ME 450 - Winter 2008

Machine for Continuous Manufacturing of Carbon Nanotube Forests

Final Report

Team 18: Stephanie Chien, Stephen Perkins, Selene Soh, Chunyi Yeo

Section Instructor: Dr. Guru Dinda

15th April 2008

TABLE OF CONTENTS

INTRODUCTION

Carbon nanotubes (CNTs) are long molecules having exceptional properties, including several times the strength of steel piano wire at one-fifth the density, at least five times the thermal conductivity of pure copper, and high electrical conductivity and current-carrying capacity. Materials containing “forests” of vertically-aligned CNTs are a potential breakthrough technology in various areas such as energy storage and biomedical applications. Current methods for producing CNTs do not allow for continuous processing of CNT forests as yet, and are time-consuming and inefficient. Thus, the main objective of our ME 450 project is to design a mechanism that will allow for continuous processing of CNT forests using the Chemical Vapor Deposition (CVD) method.

Professor Anastasios John Hart is the sponsor of our project. As a professor in Mechanical Engineering at the University of Michigan, Professor Hart’s work involves research on the growth on CNTs. He has successfully accomplished desktop growth of small samples of CNT forests using the Chemical Deposition Method (CVD) on small silicon substrates of about 1 square inch area. The current process includes several steps to be performed in order as shown in Figure 1, below.

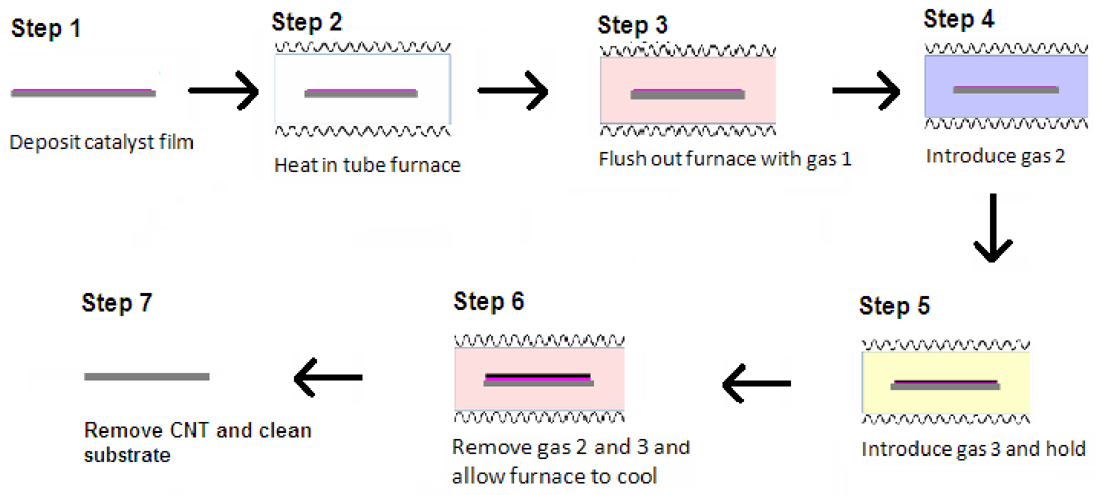


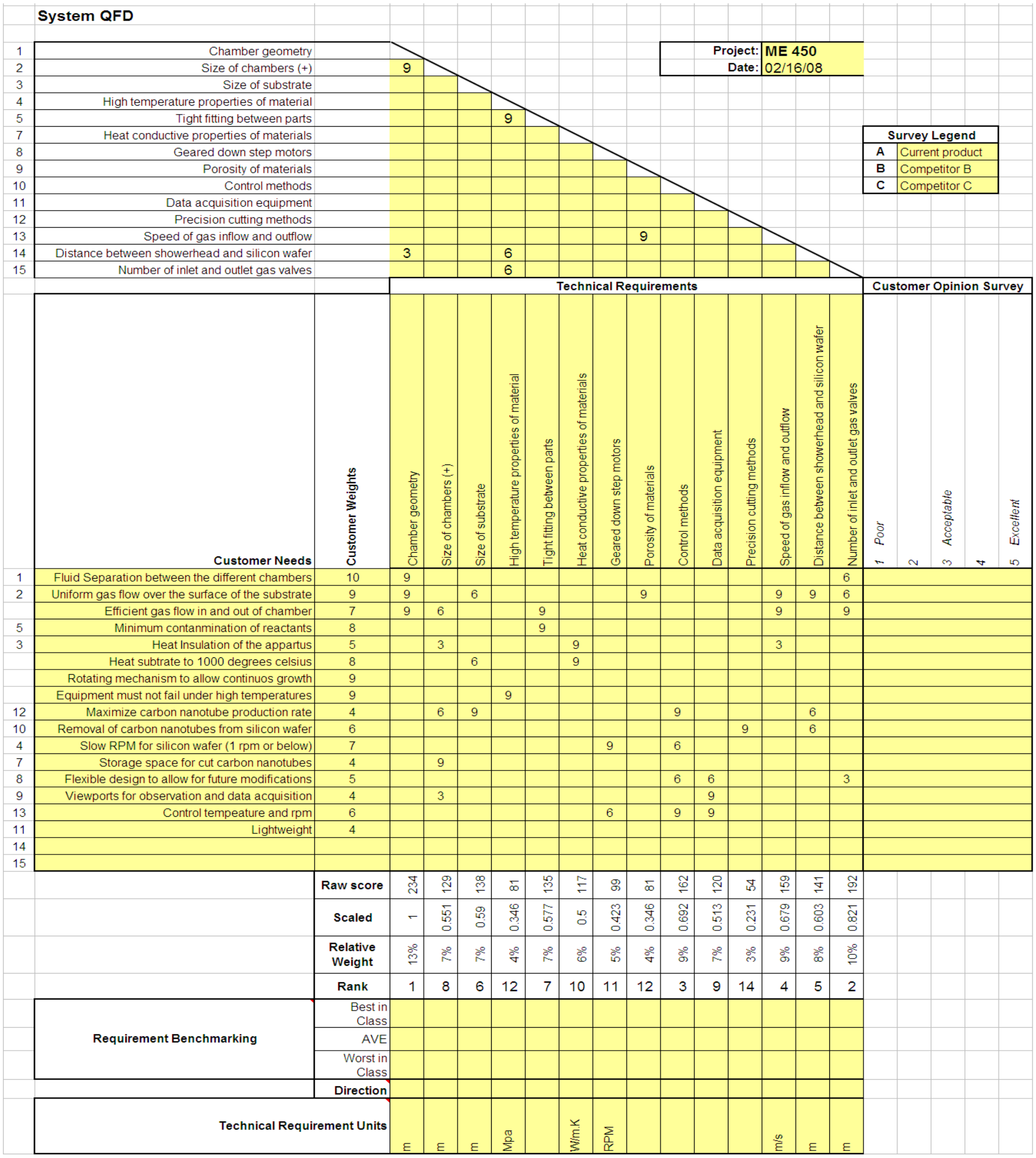
Figure 1. Schematic of steps in current CVD process

The process must be contained within a sealed reaction chamber, and will require heating of a flammable gas atmosphere up to 800-1200° C. In order to achieve the main project goals, the three main fundamental engineering concepts that need to be addressed are the continuous growth process, restricted gas flow within the device, and the high temperatures required for the process.

The successful design and fabrication of such a device would greatly benefit Professor Hart’s research efforts, aiding in further studies regarding the reusability of the substrate catalyst, the lifetime of the catalyst, optimizing conditions for different desired traits of CNT growth, and so on. Moreover, it will allow for continuous production of larger amounts of CNT films in less time. The potential for scaling this process up for large scale production of CNTs will be extremely valuable to the currently expanding market for CNTs.

ENGINEERING SPECIFICATIONS

To determine the relative importance of the customer requirements and relate these to engineering specifications, a Quality Function Deployment “house of quality” was employed, and is shown in Figure 2, below.



System QFD

Project: ME 450
Date: 02/16/08

Survey Legend	
A	Current product
B	Competitor B
C	Competitor C

		Chamber geometry	Size of chambers (+)	Size of substrate	High temperature properties of material	Tight fitting between parts	Heat conductive properties of materials	Geared down step motors	Porosity of materials	Control methods	Data acquisition equipment	Precision cutting methods	Speed of gas inflow and outflow	Distance between showerhead and silicon wafer	Number of inlet and outlet gas valves
1	Chamber geometry														
2	Size of chambers (+)	9													
3	Size of substrate														
4	High temperature properties of material														
5	Tight fitting between parts				9										
7	Heat conductive properties of materials														
8	Geared down step motors														
9	Porosity of materials														
10	Control methods														
11	Data acquisition equipment														
12	Precision cutting methods														
13	Speed of gas inflow and outflow								9						
14	Distance between showerhead and silicon wafer	3			6										
15	Number of inlet and outlet gas valves				6										

			Technical Requirements														Customer Opinion Survey				
	Customer Needs	Customer Weights	Chamber geometry	Size of chambers (+)	Size of substrate	High temperature properties of material	Tight fitting between parts	Heat conductive properties of materials	Geared down step motors	Porosity of materials	Control methods	Data acquisition equipment	Precision cutting methods	Speed of gas inflow and outflow	Distance between showerhead and silicon wafer	Number of inlet and outlet gas valves	1 *Poor*	2	3 *Acceptable*	4	5 *Excellent*
1	Fluid Separation between the different chambers	10	9													6					
2	Uniform gas flow over the surface of the substrate	9	9		6					9				9	9	6					
	Efficient gas flow in and out of chamber	7	9	6			9							9		9					
5	Minimum contanmination of reactants	8					9														
3	Heat Insulation of the appartus	5		3				9						3							
	Heat subtrate to 1000 degrees celsius	8			6			9													
	Rotating mechanism to allow continuos growth	9																			
	Equipment must not fail under high temperatures	9				9															
12	Maximize carbon nanotube production rate	4		6	9						9				6						
10	Removal of carbon nanotubes from silicon wafer	6											9		6						
4	Slow RPM for silicon wafer (1 rpm or below)	7							9		6										
7	Storage space for cut carbon nanotubes	4		9																	
8	Flexible design to allow for future modifications	5									6	6				3					
9	Viewports for observation and data acquisition	4		3								9									
13	Control tempeature and rpm	6							6		9	9									
11	Lightweight	4																			
14																					
15																					
		Raw score	234	129	138	81	135	117	99	81	162	120	54	159	141	192					
		Scaled	1	0.551	0.59	0.346	0.577	0.5	0.423	0.346	0.692	0.513	0.231	0.679	0.603	0.821					
		Relative Weight	13%	7%	7%	4%	7%	6%	5%	4%	9%	7%	3%	9%	8%	10%					
		Rank	1	8	6	12	7	10	11	12	3	9	14	4	5	2					
	Requirement Benchmarking	Best in Class																			
		AVE																			
		Worst in Class																			
		Direction																			
	Technical Requirement Units		m	m	m	Mpa		W/m.K	RPM					m/s	m	m					

Figure 2. QFD diagram for customer requirements and engineering specifications[1]

The customer requirements and engineering specifications associated with our project were then divided into three main categories- 1) requirements essential for growth of carbon nanotubes (CNTs) using the Chemical Vapor Deposition (CVD) method, 2) requirements essential for continuous growth process of CNTs, and 3) additional requirements desirable for other purposes.

