Microfabrication Lab Furnace Upgrade

Scope of Work

Prepared for:

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Statement of Disclaimer

Since this project is a result of a class assignment, it has been graded and accepted as fulfillment of the course requirements. Acceptance does not imply technical accuracy or reliability. Any use of information in this report is done at the risk of the user. These risks may include catastrophic failure of the device or infringement of patent or copyright laws. California Polytechnic State University at San Luis Obispo and its staff cannot be held liable for any use or misuse of the project.

Abstract

The Oxidation and Diffusion furnaces in the Microfabrication Laboratory on Cal Poly SLO Campus need renovation. The controls are very old and not intuitive, leading to a difficult learning process and time wasted during lab sessions for classes, hindering academic learning. Our team will be developing a new control system and user interface to facilitate improved furnace operation and student learning experience. This document outlines our process for developing the requirements needed to deliver a satisfactory product to the customer, Microfabrication Lab Director Hans Mayer. We began our development by touring the lab to understand the shortcomings of the current furnace system and interviewed our end customer to synthesize a list of needs and wants from the deliverable. The highest priority requirement stated by our customer is for the system to fulfill all the functions of the current system while improving the aesthetics and user control. The system needs to be extensively tested and will require customer review and approval prior to installation which should occur with minimum furnace downtime. A previous senior project attempted this upgrade before however did not adequately solve the issues and will be scrapped for parts. We conducted extensive background research into commercially available furnace control systems and concluded that this project requires a bespoke solution as control systems are almost exclusively sold with the associated furnace and replacing the furnaces entirely is out of the project scope. However, we will use this information to guide our design. We developed our project scope based off the needs and wants articulated by our customer. These needs and wants were then incorporated into our quality function development where we concluded that our highest design priorities were thermal and electrical safety, followed by proper functionality, resulting in a 24-hour burn-in test being our highest importance metric of evaluation. The delivery of our system will be approximately mid-May 2023.

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1: Introduction

Oxidation and Diffusion furnaces are used to augment the properties of the surface of silicon wafers. Oxidation furnaces do this by creating a thin film of silicon oxide over time by filling the furnace enclosure with oxygen and then raising the temperature to a high degree. The diffusion furnace does a similar process but instead “dopes” the surface to create desired properties from this. To get the desired properties, the main variables of the furnace that are controlled are the gasses involved (nitrogen for when an inert state is desired, oxygen when oxidation process is desired), and how long the furnace is to stay hot.

Currently the system has a functioning control system, but it is very old and finicky. The temperature controls utilize a not user-friendly UI that is prone to errors and the gas system is all controlled manually for the moment. There are also many extraneous mounts and tubes that have been added onto the system over time. These pose a hazard to the operator as they are close to the central walkway or do not have proper shielding.

The purpose of our project is to create a new user interface that enables a seamless interaction for the user to see the furnace temperature and control the gas release state. This will all be done through a central control panel that interfaces with the temperature and also enables the user to set times for when the furnace gases are in operation. All extraneous mounts and tubing are also to be streamlined and made aesthetically pleasing for safety and for public image of the laboratory.

Our team members include Benjamin Ozer Fields, Brooke Benedict, Nathaniel David Burtnett, and Thomas Mackay Taylor. We are Cal Poly San Luis Obispo Senior Mechanical Engineering Mechatronics students and share an interest in automation, robotics, and control theory.

This report will consist of a brief background summary, establish research results performed by a previous senior project team, and findings from current industrial applications of gas metering and control. A project scope establishes our relationship with the customer, a high-level overview of their desired project outcome and how the functions are decomposed into smaller functions, and the team’s deliverable product. An objective section outlines the problem, determines engineering specifications and a test plan, and identifies areas at a higher risk of underperforming. The project management section outlines when are what will happen from now until the project is delivered.

2: Background

2.1. Interview With Sponsor

To start the whole process, we scheduled a meeting with our sponsor, Professor Mayer. During our meeting with him we discussed the furnace to better understand the scope of this project. Professor Mayer is currently the Director of the Cal Poly Microfabrication Laboratory, and he teaches Micro/Nano Fabrication classes. He identified a decent number of problems with the current microfabrication oxidation and diffusion furnace control system. Through the interview Professor Mayer pointed out that; the readout to control the temperature is very unintuitive to use and partially broken, when using wet oxygen, the user must manually press a button to refill the bubbler every five minutes or so, the buttons are small and hard to use with bulky gloves on, the control also spans around three sides of the machine, making furnace operation difficult, the current furnace control system is also very hands on as well, there is automation in the system, but it is unused because of how hard it is to use, the current system is a mess of wires and tubes and old looking controls, this does not look professional or current for any potential donors or tours when looking into the lab, there is no indication for the levels of O2 or N2 in the system, and in general there is limited feedback information displayed. For a more comprehensive breakdown of the Sponsor's needs please see **Appendix A**.

2.2. More User Information

In the next few weeks, we would also like to send a survey out to either current or previous students of this lab to understand their experience with the current control system. Our plan is to make an office forms file so that data collection can be automated and sent to as many people as possible. In this survey we will ask about likes and dislikes about using the current system, if any projects were ruined as a result of the controls, and other user experience questions.

2.3. Existing Designs

While looking for products already on the market, we found that most microfabrication furnaces are sold in combination with their control system. This made it challenging to make a direct comparison as our scope for this project is only to change the controls of the current furnace. We also found that furnace with atmospheric modification control is few and far between. The number one insight gained is that the furnace itself that we must work with is stands up to its competitors in the market today in terms of features. We also looked at the previous senior project group's report to see why their project was not implemented. We found mostly that they ran out of time at the end of the project to produce the actual control apparatus [18]. Their research on the system was extensive and will be helpful to this project.

