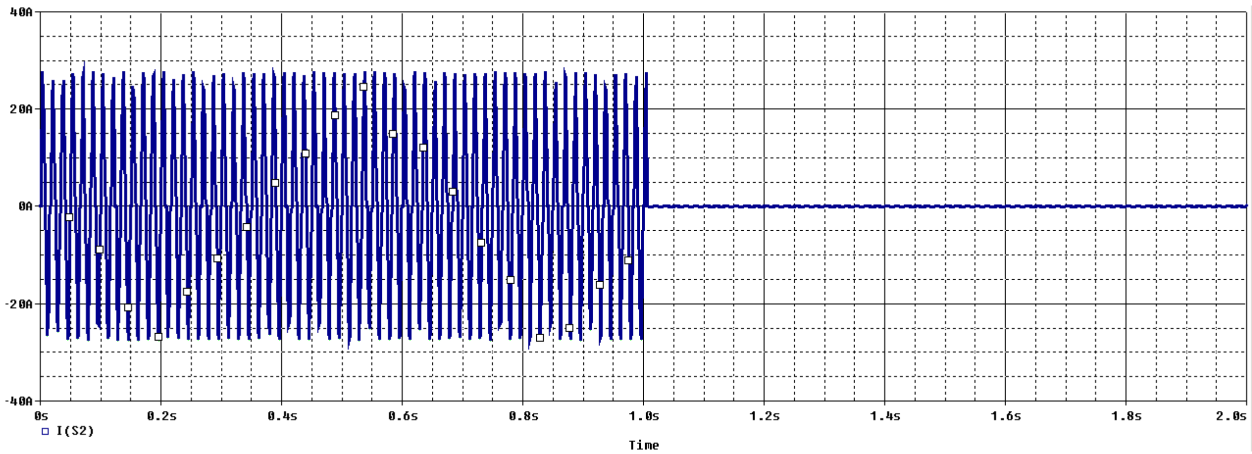

Figure 24 - Switch 2 Current

The circuit shown in figure 25 represents the thermal power in the chamber of the furnace. The current source labeled G is calculated using the voltage between nodes 1 and 3 as well as the voltage at node 3 and then this value is divided by 2, which represents the two ohm resistor. A thermal voltage and resistance are also wired in parallel. The value chosen for the thermal resistance was calculated to be 5.15 ohms such that the voltage through node 10 had a value to 3000 volts. To calculate the thermal capacitance the density of silicon, the approximate size of the block of silicon, the mass of silicon, the molar heat capacity of silicon and the atomic mass were taken into account. The average size of a block of silicon used in this silicon furnace is about 56633.69 cm^3. With this information and the other information specific to silicon I found the thermal capacitance needed to be 25.475 mega farads. The ambient temperature of the room was also taken into account, which I estimated to be 30^oC.

G 30 10 value={V(1,3)*V(3)/2}

Rt 10 30 5.15

Ct 10 30 25.475M

Vth 30 0 DC 30

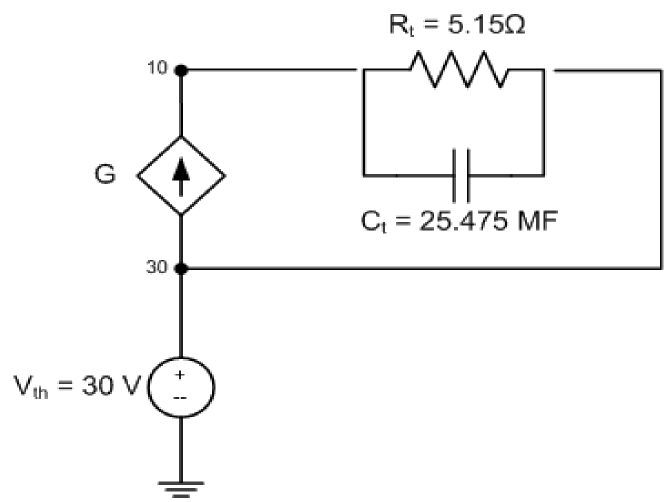

Figure 25 - Thermal Power

The graph shown in figure 26 represents the temperature within the furnace over time. As time passes the furnace will gradually heat up to its peak temperature of 3000^{o}C. To quickly represent the functionality of the furnace I scaled down the time. At the one second point a silicon spill is represented. When this occurs the temperature within the furnace begins to drop because the heaters will be turned off.