Keeping these requirements in mind, we generated a list of specifications targeted at each requirement. The descriptions of the requirements and corresponding specifications are summarized according to the three main categories in Table 1, below.

	Customer Requirements	Engineering Specifications
1) Top priority		
a)	Fluid separation between different chambers	Partition walls with low pressured outlet points to allow fluid separation
b)	High temperature tolerance material	Heating elements capable of attaining temperatures up to 1000 ºC
		Materials and parts that withstand high temperatures up to 1000 ºC (alumina/quartz/silicon)
c)	Rotating mechanism to allow continuous growth	Step motor with speeds ranging from 0.02RPM to 4 RPM
d)	Uniform gas flow over surface of substrate	Diffused air injection to allow uniform flow
2) Second priority		
a)	Efficient gas flow through chambers	Increase number of inlet-outlet points to optimize gas flow
b)	Separate heating zones	Localized or external heating mechanism for zones of different specified temperatures
c)	Minimum contamination of reactants	Usage of O-rings and lip seals to provide an air-tight environment
		Gases to be channeled to and removed from chambers separately
d)	Continuous film of CNTs harvested	Substrate platform to be continuous without breaks
e)	Continuous removal of CNTs	Removal of CNTs by mechanical, thermal, chemical means.(eg, gas treatment/gentle mechanical action)
f)	Continuous collection of CNTs	Compartment for collecting nanotubes to be designed within chamber
3) Last priority		
a)	Adjustable rotational speed	Controller for speed of rotation
b)	Adjustable temperatures	Temperature controller to be included in system
c)	CNT forests to be few inches in width	2 inch wide growth region

d)	Process to be monitored externally	Viewing port to be integrated at growth region
		Temperature sensors in separate regions

Table 1. Customer requirements and corresponding engineering specifications

CONCEPT GENERATION

The concepts generation can be broken down into four major categories: Heating, gas flow, rotation, and CNT removal. The functional decomposition shown in Figure 3 below illustrates how energy, material, and information travel through the system. Different tradeoffs were looked at for each category and concepts were generated based on assorted combinations of these subcategories through brainstorming and functional decomposition.

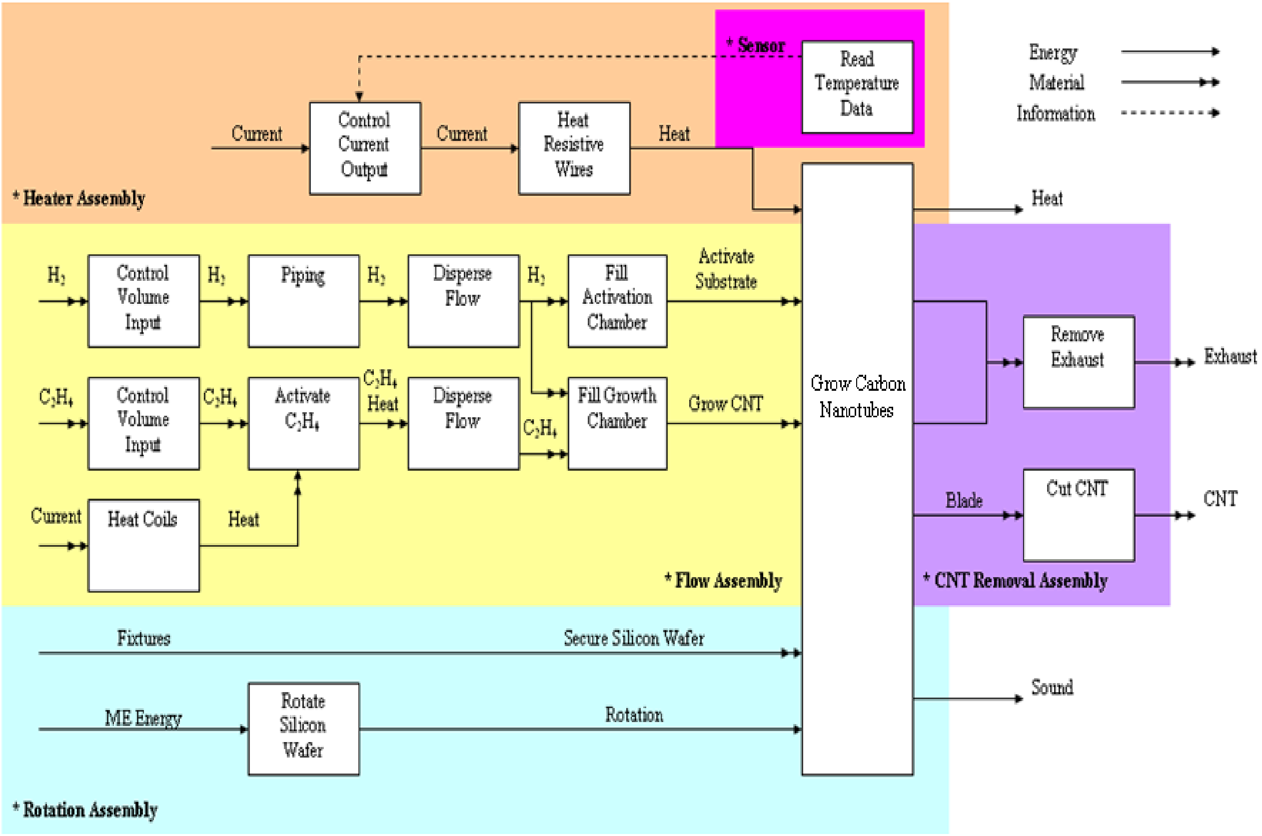


Figure 3. Functional decomposition

HEATING

Heating plays an essential role in the growth of CNTs. It is desired that there be multiply heat zones to allow isolated experiments to test the effect of heat on CNT growth in the future. The catalyst-coated substrate can be heated either resistively or externally. Since the silicon wafer is thermally conductive, resistive heating would require less energy input than external heating. However, external heating would be straightforward to attach to the system physically and allow easier control to individual heating zones.

GAS FLOW

The CNT growth process involves pre-treating the catalyst with hydrogen and helium (H_2, He) gases then subsequently introduce ethylene (C_2H_4) gas for the CNTs to initiate growth. Uniform gas distribution and gas separation are the two main concerns in this process.

The gases can be introduced into the chamber through only inlet pipes or inlet pipes leading to a porous showerhead. If showerheads are not used, there might be a denser region of gas around the inlet pipes depending on the inlet flow rate. The use of showerheads allows a backpressure to build then distribute the gases to the substrate more uniformly than without. The tradeoff here is machining time. Inlet pipes of standard sizes can be bought off the shelf, unlike the showerheads which require custom machining.

Another cause for concern is gas separation. In order for the catalyst to be reused, it has to be exposed to the pretreatment gas before the ethylene. To keep the gases from mixing, one of the following can be used as a divider: the substrate wafer, a wall, or a hollow wall with a low pressure gap.

ROTATION

A rotational mechanism is necessary in order to grow and harvest CNT continuously. The typical growth time is anywhere between a few minutes to half an hour and so a motor with RPM ranging from 0.02 to 4 is required. At such low RPM there are two choices of motors: a DC brush motor or a step motor.

The silicon substrate needs to be held stable when rotating. This can either be achieved by drilling a hole through the substrate wafer and attaching the motor shaft to it or to use magnets on either side of the wafer to secure it. Also, the use of bearings can be employed outside the chamber to stabilize the rotation of shaft and thus the motion of the substrate disc.

CNT REMOVAL

Currently, the non-continuous CNT growth process does not have a particular method to remove the CNTs from the substrate. For continuous reuse of the same catalyst and substrate, a CNT removal system is needed. There is only one mechanical possibility currently and it utilizes a razor blade to tap and cut off the CNTs at the base, right above the catalyst-coated substrate. There may be a chemical reaction that might aid this removal process which is still unexplored, and thus inlets should be machined for possibly introducing this chemical in the future.

CONCEPT CLASSIFICATION

Concepts were generated incorporating one idea from each of the four main subsystems.

CONCEPT 1

As seen in Figure 4, page 7, the uniqueness of this concept is to separate the gas using a liquid reservoir. The system would be heated externally and introduce different gases at different locations along the tube. The gases would be pulled out through the vacuum/exhaust so there should be little backflow of ethylene into the pretreatment region. The design requires two rotary shafts to be partially submerged in liquid and requires rotating seals where the shafts go through the tube. The CNT will be cut off by a razor sitting right before where the belt will emerge into the liquid. The razor would then be attached on a shaft that is held in place by holes on either side of the glass.