After going to some furnace postings, we found that the Siemens S 7 control system seems to be in many new furnaces [1]. The starting pack contains: a CPU, memory, a software package, a power supply, professional help to install or call when the system encounters problems, and a few more extraneous things [2,3]. Much of which we already have, and it would be unnecessary for us to purchase this all included product. We also encountered another microfab furnace line from Carbolite Gyero. They sell many furnaces in combination with a set number of control systems to choose from [4,5]. The main issue with these furnaces is that while they offer inert gas controls and PID temperature controls, like our current furnace, they do not have any oxygen controls. Also, you cannot buy the control system separate from the furnace. For the large batch Jteket systems, the control system is completely incorporated with the furnace, and all control system details are completely absent from their website [6]. Though this furnace does everything we would need it to do, it is not that helpful to look at as all the control system details are absent. We also found a smaller scale new furnace more like the furnace that is currently in the lab from McQueen Laboratory supply that again does not have any atmospheric modification included, and there is no information about the control system on the website either [7].

2.4 Patent Research

As for the patent search we found a few related patents but none that patented a just a furnace control system. We found patents that were about the fabrication process of microchips, and systems to control and move gases around. However, much of the patent literature about semiconductors is in Japanese, and though translated, it is still challenging to decipher.

Specifically, the first related patent we found was about a HVAC building system [8]. that is surprisingly like what we are trying to do minus the furnace control. As we will be modifying the atmosphere in the oxidation furnace, the control and moderation of gasses will be important. The control diagrams and other feedback control will be useful information for us to look at more in the future. We also found a Japanese patent detailing an entire factory process for manufacturing DRAM semiconductors [9]. There is a furnace section, but it has been google translated from Japanese, and it is particularly hard to understand without use of the diagrams, which are all still in Japanese. Mostly it talks about making an oxide layer on a wafter that is 10nm thick, which is what our furnace system will do, however there is no mention of wet or dry oxygen which is what we are controlling. We also found a Chinese patent about a diffusion furnace [10]. Though it did not contain any information about a control system, it described a method for smoothing out an oxide layer on a wafer. The main method it cited was moving high purity gases over the wafers while being heated. While our diffusion furnace does not have a fan, it modifies its atmosphere and heats the wafers. We also found a patent about an oxidation furnace as well that even mentions using wet oxygen [11]. From this patent we gained a very helpful graph (**Figure 1**) that shows the oxidation process being done to the wafer through the introduction of steam. It shows the timing of how their process goes. Though we do not care much about the pressure since we have a modified atmosphere furnace and not a vacuum furnace. The information is still helpful.

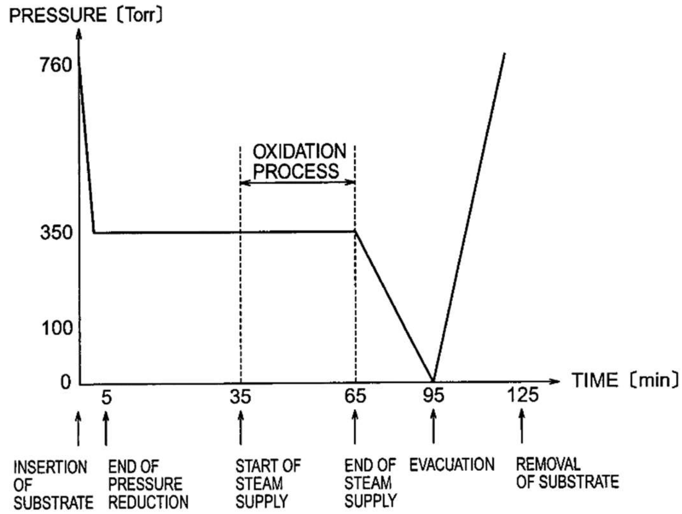


FIG. 5

Figure 1 - Picture of timing of oxidation process [11]

And finally, we found a Chinese patent that detailed how the control system of a furnace was wired, but again, the diagram was in Chinese and therefore maybe a little bit less useful than it maybe could have been [12].

2.5 Journal Research

Though no single academic journal we could find related perfectly to our topic of furnace controls, we found a conglomeration of many others that were still helpful to our project. Specifically, we found journals about the control of the heating elements [13], modeling of a furnace system [14], one discussing the use of wet oxidation [15], a fuzzy sliding mode to control a furnace [16], and finally a journal about an automated oxidation furnace system [17].

Through this research, we found that there are many ways to control the furnace heat. Specifically, we could use PID controls, model biased control, or a fuzzy sliding mode control method. All these control methods have been used to control furnace temperature before as can be seen in the cited journals. Our sponsor has said that he wanted the use of the already existing thermocouple to provide a visual temperature read out, this data can also be used for any control we wish to do with the furnace. The main difference from all the control journals [13, 14, 16] and our system is the methods described were for more complicated furnaces than ours. Each of the furnaces described in the journals were multizone, while we will only deal with single zone furnaces.

We also did some research about the oxidation process as well. Through the research about the oxidation process, we learned that through the temperature ramp up and down process the wafers will start oxidating before the furnace reaches the set temperature [17], which will decrease the quality of the oxidation. This means that the atmosphere modification that the current furnace does with pure nitrogen is very important as current ramp up and down times are quite long. We also learned that wet oxidation (done with steam) produces a much thicker oxide layer in comparison to dry oxidation (done with pure oxygen) [15]. This means that it is important the bubbler can put out enough steam at a stable rate to achieve an expected oxide thickness. For further guidance on the oxidation, we looked at other university's' recommendations and findings. The University of Kentucky stated that in their microfab labs when oxidizing a wafer, they like to use a dry-wet-dry cycle to get the quality of the dry oxide layer and the quickness of the wet oxide layer [20]. The final source we looked at was from a Utah Sate University capstone project, there it was detailed that the flowrate of oxygen during the oxidation process is not that important, but when the wafers are in contact with nitrogen at all, oxidation does not occur [19]. Why is all of this useful to us? It helps us to understand how critical it is for us to make a device that finely controls all aspects of the oxidation process from ramp up and down to the introduction of nitrogen, to the selection of wet and dry oxygen.