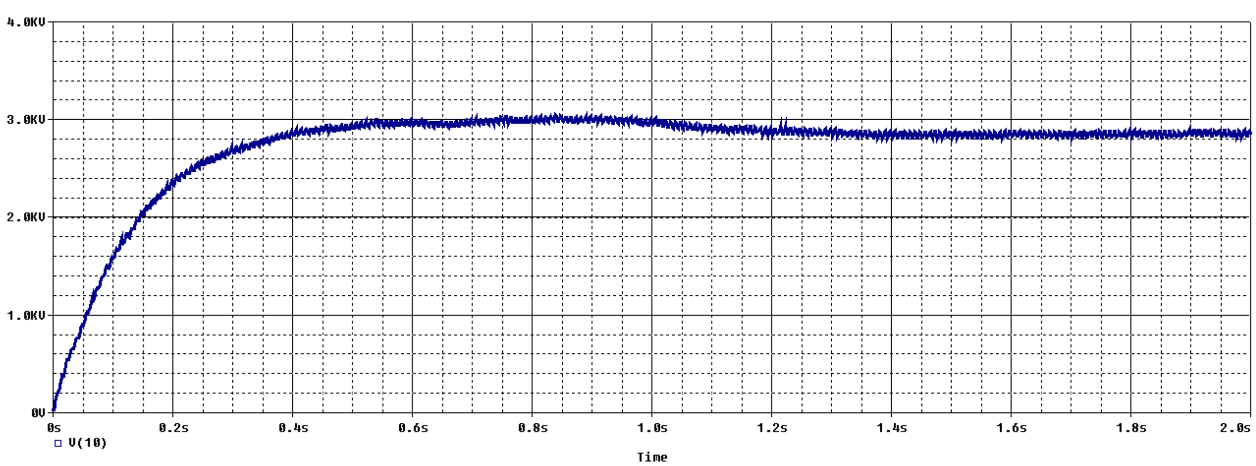

Figure 26 - Temperature within Furnace

The circuit shown in figure 27 represents the spill wire within the silicon furnace. Each of the switches shown in the circuit, S and S3 are trigged by the voltage supplies that they are directly connected to.

```
V2 11 0 12
L 11 12 100m ic=0
R11 12 A 1
R22 A 0 4
S A 0 C 0 SW
.model SW vswitch( ron=0.1
roff=1meg von=5 voff=2)
S3 A B F 0 SW
R3 B 0 3
Vt2 F 0 PWL(0,0 1.1,0 1.2,10 20,10)
Vt C 0 PWL(0,10 1,10 1.01,0 2,0)
.tran 2 2 0 1 uic
.print tran I(G)
.probe
.end
```