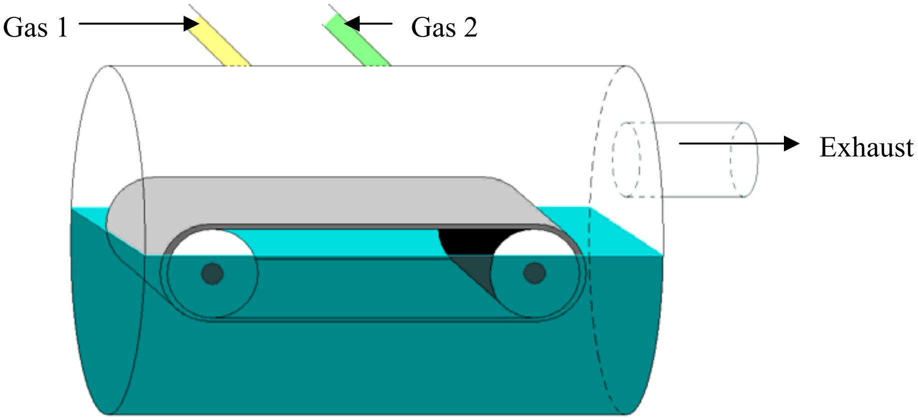


Figure 4. Concept 1 front view

CONCEPT 2

Concept 2 shown in Figure 5 below reveals a much familiar idea of a screw. This machine would also be heated externally since the edge of the substrate needs to form a tight seal with the inner tube. The introduction of the gases takes advantage of the density of the gases. By placing the lighter pretreatment gas on top, there is a slight division of gases as gas 2 would tend to want to flow downwards. However, there is still mixing through diffusion. A motor can be attached easily to this assembly with a simple lip seal. The CNT will be collected at the top of the inner tube with a razor blade.

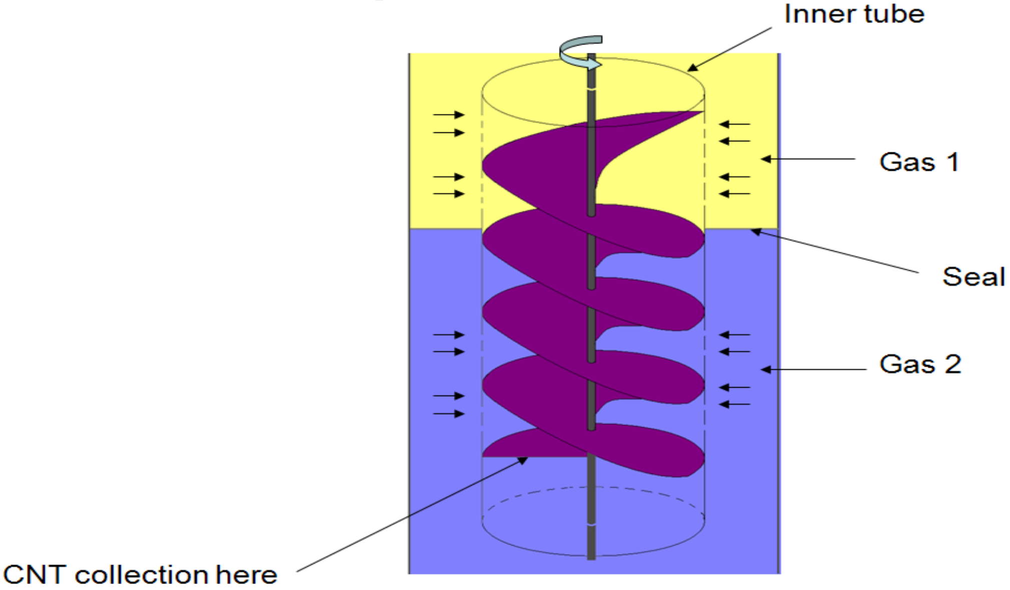


Figure 5. Concept 2 front view

CONCEPT 3

The third concept, shown below in Figure 6, makes use of a large porous drum. Ideally, the local surface of the drum will be heated by the preheated gases. The pretreatment gas would be introduced from inside the drum with different inlets for various temperatures of the gas and the second gas is introduced from the outside. The separation of the gases would be the porous material itself and the walls and wheels inside the drum. The mechanism would be driven by a motor on the side while the CNTs will also be collected using a razor blade.

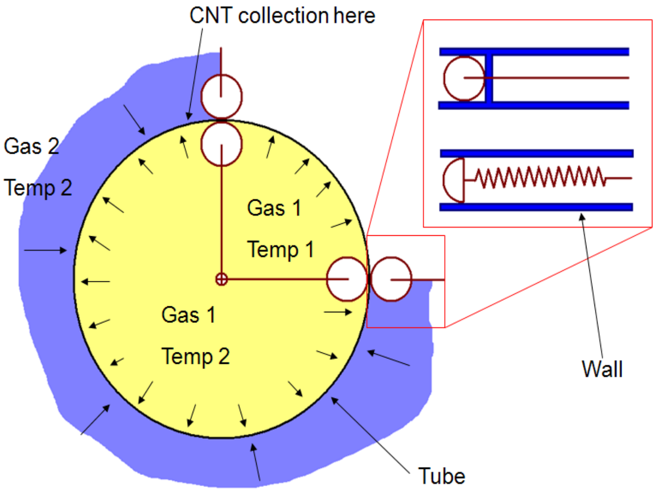


Figure 6. Concept 3 side view

CONCEPT 4

Concept 4, below in Figure 7, has a large rotating system with plates attached at set increments. The heating would have to be done externally since the disks have to provide a tight seal with the tube. The gas is introduced through holes in the tube and separated by the disks. In order to move this large rotating ring, a gear-like system with claws would be needed to grab the ring between the disks and pull it through. The removal of CNT would have to be done manually with a razor.

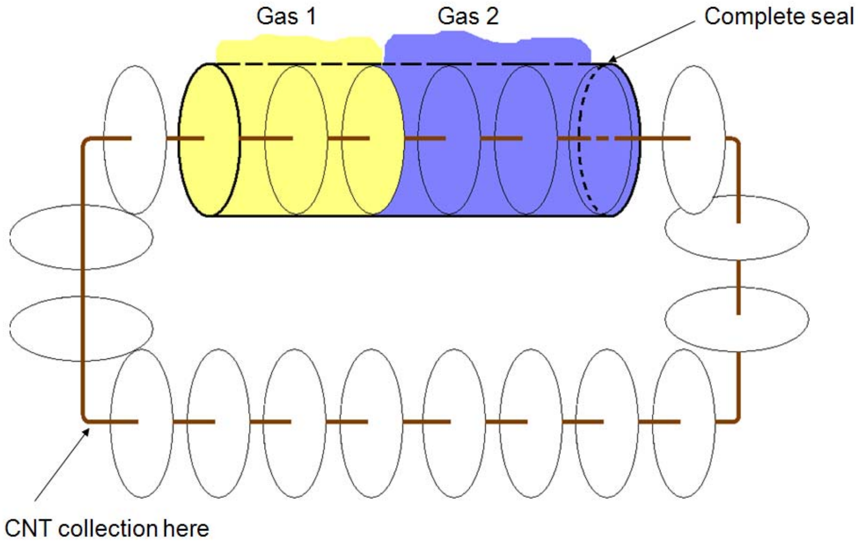


Figure 7. Concept 4 front view

CONCEPT 5

The fifth and last concept we came up with, as shown in Figure 8 below, would use resistive heating on the opposite side of the chamber as the walls. The gases would be introduced through the shaft that runs through the center of everything. The motor would be attached at one end of the shaft and the CNTs collect by a blade placed directly on the silicon wafer.

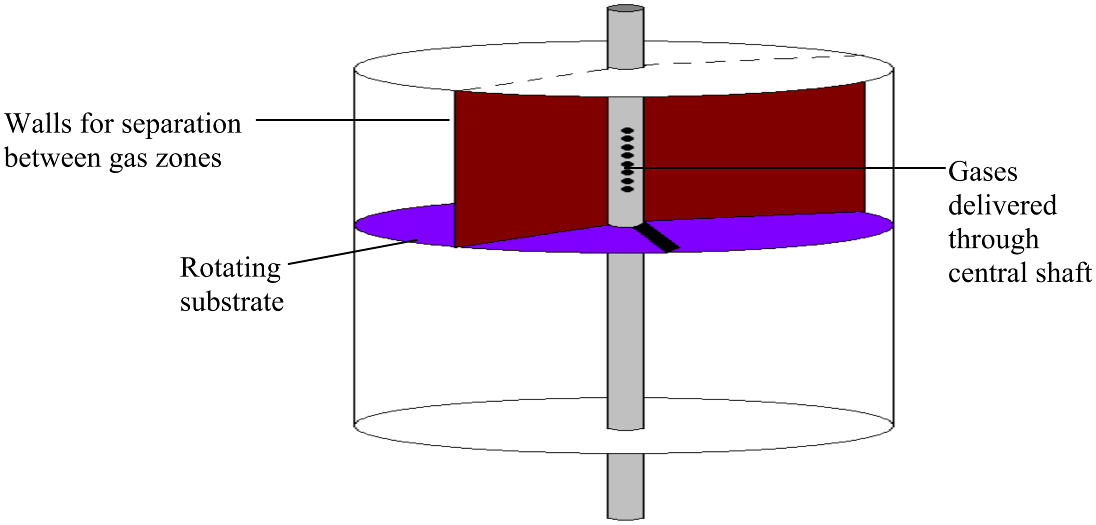


Figure 8. Concept 5

Other important aspects of concept generation can be found in Appendix A.

CONCEPT SELECTION PROCESS

The final concept was chosen using a scoring matrix based on the customer requirements. In Table 2 below, the scoring matrix for the five concepts described above, rates how the system satisfies each of the requirements by assigning a 0, 1, or 2. 0 being impossible or extremely difficult to implement, 1 being possible to implement but hard to control the effects, 2 being easy to implement and achieves the task desired.