3. Project Scope

3.1 Boundary Diagram

A boundary diagram was created to differentiate between internal and external system parameters. Our control system will operate as a subset of the furnace system, which itself a subset of the clean room system. The design decisions made by the team will be influenced by the project boundaries. The furnace control system must interface with existing furnaces as well as any future upgrades. Our control system will be mounted to the existing furnaces. The control system will take user inputs and signals from furnace temperature and various sensors and use that information to control the fluid type that is routed to the active furnace, and for what duration. The system will then give process control feedback to the user, such as graphical representations of the current system configuration, along with timers and any alarms such as low gas or water levels.

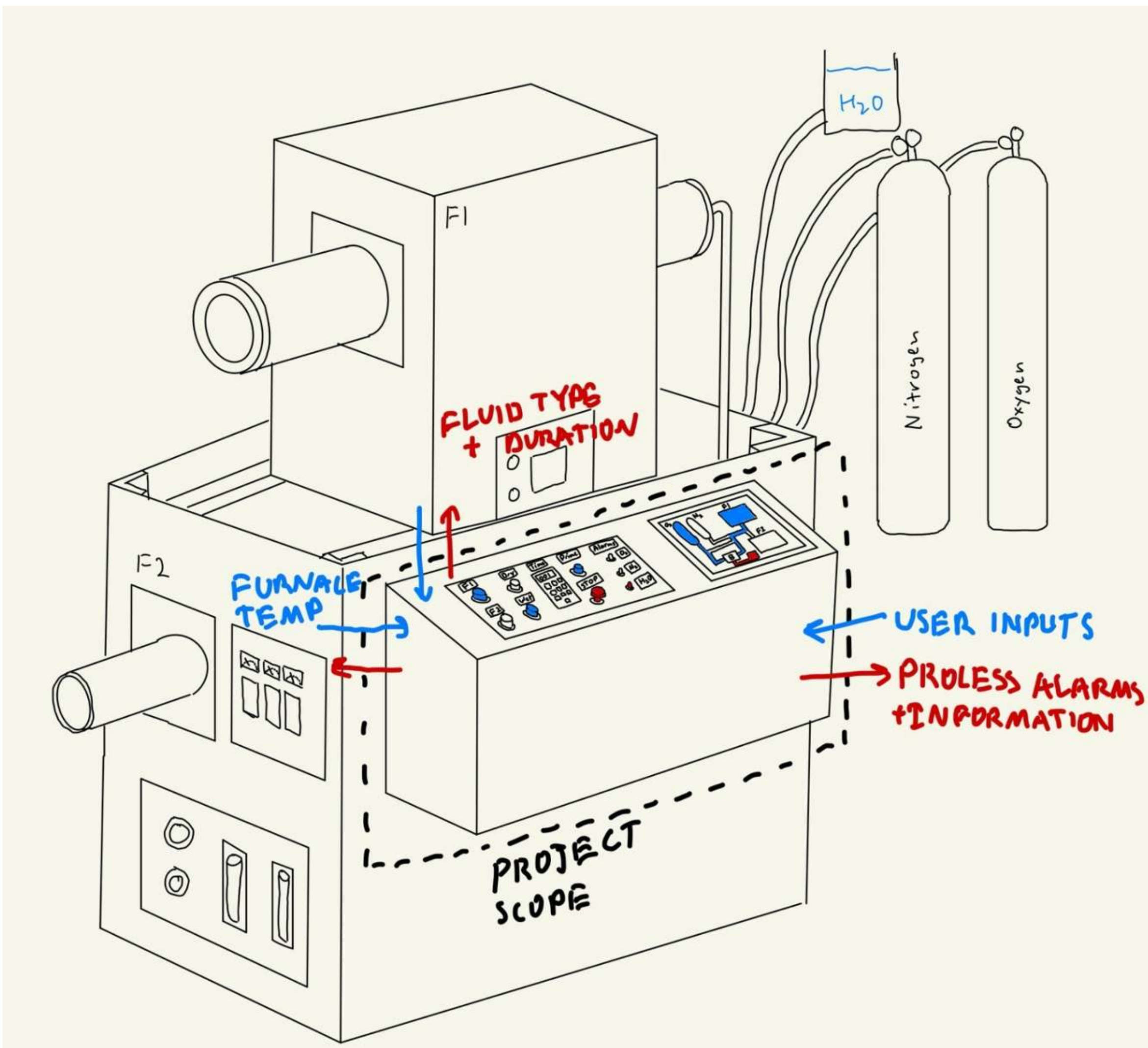


Figure 2 - System boundary diagram.

3.2 Stakeholder Wants and Needs

The stakeholder wants and needs describe the set of project requirements that have been described or inferred by discussing with Professor Mayer, the project sponsor. Some requirements are critical to project success, while other requirements are non-critical but would improve system usability. These requirements have been separated into specific categories and will be subsequently used in our Quality Function Development (QFD), which can be found in section 4.2.