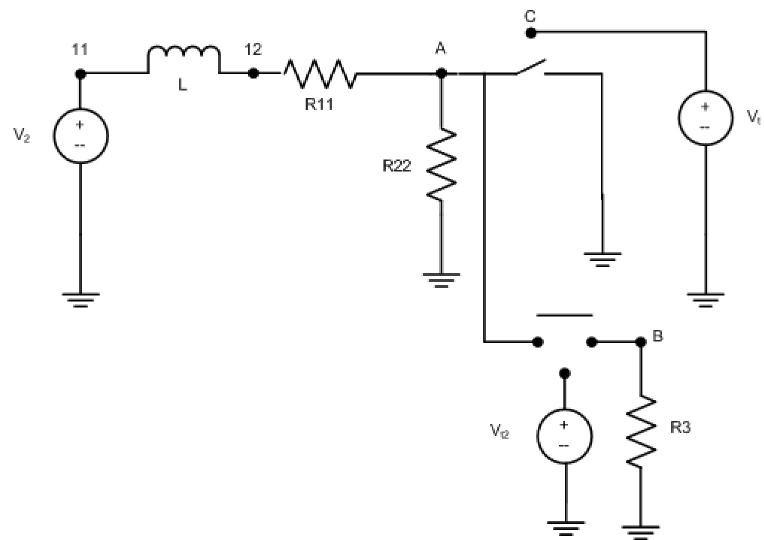

Figure 27 - Silicon Spill Wire

The graph shown in figure 28 represents the current through the spill wire over time. The inductor causes the gradual increase in the current through the spill wire which occur from time zero to time one. At the one second point a spill occurs and the spill wire is cut through by the molten silicon. Silicon acts as a conductor when in its solid form, so when the silicon hardens the current through the wire will increase to a constant value again. The reasoning for the difference between the two constant currents through the wire is because the silicon will be more resistive than the original copper wire.

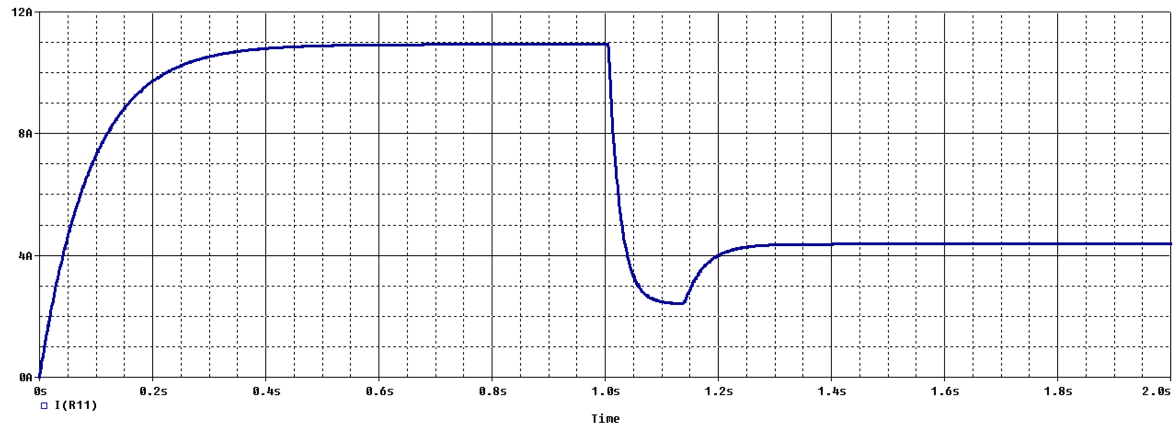

Figure 28 - Current through Spill Wire

6.0 Conclusion and Results

After the completion of the silicon furnace upgrades a 24 hour run of the machine was conducted to ensure that each of the components were working properly. During this 24 hour time period a manufacturing employee observed the machine and its actions during each process. During the heat up and cool down cycles, the temperatures collected by the thermocouple were recorded and later used to determine if any changes to the machine needed to be made. From the recorded temperatures it was concluded that the furnace was changing cycles at the appropriate temperatures and was working properly.

Other tests were conducted to test the alarm features. A manufacturing employee tested that each of the alarms sounded and the tower lights turned on by using a feature that was programmed into the machine. This feature allows an individual to press an image, on the computer screen, of either an alarm or a tower light and that action will trigger and a visual or audio test can be conducted.

Finally, the control cabinet components were tested. Such components were the individual modules and terminal blocks. These were tested by triggering an action through the computer program and visually watching the modules for a reaction as well as checking the power going to the individual components with a multimeter. The project was completed successfully by its end of July deadline and is functioning properly.

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