Concept number	Delivered gas uniformity	Gas separation	Continuity of CNT growth	Temp. zones	CNT collection	Temp. sensor	View port(s)	Total
1	1	1	2	1	2	1	1	9
2	1	1	1	1	1	0	1	6
3	2	2	2	1	2	1	1	11
4	1	2	1	1	0	1	1	7
5	2	2	2	2	2	2	2	14

Table 2. Scoring matrix for concept selection

CONCEPT 1

The system is characterized by a ceramic conveyor belt system with a liquid reservoir to facilitate gas separation. There is good gas separation going from after the CNT removal to the restart of the cycle. However, there are a few main disadvantages to this system: the only thing that keeps the gases apart between pretreatment and growth region is the exhaust/vacuum at one end of the chamber which means there could still be gas interaction due to diffusion, and the liquid reservoir might start boiling under the high temperature and contaminate the substrate. In addition, the gas delivered would not be uniform and there would only be one temperature zone. There would also be no way to store the CNT which is likely to fall into the liquid reservoir.

CONCEPT 2

CNT growth on a spiral screw spinning clockwise around a center shaft depicts this concept. The gas is separated using the screw itself sealing against the inner tube and by density but mixing still occurs by diffusion. The gas dispersed would be denser closer to the screw-tube interface and get less dense traveling closer to the center shaft. CNTs can be grown continuously on the screw but that is only a set length since the screw would be made from a material such that it would be hard to recycle the screw through once it leaves the chamber. A fundamental problem would also be to manufacture a substrate in the shape of a screw. There can also only be one temperature zone with the kind of external heating used. The CNT removal blade would have to sit at an angle collecting the final product but there would be no place to store it.

CONCEPT 3

The porous ceramic drum would have roller wheels at different locations inside the drum to rotate the drum and to act as separators of gas leaks. The porous ceramic would create a backpressure enough to distribute the gas uniformly. The CNTs would be easily collected and a continuous film of CNT forest would be highly possible. The major challenge of this machine is to actually find a ceramic that can be made into this drum shape. It would also be very difficult to try to seal off the same gas of different temperatures to provide stable temperature zones. Friction between the rollers and the wall of the drum also causes concern as a tight seal is desired without wearing out either material. There is also one major fundamental error in assuming that the gas would be hot enough to heat the ceramic locally. Unless there is an external source of heat, the gases would not be able to heat up the ceramic enough for the CNTs to initiate growth.

CONCEPT 4

This idea is comprised of a belt of individual disks that seal against the chamber wall as they pass through it. The major advantage of this system is that it is possible to use the substrate in the current non-continuous-growth form. This setup also allows the gases to be separated by the disks with no diffusion. However, this is only true if there is a perfect seal between the disks and the walls which is hard to perfect and the large friction would cause fast wear. A major difficulty facing this mechanism is rotating the belt. It is unlikely to find a mechanism that would be able to do this efficiently. In addition, CNTs would be grown on the individual disks, therefore not continuous, and harvesting of these CNTs would have to be manual. The heating of this system would be external and thus only one temperature zone is likely.

The characteristics of this model are a horizontal substrate disc on spinning shaft contained in a cylindrical chamber with divided regions for different gases. This idea also allows the use of substrate in its original form while producing a continuous film of CNT. Figure 9 shows that the inlet of the gas is located on the center shaft and thus hard to deliver uniform gas flow to the substrate. Then again, the location of the inlet holes can be changed easily for this design to fit a showerhead which would then produce and even flow. The gases would be separated by the dividers which are hollow walls with vacuum. And the orientation of the disk allows external heating to be wired independently thus creating different temperature zones. The CNT collection blade would have to be attached to a shaft drilled through the chamber. It seems as though there is no room to store the collected CNTs but as soon as the machine is inversed, the cut CNT would fall down to the bottom of the chamber and collect there.

According to the scoring matrix, the final concept was chosen as shown in Figure 9, below.

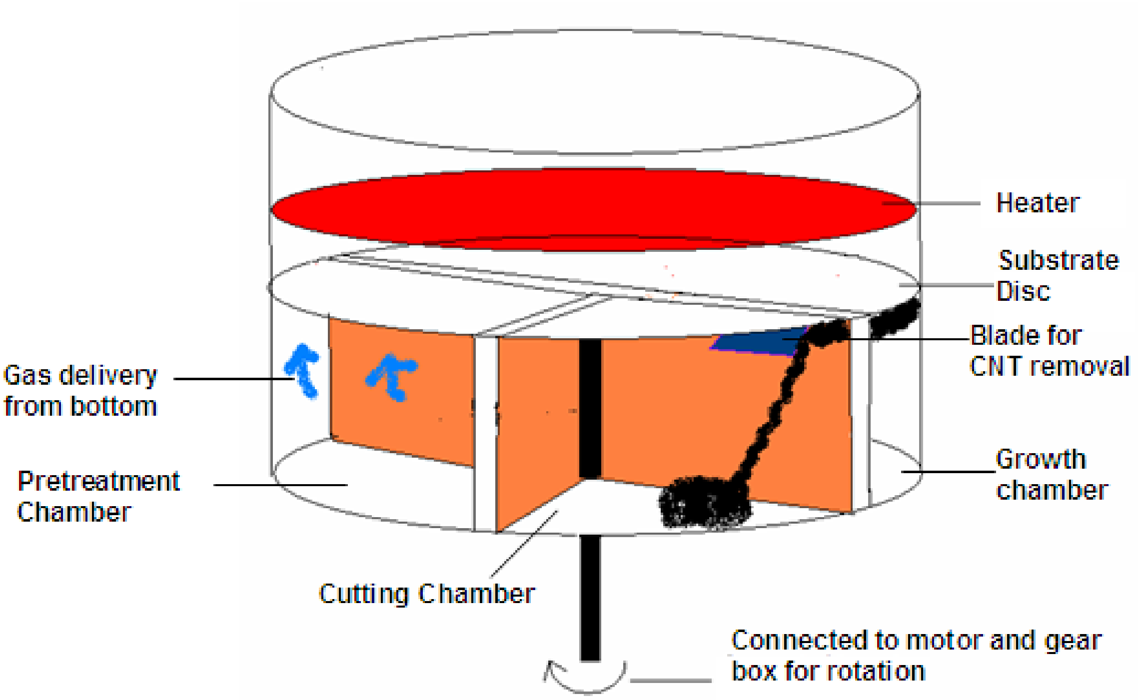


Figure 9. Detailed and modified version of selected concept design

CONCEPT DESCRIPTION

Upon finalizing the details of our selected design, we created a three dimensional CAD model of this design. The CAD model consists of two main sections, the top section consisting of the heating assembly, and the bottom section consisting of the flow assembly. These two sections are separated by a glass plate as seen in Figure 10. The bottom consists of the magnet and shaft holder, which is connected to the external rotational assembly.

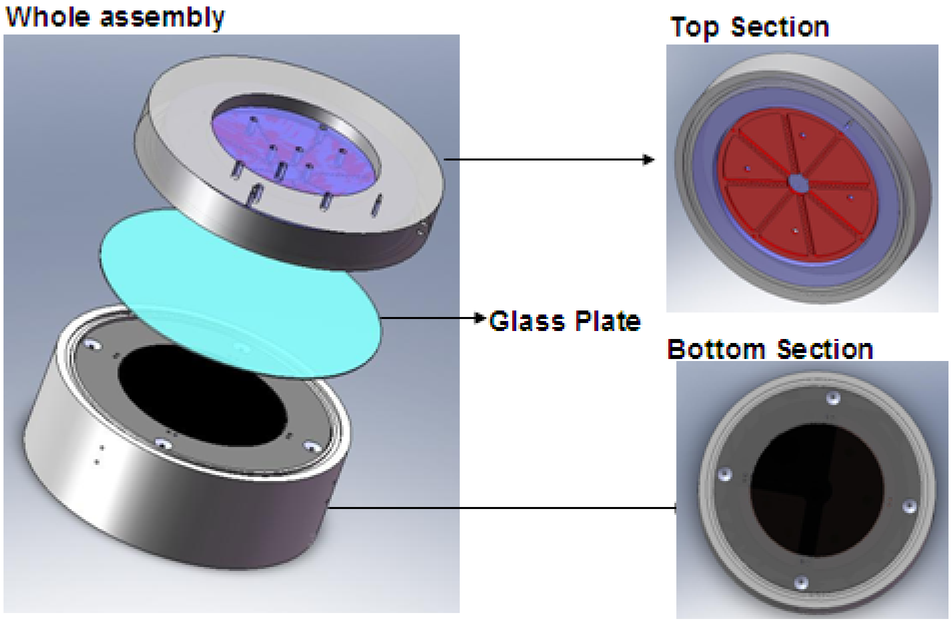


Figure 10. Assembly of CAD model- top and bottom sections separated by glass plate

The glass plate serves to isolate the top and bottom sections from each other to prevent contamination of gases in either section. This will prevent the gases from the heater wire from mixing with the gases in the processing chambers, which will affect CNT growth. At the same time, it will prevent the pretreatment and growth gases from contacting the heating wire and possibly result in undesired growth of CNTs on the heating wire.

The following sections will outline the main features of each part and explain the relation between components and assemblies.

TOP SECTION

The top section consists of three parts- the outer wall casing, the firebrick insulator, and the heater element. These will be assembled as shown in Figure 11 below.