- Geometry: Project size bounds must be within the existing footprint of the furnace system. Panels should cover the front surface from the ground to below the top furnace control panel. The right-side panel should replace the existing bubbler framework and cover the tubing array. Panels can extend past vertical support struts but not past ground the footprint. Shrouding should be aesthetically pleasing.
- Energy: Distribute high purity dry or wet oxygen, and dry nitrogen at 40 PSI to either furnace at a user-controlled flowrate. The system should not have leaks or cross contamination.
- Material: Any tubing and valves need to be compatible with high purity nitrogen and oxygen.
- Flow/transport: 40psi High Purity Nitrogen and Oxygen must be delivered reliably. Oxygen must be able to be passed through a bubbler.
- Signals:

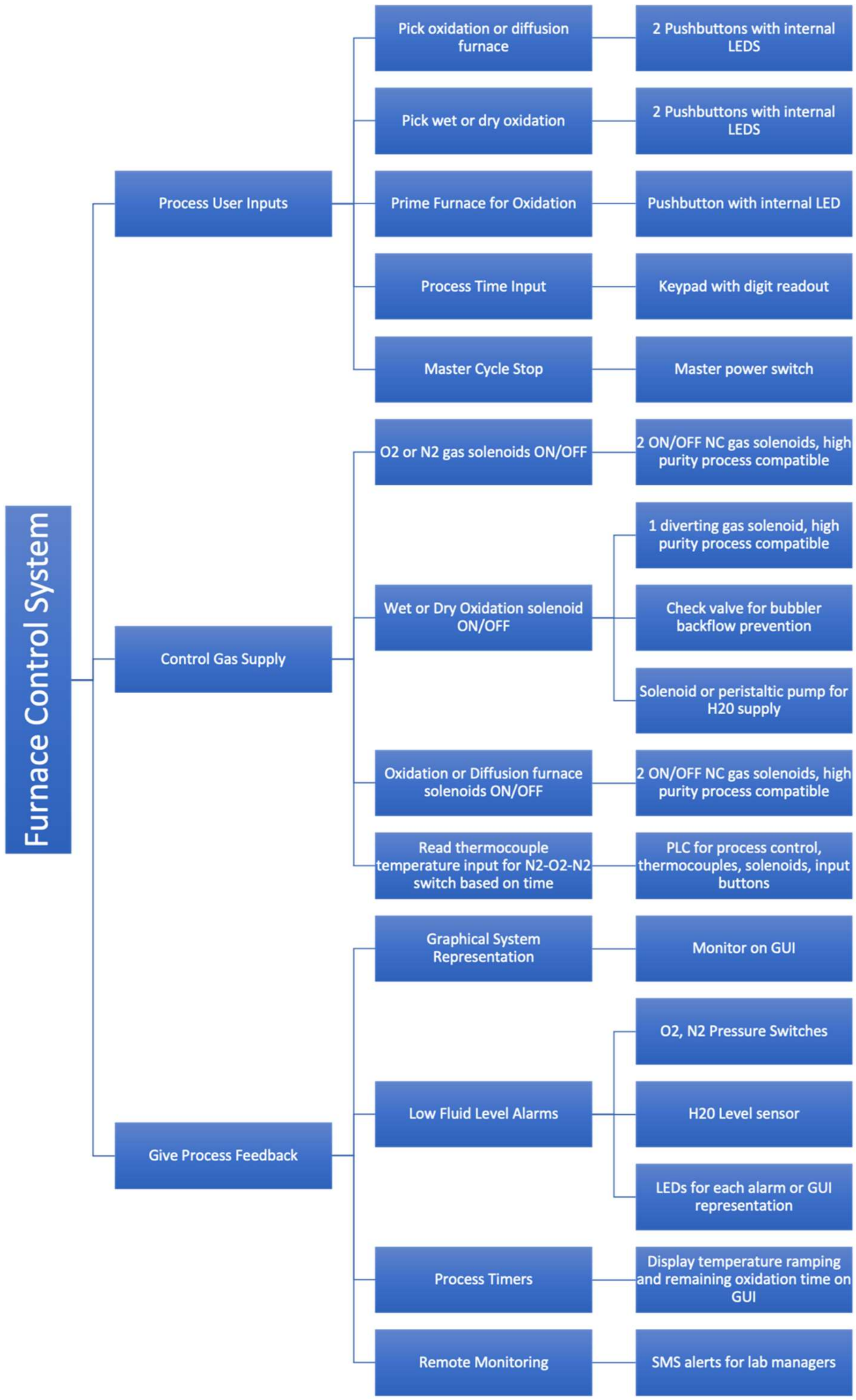
Table 1 - Signals breakdown for PLC I/O.

Digital System Inputs	**User Inputs**	**System Outputs**	**Visual Display**
Temp. Furn. 1	Furnace1 or Furnace2	O2 Flow On/**Off**	Furn. 1 Temp (plot)
Temp. Furn. 2	Wet or Dry O2	N2 Flow On/**Off**	Furn. 2 Temp (plot)
O2 Pressure Switch	Parts Loaded Button	O2 Diverter On/**Off**	O2 Flowing/Time
N2 Pressure Switch	Desired Oxidation Time	Bubbler Power On/**Off**	N2 Flowing/Time
Bubbler Water Level	Emergency Stop	Water Dispense On/**Off**	Warning Messages
		Furn. 1 Flow On/**Off**	
		Furn. 2 Flow On/**Off**	
		TimeTemperature **CSV**	
		Warning Light **Color/Rate**	

- Safety: Operators will be in cleanroom clothing and using heat resistant shielding for operation of the furnace. System itself should not have dangers of exposed wiring, pipe failure, or thermal dangers.
- Human Factors/Ergonomics: Be able to be operator at average standing height comfortably for majority of operations, tactile user controls, visual operation feedback for furnace, gas, and mode selection.
- Production: Maximum dimensions is the footprint of the existing furnace.
- Quality Control: Fluid control system must be compliant with cleanroom standards for high purity gas control applications. Installed equipment should be as particulate free as possible to prevent contamination.
- Assembly: Control system assembly is required to be fully prepared (Built, tested, etc) for installation prior to installation. Entire control system should be installed within a day to minimize furnace downtime.
- Operation: Cleanroom operation.
- Maintenance: Valve and control system access should be easily accessible in case of failure, problem diagnosis and general maintenance.
- Costs: Use existing hardware purchased by the previous project group, additional costs can be addressed as needed.
- Schedules: Delivery at end of senior project term, mid-May 2023.