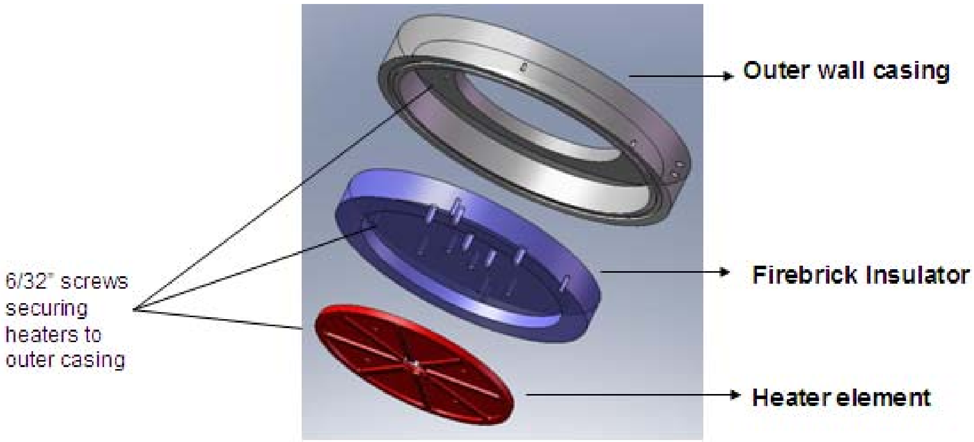


Figure 11. Assembly of top section of CAD model

OUTER WALL CASING

The outer wall casing serves to house the components in the top assembly. The center of the part will be hollowed out to reduce the amount of material and hence the weight of this part. A groove will also be incorporated on the bottom surface of the part, allowing for a viton o-ring to ensure that the seal between the top chamber and the glass plate is air-tight. There will be four 6-32 tapped holes for screws to secure the top assembly. These screws will be screwed from the heater element, through the spacer and firebrick insulator, and finally secured into this outer wall casing. An additional four 6-32 tapped holes are located on the cylindrical surface for mounting the latches that will hold the entire assembly together. The location of the screw holes and groove are shown in Figure 12, below.

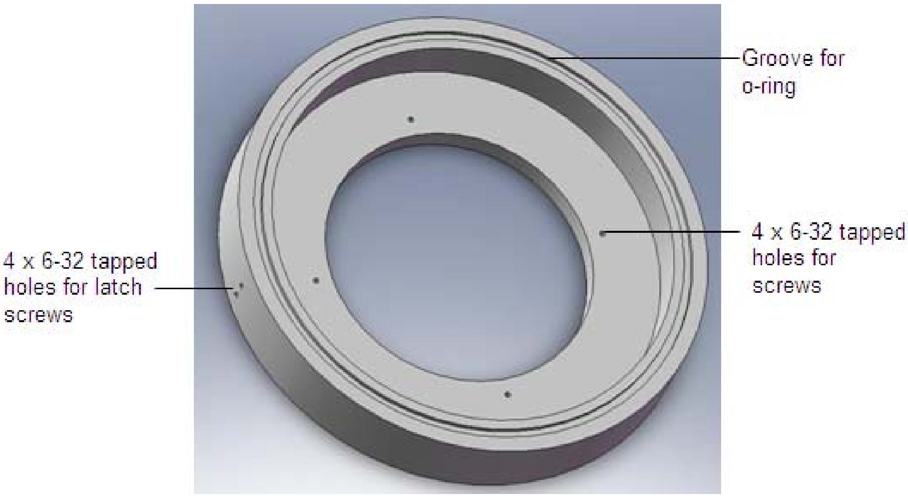


Figure 12. Bottom view of outer wall casing part

FIREBRICK INSULATOR

The firebrick insulator serves to insulate the heating elements from the outer wall casing to minimize the heat loss through convection and conduction effects. There will be four 6-32 clearance holes for the securing screws, four ¼” holes in the center of the part for routing of the heater wire, and two ¼” holes for air flow through the top section. An additional four ¼” holes are included for possible future incorporation of infra-red temperature sensors. These additional holes may be plugged when not in use. The locations of the holes on the part are as shown in Figure 13, below.

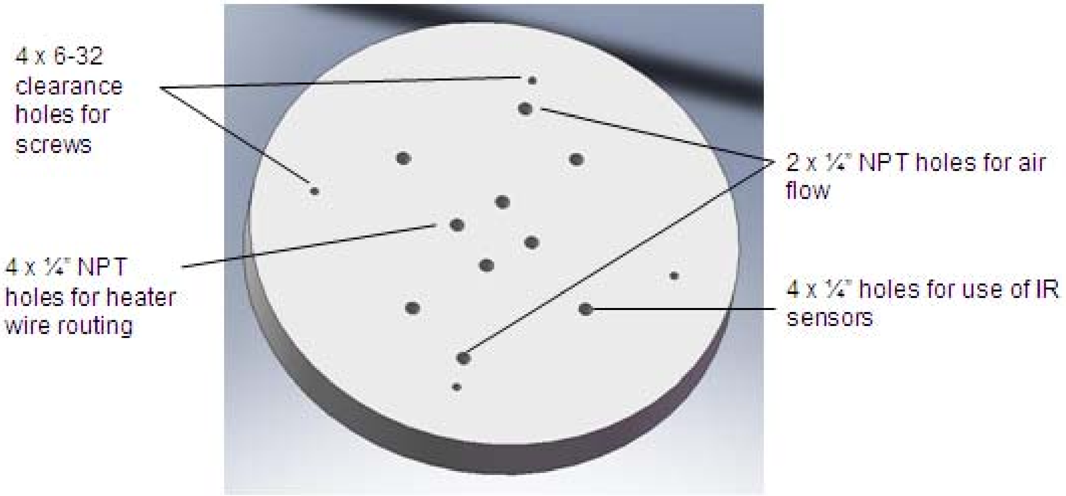


Figure 13. Top view of firebrick insulator part

HEATER ELEMENT

The main objective of the heating subsystem is to allow uniform heating of the substrate disc to temperatures of up to 1000ºC. Due to the geometry of our selected design and the high heat requirement involved in our project, ready-made heaters and heating elements cannot be employed in our design. Thus, we have decided to design and manufacture our own heaters.

The heater will be in the form of a whole disc eight pie-wedged segments. At 45º angles, an elevated wall with staggered holes will serve to hold the heater wire at in an evenly spaced configuration while ensuring that the bare hot wires do not come into contact with each other to prevent possible shorting of the heating circuit. Each of the eight “pie wedges” also consist of a recessed cavity to minimize contact between the wires and the heater disc, thereby reducing conduction losses. In addition, four ¼” holes are incorporated at 60º angles from the horizontal and vertical raised walls for the future incorporation of infra-red temperature sensors. Together with the similar configuration of the holes in the fire-brick insulator piece as seen previously in Figure 13, this enables these two parts to be assembled such that either the holes are aligned for use, or such that the holes are not aligned and will be blocked. A diagram of the heater disc and the threaded wire for a single segment is shown in Figure 14, below.

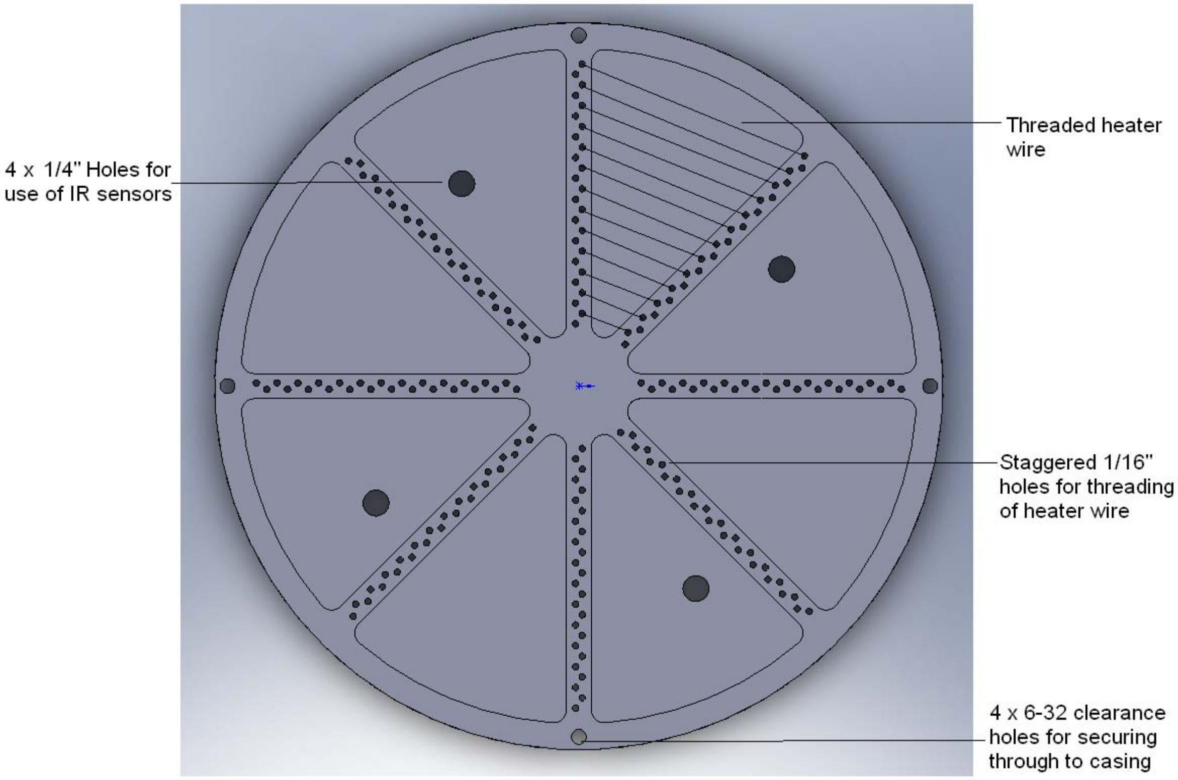


Figure 14. Bottom view of heating element

The wires will be connected such that there will be four 90º heating segments whose current and temperature can be individually controlled. For the initial use of our design, we will be connecting the segments such that there will be two 90º heating segments for the pretreatment and cutting chambers, and a larger 180º heating segment for the growth chamber. In addition, four 6-32 clearance holes around the periphery of the disc serve to secure the heater element to the rest of the top assembly.

BOTTOM SECTION

The bottom section consists of the fake wafer, substrate disc, showerheads and ceramic top layer (porous ceramic gas diffuser), stainless steel insert, and main processing chamber, as shown in Figure 15, below.