3.3 Functional Decomposition

The functional decomposition for our system breaks down the overall system required functionality into a series of subfunctions, which are then further broken down into subsequent subfunctions until a collection of basic functions are reached. The breakdown of our system is displayed below.



3.4 Final Deliverable

Our final deliverable for this project will be the full control system and user control panel for the oxidation and diffusion furnaces. The project will culminate in the installation and verification of the system into the cleanroom with a minimal amount of downtime. Success in this will require the system to be fully functional, extensively tested, and having received sponsor review and approval prior to installation, along with a planned and choreographed installation process to ensure a minimal amount of required troubleshooting.

4. Objectives

4.1 Problem Statement

The problem statement for this project is defined as follows: Professor Hans Mayer, Director of the Cal Poly Microfabrication Laboratory has requested a redesign of the Oxidation and Diffusion furnace control system. The current control system is cobbled together, outdated, ergonomically inefficient, and aesthetically unpleasing. The system itself is difficult to program, read outputs, and teach unaccustomed users how to operate. Our solution would need to interface with the existing furnace and gas supplies while incorporating a new intuitive control system and interface that is more conducive to academic learning while also renewing the aesthetics of the system to promote an improved view of microfabrication to both prospective students and sponsors. A full list of customer needs can be found in Appendix A.

4.2 Quality Function Deployment (QFD) Process

Our team performed a Quality Function Deployment plan by using a House of Quality worksheet (Appendix B). We started by identifying the customers of our product. Dr. Mayer will be guiding us through constraints and specifications initially while microfabrication students and lab techs will be using the equipment more frequently. Our final customer is anyone passing through the halls (tour groups, guests, potential students, etc.). The control system must meet several technical, ergonomic, safety, and aesthetic requirements to please each customer.

We then listed each aspect of the control unit. A few examples include intuitive controls, monitor tank pressure, and refill the water bubbler. The importance of these aspects was ranked for each customer. Engineering specifications were then created. Several specifications are able to qualify several functions simultaneously. Creating discrete pass/fail tests for each aspect of the control system will guide the design process as well as eliminate unnecessary features or tests.

We ranked the current system against our design aspects and found it lacking (hence the need for an upgraded control system). Unfortunately, this is a bespoke system, and no direct competition exists. In order to rank competition, we would need to request quotes from engineering firms for custom solutions. This would be disrespectful to professional engineers' time. If a quote(s) were obtained, we would then rank their proposal(s) on assumptions alone.

4.3 Engineering Specifications

We must be able to assess our final design. The specifications we listed are inspired by interviews with Dr. Mayer and a review of the previous senior project report. It is important that each design specification be able to be tested empirically. Hardware tests, such as actuators and sensors, can be tested repeatedly. A long-term test will probe system stability, thermal loading of relays, reliability, and for leaks. User feedback via surveys will be used to rate qualitative features on a scale of one through ten. For the soft tests, we will time lab students as they configure the furnace system.

Table 2 - Design specifications.

Spec #	Specification Description	Requirement or Target (units)	Tolerance	Risk*	Compliance**
1	Monitor Tank Pressure	1 [psig]	±0.5	M	T
2	Leakproof	Soap Bubble [2/min]	Max	H	I
3	Ergonomic	Survey: 8/10 [stars]	min	M	A
4	Not Catch on Fire	Pass/fail	n/a	L	I
5	Gas Delivery Time	1 Minute	Max	H	T
* Risk of meeting specification: (H) High, (M) Medium, (L) Low ** Compliance Methods: (A) Analysis, (I) Inspection, (S) Similar to Existing, (T) Test					

Table 2 is a specifications table that includes a compliance column. The methods included are Analysis (A), Test (T), Similarity to Existing Designs (S), and Inspection (I). Each compliance method was determined based on the parameter descriptions. For the testing and analysis, our group will need to use components that meet or exceed the design targets. The risk specifications were assigned with High (H), Medium (M), and Low (L) risk factors. For example, the gas delivery time specification was given a high rating because time of oxidation can be hard to pinpoint throughout a long plumbing system and is important for precise oxide layer growth control. In order to meet all specifications, the team will prioritize high quality components (valves, actuators, and control hardware) as well as a thorough software design review.

4.4 Descriptions of All Specifications

Aesthetics and ergonomics must be determined by survey and user feedback. This will be an ongoing process as ideation becomes more tangible for user experience. Dr. Mayer will be asked for initial feedback as we create a control panel. Once we reach final hardware design, we can fine tune the graphical user interface upon group testing with lab students. Although the system performs mechanical tasks, it must be intuitive to use and have visual appeal.

Hardware can be tested for leaks, sensor output, and solenoid actuation in a test box before implementation in the clean room. We will be able to simulate temperature inputs with potentiometers to trigger screen messages, actual solenoids, and produce warnings. Some of the tests will only be able to be done once the entire system is installed into the clean room, at which point changes will not be able to be made other than software updates. Sensors should reliably determine simultaneous furnace temperature, incoming gas pressure, and bubbler water level. These system inputs, along with user input parameters, will control the outputs. The system needs to reliably switch between delivering to the two furnaces: dry nitrogen, dry oxygen, and wet oxygen.

4.5 Discussion of High-Risk Specifications

Gas delivery time is critical. If the users believe oxygen is running but it isn't, their calculations for oxide layer growth will not reflect reality. It is extremely important that we make very clear when oxygen is flowing and when it has been shut off. This timing will be fine-tuned on a test bed to test actuator switching time and consistency.

Leakproof has a high impact as well. High purity nitrogen and oxygen are expensive to refill. Any leaks of nitrogen are not immediately hazardous, but a buildup of high purity oxygen can be ignited rather easily. If the furnace chamber were to fill with high purity oxygen and a spark were then introduced, the lab could undergo spontaneous structural reconfiguration.

5. Project Management

Our project design process began with visiting the Microfabrication Lab and discussing customer requirements and inspecting the current system. We will proceed by first taking inventory of all the material that we are being given from the previous team, and by creating a 3D model of the system so we can have reference to design from. After having all our resources and initial setup done, we will draw out both a current system diagram and then a renewed system diagram. Once these initial steps are completed, we can then move on to the main sections of design, which are: Mechanical System Design, Furnace Aesthetic Design, and User Interface Design. Since these sections are supposed to run concurrently as opposed to sequentially, they will each have their own goals to have completed by the Design Reviews. The Project Management outline is detailed below in Table 5.1. This can also be viewed in more detail in Appendix C.

***Table 5.3**: Project Management Timeline*

Major Deliverable	Due Date	Description
Scope of Work	10/19/22	Document outline of the entire project
PDR	11/15	First major review of design concepts
IDR	1/24/22	A detailed review of the planned design
CDR	2/14/22	A full review of all design elements
Test Plan	3/16/22	A document detailing our planned test procedures
Manufacturing Plan	3/16/22	A document detailing our plan for fabricating all constituent elements of the design
Operations Manual	5/6/22	A manual that can be given to the end use
FDR	6/1/22	A final review of the product and its resultant mode.
Wrap Up Paperwork	6/9/22	Completing all final documentation.

6. Conclusion

This statement of work is an agreement between the project team and the sponsor about the scope that is to be expected. Any content in this document is subject to change under guidance from an advisor and agreement with the sponsor. This document is facilitated by the advisors of the Senior Design Project and will be used in further documentation as evidence of past agreements.

References

[1] "Products," *Direct Industry*. [Online]. Available: https://www.directindustry.com/prod/linn-high-therm-16483.html. [Accessed: 17-Oct-2022].

[2] "Starter kits," *Industry Mall - Siemens WW*. [Online]. Available: https://mall.industry.siemens.com/mall/en/WW/Catalog/Products/10397941?activeTab=productinformation®ionUrl=WW#. [Accessed: 17-Oct-2022].

[3] Siemens, *Product overview for SIMATIC S7- 1500 TIA Selection Tool Web*. Siemens Industry Inc., Alpharetta, GA, 2022. [Accessed: 17-Oct-2022]

[4] "TF Tube Furnace range," *Carbolite Gero*. [Online]. Available: https://www.carbolite-gero.com/products/tube-furnace-range/universal-tube-furnaces/tf-range/. [Accessed: 17-Oct-2022].

[5] "CC-T1 Touch screen controller," *Carbolite Gero*. [Online]. Available: https://www.carbolite-gero.com/products/control-options/cc-t1-controller/. [Accessed: 17-Oct-2022].

[6] "VF-5900 vertical furnace for 300-mm wafers," *JTEKT Thermo Systems*. [Online]. Available: https://www.jtektthermos.com/products/semiconductor/vf5900/. [Accessed: 17-Oct-2022].

[7] "Thermo Scientific Lindberg/Blue M 1100 °C tube furnaces," *Mcqueenlabs*. [Online]. Available: https://www.mcqueenlabs.com/docs/thermo-furnaces.pdf. [Accessed: 18-Oct-2022].

[8] I. Hasan, G. H. Fasullo, and F. I. Menocal, "Method of auto association of HVAC energy with control signal for self diagnostics of the HVAC system," 30-Mar-2021.

[9] 幸広 牛久, 章 小川, 英則 柿沼, 俊次 首藤, 正泰 安部, 龍雄 秋山, and 茂 小松, "Semiconductor device manufacturing system and semiconductor device manufacturing method," 14-Nov-2005.

[10] 陆益, 邹威, 赵晓非, 张凡文, 裘俊庆, and 王毅, "Quartz tube of horizontal diffusion furnace," 20-Mar-2020.

[11] T. Hoshi and M. Kiyotoshi, "Semiconductor device fabrication method," 06-Oct-2009.

[12] E. M. Bethune and D. Olmsted, "Semiconductor processing furnace heating control system ," 01-Nov-2001.

[13] E. Grassi and K. Tsakalis, “PID controller tuning by frequency loop-shaping: Application to Diffusion Furnace Temperature Control,” *IEEE Transactions on Control Systems Technology*, vol. 8, no. 5, pp. 842–847, Sep. 2000.

[14] A. Emami-Naeini, J. L. Ebert, D. de Roover, R. L. Kosut, M. Dettori, L. M. L. Porter, and S. Ghosal, “Modeling and control of Distributed Thermal Systems,” *IEEE Transactions on Control Systems Technology*, vol. 11, no. 5, pp. 668–683, Sep. 2003.

[15] C. Barker, A. Badowski, B. Whitefield, K. L. Levien, and M. D. Korestky, “Factors Affecting Thickness Variation of SiO2 Thin Films Grown by Wet Oxidation,” *IEEE Transactions on Semiconductor Manufacturing*, vol. 24, no. 2, pp. 348–357, May 2011.

[16] S.-J. Huang and H.-Y. Chen, “Un-symmetric Input Temperature Control by using Fuzzy Sliding Mode Controller with Gain Auto-tuning,” *International Journal of Control, Automation, and Systems*, Dec. 2014.

[17] S. A. Faruque, D. Biswas, S. Saha, and S. Chakraborty, “Development of a linear temperature ramp-based automated system for furnace oxidation of semiconductor wafers,” *International Journal of Instrumentation Technology*, vol. 1, no. 4, p. 259, 2015.

[18] K. Anzai, E. Fedor, and P. Zailaa, “Furnace Improvment Systems,” *Digital Commons @ Cal Poly*, 08-Dec-2018. [Online]. Available: https://digitalcommons.calpoly.edu/mesp/456. [Accessed: 01-Oct-2022].