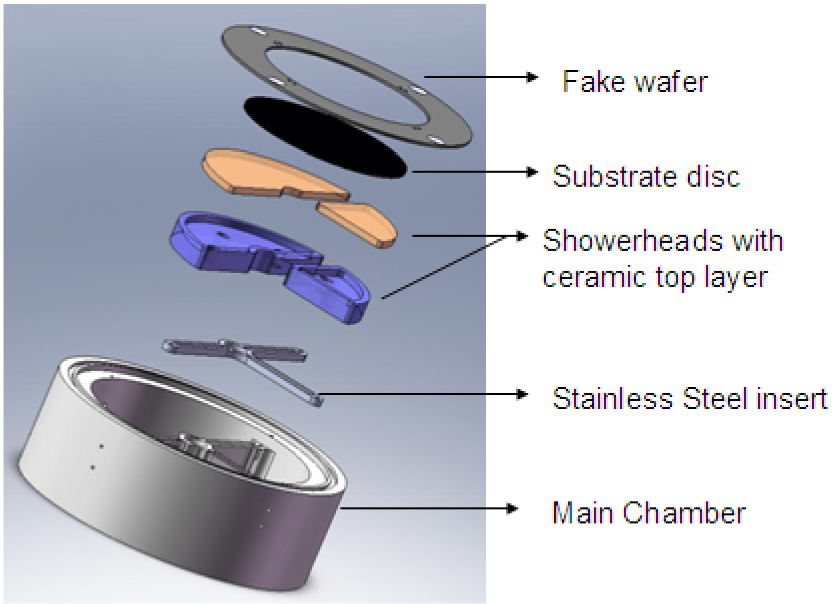


Figure 15. Assembly of bottom section of CAD model

FAKE WAFER

The main purpose of the fake wafer is to eliminate the gap between the substrate disc and the walls of the main chamber as far as possibly, in order to minimize uncontrolled movement of gas.

Two fake wafers have been designed, one accommodating a 6" substrate disc, and another accommodating a 4" substrate disc, since these sizes are commonly available sizes that are currently in use in lab work and research.

The fake wafer will feature 4 countersunk 6/32" clearance holes (0.144" diameter holes) for screws securing the fake wafer to the main processing chambers. In addition there will be 4 pairs of 1/8" holes for wiring of thermocouple wires for temperature sensing and control purposes. The CAD model of this part is shown in the Figure 16, below.

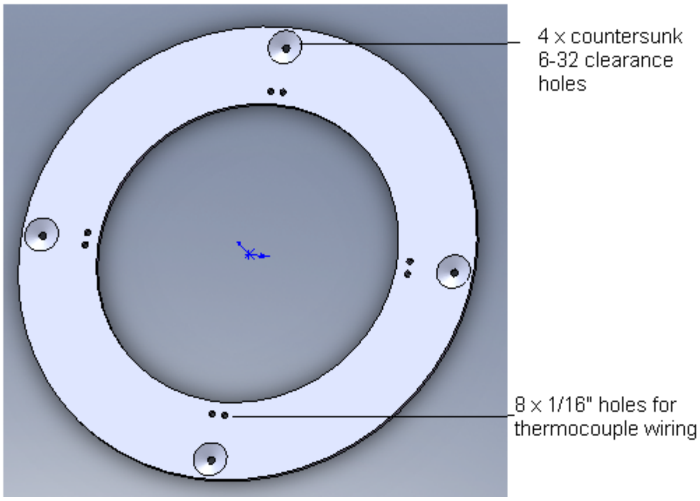


Figure 16. CAD model of 6" fake wafer

SUBSTRATE DISC

A silicon substrate disc coated with catalyst required for the CNT growth process will be used in our device. As mentioned previously, there are two available sized of this silicon substrate disc that our device has been designed to accommodate, including the 4” and 6” diameter wafer discs. The exact composition of the substrate and the catalyst to be used will be up to the user of our device and may be varied to achieve the purposes of using our device to determine the factors and parameters for different characteristic CNT growth.

The substrate disc will be held in place between a steel plate and magnet, which will be held by a magnet holder and shaft, linking to the external motor subsystem assembly. A schematic diagram of this setup is seen in Figure 17 below.

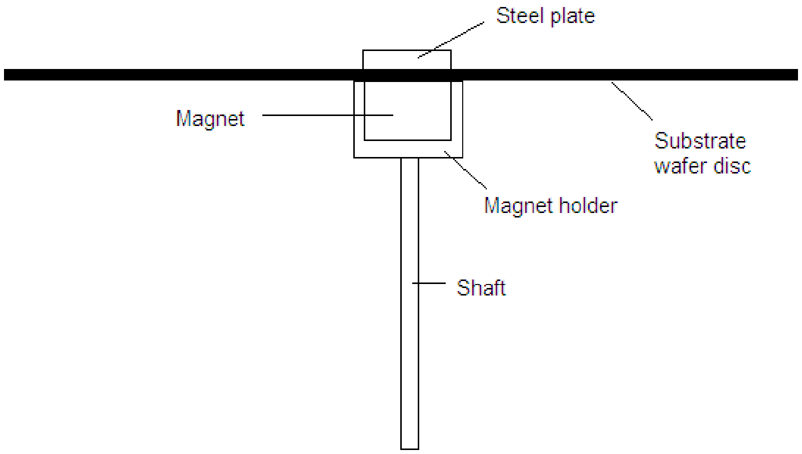


Figure 17. Diagram of substrate wafer disc placement

SHOWERHEADS

The main purpose of the showerheads (porous ceramic gas diffuser) is the deliver the gas uniformly over the substrate. There are two showerheads- the half showerhead and the quarter showerhead, which will deliver the required gases to the growth region and pretreatment region of the substrate disc respectively. Each shower head comprises of two parts, the showerhead cavities and the ceramic top layer for uniform gas diffusion. They will have ¼” NPT holes at the bottom surface for these pipe fittings, which will be connected to steel pipes. The steel pipes serve the purpose of supporting the showerheads, as well as supplying the required gases to the showerheads. The steel pipes will be connected to the inlet holes at the bottom of the processing chamber. The CAD models of the showerhead cavity parts are shown in Figure 18, below.

(a) (b)

Figure 18. Top view of (a) Half showerhead part and (b) Quarter showerhead part

In addition, the top of the showerheads will be covered with a porous ceramic material with a high pressure drop to ensure the even distribution of gas across the substrate disc area. These pieces will have the same geometry as the cavity parts and will cover the top of the aluminum parts completely to prevent possible CNT growth on the top of the aluminum walls. The porous ceramic layer will be attached to the showerhead cavity using cement. These parts are shown in Figure 19, below.

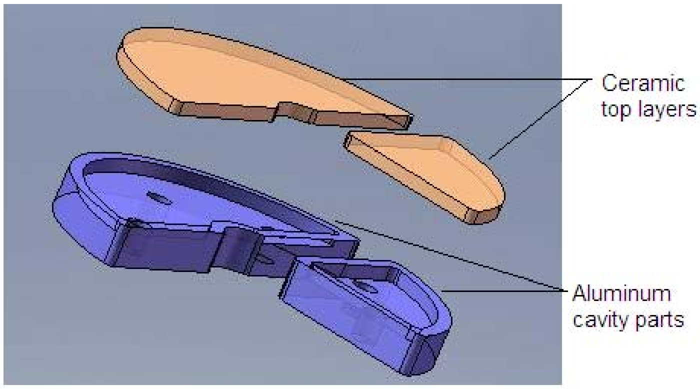


Figure 19. Showerhead cavity and ceramics layers

STAINLESS STEEL INSERT

An additional stainless steel insert was designed to be secured to the top of the internal separating walls in the main chamber and is shown in Figure 20, below.

Figure 20. CAD model of Stainless steel insert

The purpose of this piece is to withstand the high temperatures near the substrate wafer disc and thus this is to be made out of stainless steel. Three 6-32" clearance holes on the ends of each "leg" will serve to secure this piece to the main processing chambers and will be assembled on top of the main processing chamber as shown in Figure 21, below.

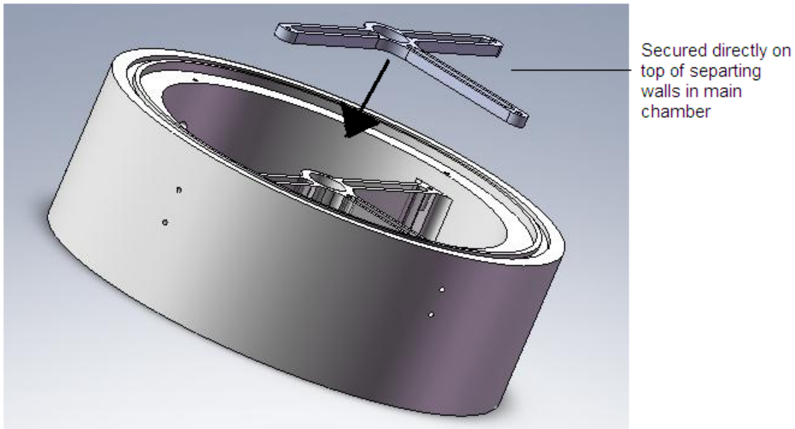


Figure 21. Stainless steel insert in relation to main processing chamber

MAIN PROCESSING CHAMBER

The processing chambers consists of three separated chambers- the pretreatment chamber, the growth chamber, and the cutting chamber (or delaminating chamber) as shown in Figure 22, below. These chambers are separated by doubled layered walls with a low pressure gap in between the walls. This is to prevent the mixing of gases between chambers by removing gases at the interface of the two chambers.