[19] J. Koskan, “Thermal Oxidation of Silicon in a Home-Made Furnace System,” *DigitalCommons@USU*, Apr-2019. [Online]. Available: https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=1073&context=phys_capstone project. [Accessed: 17-Oct-2022].

[20] “Furnaces,” *UK College of Engineering Center for Nanoscale Science and Engineering*. [Online]. Available: https://cense.engr.uky.edu/equipment/furnaces. [Accessed: 19-Oct-2022].

Appendices

Appendix A – Customer Needs

Customer Needs List:

- Geometry: Project size bounds must be within the existing footprint of the furnace system. Panels should cover the front surface from the ground to below the top furnace control panel. The right-side panel should replace the existing bubbler framework and cover the tubing array. Panels can extend past vertical support struts but not past ground the footprint. Shrouding should be aesthetically pleasing.
- Energy: Distribute high purity dry or wet oxygen, and dry nitrogen at 40 PSI to either furnace at a user-controlled flowrate. The system should not have leaks or cross contamination.
- Material: Any tubing and valves need to be compatible with high purity nitrogen and oxygen.
- Flow/transport: 40psi High Purity Nitrogen and Oxygen must be delivered reliably. Oxygen must be able to be passed through a bubbler.
- Signals:

Digital System Inputs	User Inputs	System Outputs	Visual Display
Temp. Furn. 1	Furnace1 or Furnace2	O2 Flow On/**Off**	Furn. 1 Temp (plot)
Temp. Furn. 2	Wet or Dry 02	N2 Flow On/**Off**	Furn. 2 Temp (plot)
O2 Pressure Switch	Parts Loaded Button	O2 Diverter On/**Off**	O2 Flowing/Time
N2 Pressure Switch	Desired Oxidation Time	Bubbler Power On/**Off**	N2 Flowing/Time
Bubbler Water Level	Emergency Stop	Water Dispense On/**Off**	Warning Messages
		Furn. 1 Flow On/**Off**	
		Furn. 2 Flow On/**Off**	
		Time-Temperature **CSV**	
		Warning Light **Color/Rate**	

- Safety: Operators will be in cleanroom clothing and using heat resistant shielding for operation of the furnace. System itself should not have dangers of exposed wiring, pipe failure, or thermal dangers.
- Human Factors/Ergonomics: Be able to be operator at average standing height comfortably for majority of operations, tactile user controls, visual operation feedback for furnace, gas, and mode selection.
- Production: Maximum dimensions is the footprint of the existing furnace.
- Quality Control: Fluid control system must be compliant with cleanroom standards for high purity gas control applications. Installed equipment should be as particulate free as possible to prevent contamination.
- Assembly: Control system assembly is required to be fully prepared (Built, tested, etc) for installation prior to installation. Entire control system should be installed within a day to minimize furnace downtime.
- Operation: Cleanroom operation.
- Maintenance: Valve and control system access should be easily accessible in case of failure, problem diagnosis and general maintenance.
- Costs: Use existing hardware purchased by the previous project group, additional costs can be addressed as needed

Appendix B – House of Quality

Correlations	
Positive	+
Negative	–
No Correlation	

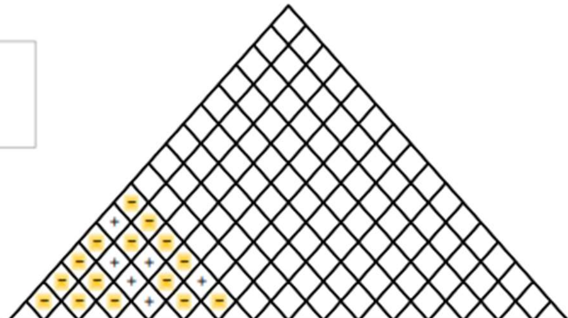
Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

QFD House of Quality

Project: F94 MFLU

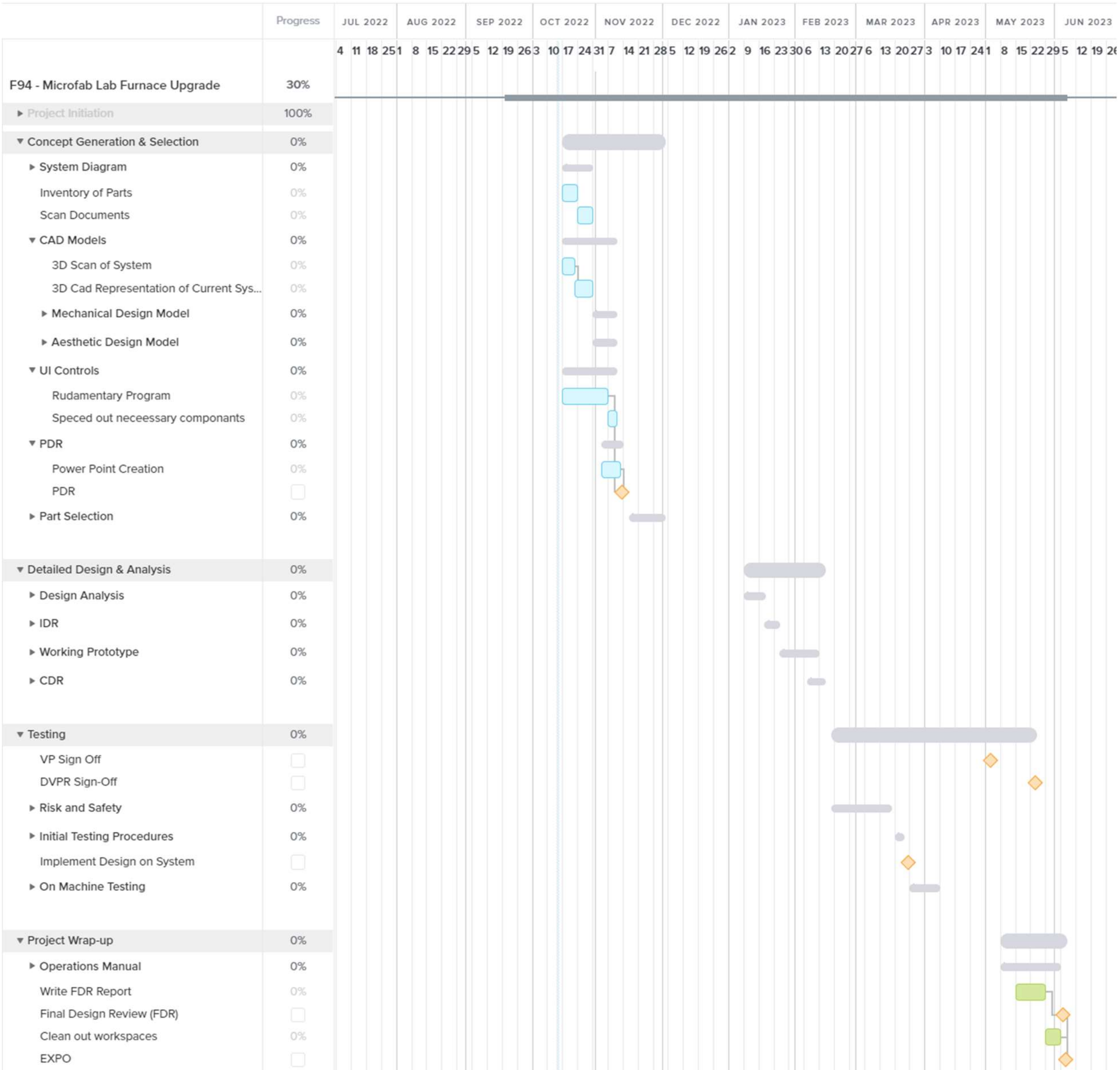
Revision Date: 2022-10-11



Column #								1	2	3	4	5	6	7		
Direction of Improvement								▲	▼	◇						
Row #	Relative Weight	Mayer	Students	Lab Techs	Cal Poly PR	Maximum Relationship	WHAT: Customer Requirements (Needs/Wants) / HOW: Engineering Specifications (Tests)	Human Factors	Soap Bubble Test	Burn In Test	Simulated Furnace Run	MTBF Analysis (Hardware)	Inspection (Software)	Total Cost	NOW: Curr. Products – Current Lab Furnace System	Row #
1	5%	8	6	1	9	9	Aesthetic	●	●						3	1
2	5%	8	7	7	3	9	Ergonomic	●							2	2
3	6%	10	10	10	2	9	Intuitive Controls	●							2	3
4	5%	10	9	9	1	9	Not Leak		●	●					9	4
5	7%	10	10	9	5	9	Deliver Gas			●					9	5
6	6%	7	4	8	7	9	Monitor Tank Pressure			●					1	6
7	8%	10	8	10	10	9	Not catch on fire		●	●					9	7
8	6%	9	8	8	5	9	Monitor Furnace Temperature				●				9	8
9	7%	10	10	8	5	9	Deliver the right gas				●				9	9
10	5%	8	8	7	4	9	Deliver at the right time				●				9	10
11	6%	10	10	9	3	9	Deliver wet or dry o2				●				6	11
12	6%	8	10	10	2	9	Automatically refill bubbler			●	●				1	12
13	4%	7	2	5	6	9	Remote monitoring				●				1	13
14	8%	10	10	10	7	9	Thermal Safety			●					4	14
15	8%	10	10	10	7	9	Electrical Safety			●					7	15
16	7%	9	9	8	7	9	Operates Reliably					●	●		5	16
17	2%	9	1	1	1	9	Affordable							●	5	17

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
HOW MUCH: Target Values	Survey Score > 8	Pass / Fail	24 Hours	10/10 Varied Conditions	Pass / Fail	Pass / Fail	< $5000									
Max Relationship	9	9	9	9	9	9	9									
Technical Importance Rating	146	169	418	307	61.2	61.2	19.3	0	0	0	0	0	0	0	0	0
Relative Weight	12%	14%	35%	26%	5%	5%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Curr. Products: Current Lab Furnace System	1	3	4	2												
0	2	3	5	1												
0	3	0	4	5												
0	4	1	5	4												
0	5	5	2	1												
Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

Appendix C – Gantt Chart



Appendix D – Preliminary Analysis of Current Solution

Current System:

Need	Ranking	Description
Geometry	Low	Fits within the footprint but there are many overhanging pipes and wires. These should be covered so they can't be damaged by a cart.
Energy	High	The current system does it's intended job once programmed.
Material	High	The piping and valves in use seems to be moving gas without issue.
Flow/transport	High	Once programmed, the correct fluid is dispensed to the correct furnace.
Signals	Low	There are no displays indicating what's happening in the system. The system doesn't sense low gas pressure. There is no user input to confirm parts are loaded and ready for oxidation. There is no visual graph display.
Safety	Medium	There is a mild thermal risk with the exposed bubbled O2 line warmer exposed. There are quite a few places where clothing can be snagged.
Human Factors and Ergonomics	Low	Control operation is done at waist height. User controls are not tactile, and half of the buttons don't work as expected or at all. The screen is tiny and laggy.
Quality Control	High	Every component is highly rated and industrial strength.
Operation	High	The system does not pose a risk to cleanroom particle count.
Maintenance	Low	Piping system is obfuscating, and many actuators are hidden away in the center of the bottom of the system.
Cost	n/a	
Schedule	n/a	

Competition units:

As discussed in background, there are not commercially available units that control 3 fluids on the input of two temperatures. Such systems are made to order and require custom quoting.