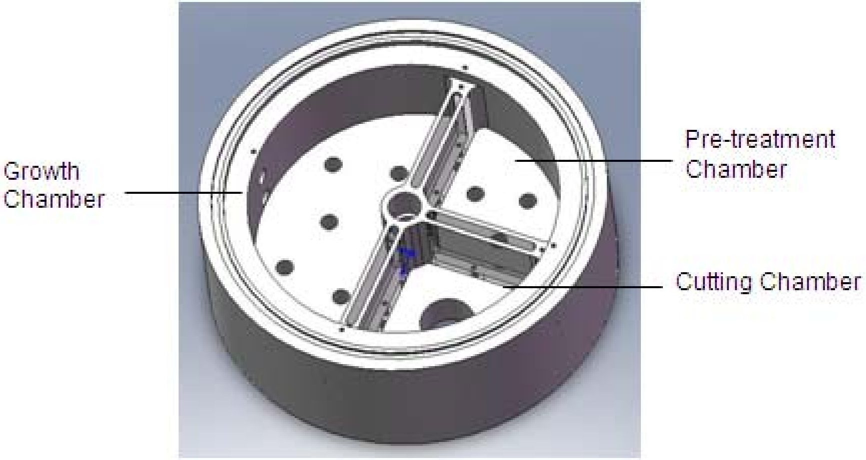


Figure 22. CAD model of main processing chamber

The main processing chamber will have an outer diameter of 10.5" and 1.25" thick side walls. The total height of this part will be 3.6" with a bottom floor of 1" thickness. The internal separating walls rise to a height of 2" above the bottom floor of the chambers. The fake wafer will be secured at 2.4" above the bottom floor of the chambers, leaving

0.1” clearance between the top of the fake wafer/substrate wafer disc and the glass plate above the bottom section assembly.

The periphery of the processing chambers will allow for an o-ring groove to ensure an air tight seal between the bottom section and the glass plate. ¼” NPT holes are incorporated in the bottom of the chambers for inflow and outflow of gases. 1/8” outlet holes will be made between the separation walls to create a low pressure gap. In addition, the cutting chamber will feature a 1.4” diameter viewing hole for the view port, as well as a hole on the side wall. This side hole will be the link between the flow assembly and the CNT removal assembly, allowing for attachment of a cutting blade. The center of this part also has a hole for the rotating shaft and magnet holder. Four 6-32 tapped holes for securing the fake wafer to the chamber, and an additional three 6-32 tapped holes are included on the edges of the separation walls for securing the fake wafer. These features are shown in Figure 23, below.

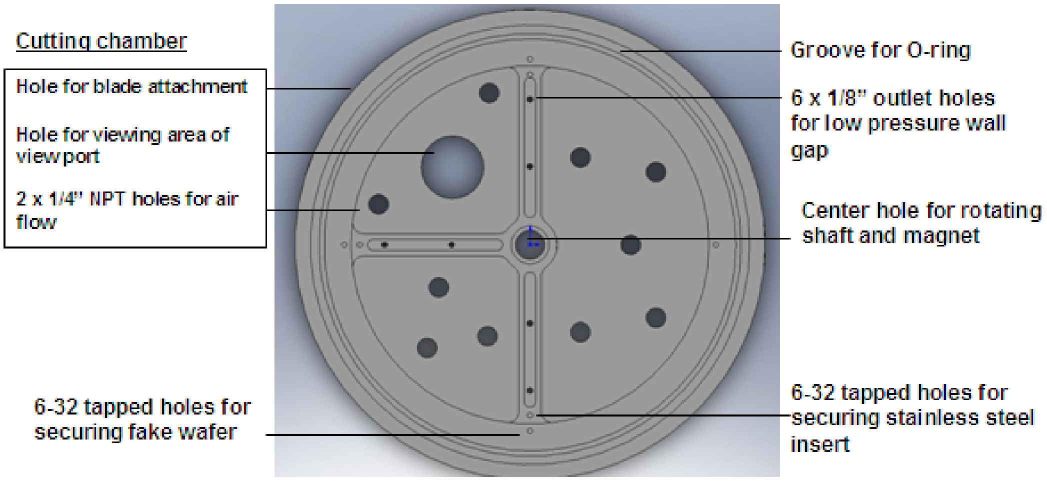


Figure 23. Top view of processing chambers

MAGNET HOLDER AND SHAFT

The rotating substrate disc will be held between a magnet on the bottom and a disc made out of magnetic material on the top. The bottom magnet will be held by a magnet holder made out of stainless steel. The magnet holder will include set screw holes on the side walls to secure the magnet and prevent slipping during the rotating motion. The magnet holder and shaft are shown in Figure 24, below. The shaft will then be connected to the external rotational assembly. To ensure that the chambers are air tight at the interface between the shaft and the chambers, we used a lip seal that allows rotational movement but not vertical flow of fluidic material.

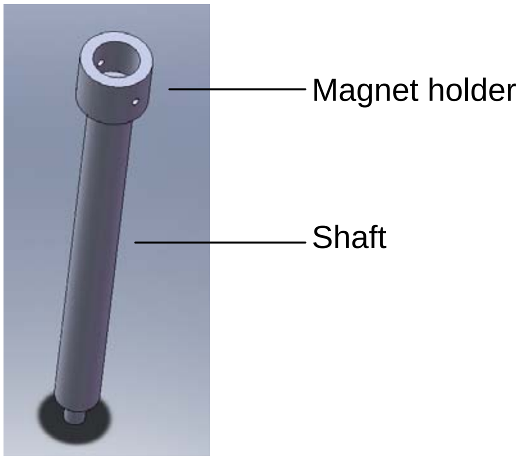


Figure 24. CAD model of magnet holder and shaft

EXTERNAL ROTATIONAL ASSEMBLY

The bottom of the shaft attaches to the external rotational assembly, consisting of the lip seal flange, the bearing housing, a coupler, and finally a NEMA 17 Hybrid stepper motor. These components will be assembled in the order as shown in Figure 25, below.

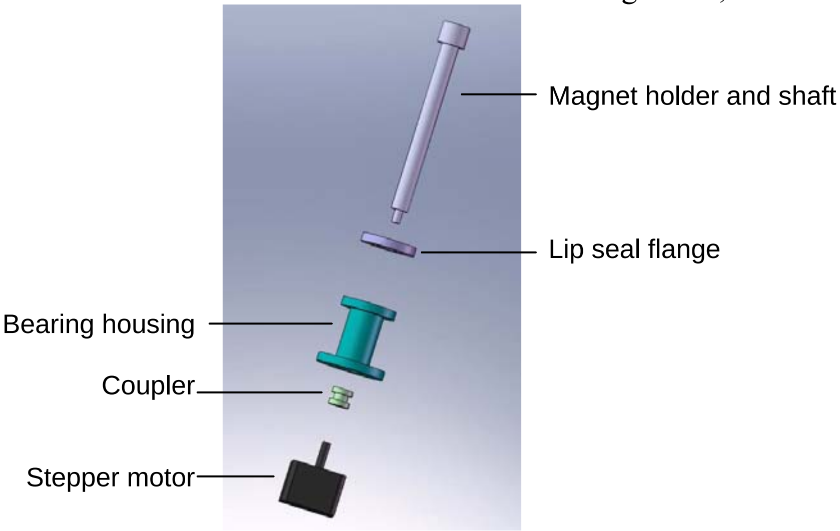


Figure 25. CAD model representation of external motor assembly

The lip seal flange serves to secure the lip seal in place at the bottom of the main processing chambers to prevent any leakage of gases. This will have four 6-32 clearance holes for securing to the main processing chamber. The bearing housing serves to house the bearings for smooth and stable rotation of the shaft. This part will also have clearance holes for 6-32 clearance holes for securing through the lip seal flange to the main processing chamber. In addition, there will be another four 6-32 clearance holes for securing to the motor. These screws will also serve as height adjustors for the shaft, and consequently the silicon wafer disc inside the chamber.

The coupler will be used for connection of the motor to a shaft of larger diameter for the purposes of our device and this will be a readymade part to be purchased. Finally, the motor will provide the driving torque for the entire rotational assembly. This too, will be purchased from a motor supplier. Although a stepper motor is being used, the micro-stepping capability will smooth out the rotation such that a smooth, even motion will be achieved.

TEMPERATURE CONTROLLER

In order to control the temperatures involved in our device, a temperature controller needs to be built to create a feedback loop that will use temperature sensing to control the amount of power delivered to the heating element. The power supply will be connected to the controller and the relay through a switch. Using a LabView interface, the user can define a desired temperature. This input signal will be sent to the controller, which will send a command to the relay to deliver some amount of power to the heater wire. At the same time, a thermocouple placed within the device at the desired strategic location will be connected to the controller, sending feedback signals of the temperature reading. The controller will then relay this reading to the LabView interface, and at the same time use this temperature reading to determine the required amount of power to adjust the temperature as needed. It will then send a corresponding command to the relay again, and the loop continues until a desired steady state is reached. The controller used in this application will be a PID controller that will eliminate steady state error and has been tested in the current research of Professor John Hart's lab. A schematic of the temperature controller is shown in Figure 26, below.

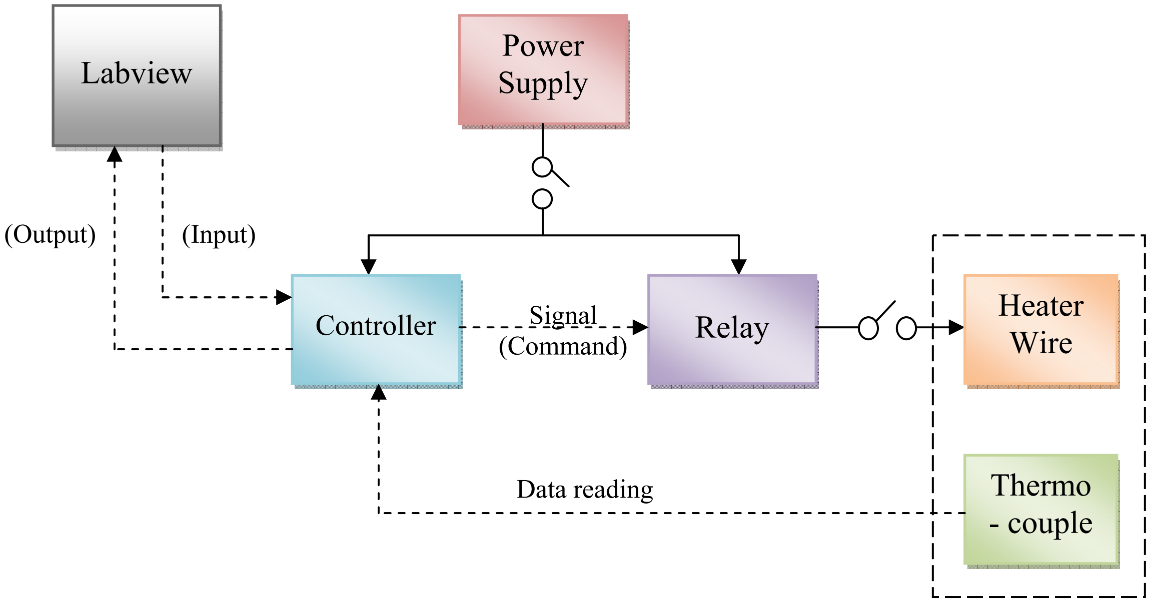


Figure 26. Schematic of temperature controller

ENGINEERING DESIGN PARAMETER ANALYSIS

After the final design has been conceived and represented as preliminary CAD models, the next step is to decide on the specific parameters for the product. This is done through performing a standard set of actions that aims to help us determine materials and methods to manufacture the parts from. A table of actions we follow is shown below:

Number	Action	Parameter/Scenario
1	Identify critical part requirements	High melting temperature
		High stress tolerance
		High precision
		Weight
		Budget Constraint
2	Identify possible failure scenarios	Melting at operating temperature
		Change in material characteristics at high temperature
		Thermal expansion
		Part breakage at high pressure
		Machinability
3	Experimentation/Analysis	Part specific
4	Contact suppliers/manufacturers	Consultation
5	Design revision	Part specific
6	Finalize parameters	Part specific

Table 3. Actions that we perform to help determine product parameters

The final design is then separated into its individual features during analysis.

UPPER AND LOWER CHAMBER CASING

The critical requirements for both chamber casings have been identified to be light weight, moderate melting temperature and machinability. The main reason for light weight is because the product is designed as a desktop scale fabricator and requires high mobility. The chambers also have to have moderate melting temperature due to the heating element within it which is expected to attain temperatures close to 1000˚C. Lastly the chamber material must be highly machinable due to its complex design and our budget constraint.

We then identified 2 possible failure scenarios which include chamber deformation at operating temperature and high machining cost. Through research, we narrowed our selection of material down to Type 303 stainless steel and 6013 aluminum alloy. Type 303 stainless steel has a higher melting temperature of 1500˚C but has a high machining cost, while 6013 aluminum alloy has a lower melting temperature of 500˚C but low machining cost. Potential manufacturers are then contacted to verify their ability to meet our specific parameters and budget constraints. After consultation, several design revisions were required to accommodate the capabilities of the machine shop. These include limiting all cavities and holes to a depth of 3 inches maximum and reducing non critical tolerances to two decimal places. All chamber dimensions are finalized for final quotation and sent for machining. 6013 aluminum alloy is our material of choice because of the low-cost machining and its light-weight properties.

INSULATION ROOF

The critical requirement for the insulation rood is low thermal conductivity and high melting temperature. This is because the insulation roof shields the upper chamber casing from direct contact with the heater element thus reducing the chamber casing's temperature. A possible failure scenario is melting during operating conditions.

Through research, we have identified firebrick as the material of choice with a very low thermal conductivity of 0.19W/m.k and a melting temperature of 1260˚C. This allows us to safely contain the heat from heater disc away from the outer chamber casing. Specific calculations are still being done to determine the outer wall temperature, however due to a shortage of time we have decided to proceed with machining the part.

HEATER DISC

The critical requirements for the heater disc have been identified as high melting temperature, high thermal shock, small thermal expansion factor, low porosity and high machinability. The reason for high melting temperature and high thermal shock is because the heater disc which holds the heating wires is expected to reach 1000˚C within a few minutes. Low porosity and high machinability is required to machine the complex holes patterns as shown below:

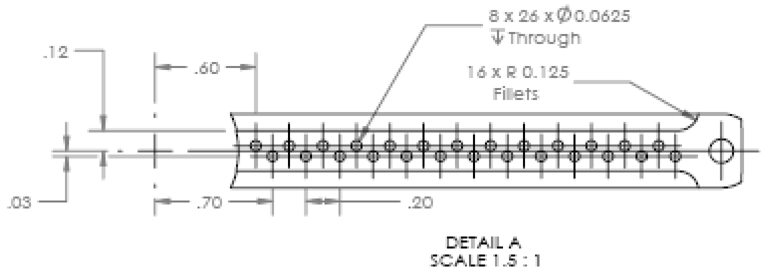


Figure 27. Detailed engineering drawing of heater disc hole

A low thermal expansion factor is also desired because of the high operating temperature experienced which may cause structural deformation. 2 failure scenarios were identified for this part which include melting at operating temperature and crumbling during machining.

Firebrick and alumina 99.5 are the two materials currently being considered. Firebrick has a high melting temperature of 1260˚C, low thermal shock, a small expansion factor of 0.5% at 1000˚C, high porosity and high machinability. Alumina 99.5 has a high melting temperature of 1750˚C, high thermal shock, a small expansion factor of less than 0.1% at 1000˚C, low porosity and low machinability.

In order to make a final decision, an experiment has been designed. A section of the desired hole pattern will be machined manually into both materials, after which they will be subjected to high thermal shock. The material that performs the best will then be selected for part production. However currently we are still waiting on the arrival of the materials and thus have not been able to come to any conclusions.

POROUS CERAMIC GAS DIFFUSER

The critical requirements for the porous ceramic gas diffuser are high flexural strength, high melting temperature and high porosity. High flexural strength is required because of the pressure buildup experienced within the showerhead as shown below:

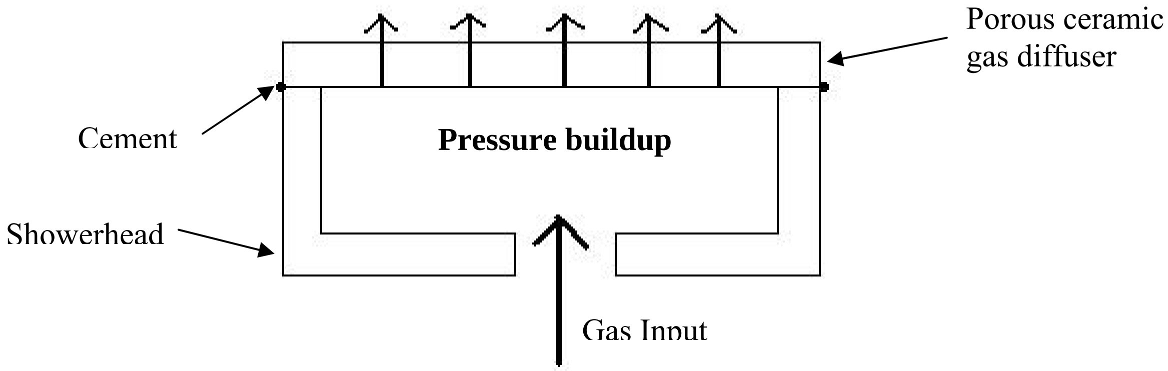


Figure 28. Porous ceramic gas diffuser cemented to showerhead

High melting temperature is required because the gas diffuser is very close to the heating element and high porosity is desired to facilitate a high volume gas flow of 1000 ml/min. 3 failure scenarios were identified for this part which are breakage under high pressure, melting at operating temperature and low volume flow rate.

Subsequently we have ordered 3 sample materials P-3-C, P-55-C and P-6-C from Coorstek to perform experiments on. The first experiment we performed aims to determine if the porous ceramic is capable of diffusing the gas flow uniformly across its surface. The setup of the equipment is shown below:

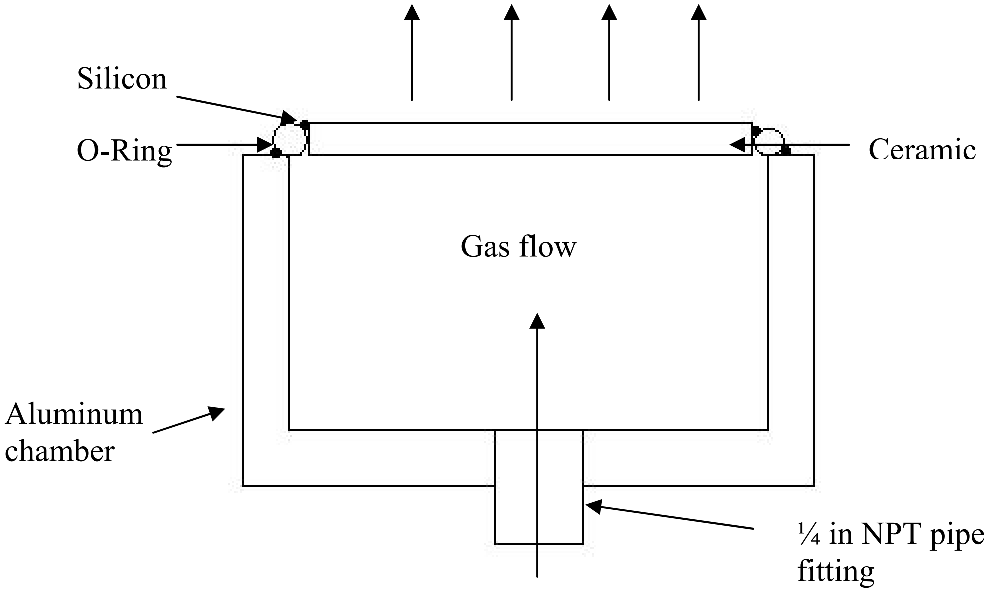


Figure 29. Porous ceramic gas diffuser experiment setup

The silicon and o-ring secures the ceramic in place and prevents possible leakage from the sides. This creates a buildup of pressure within the aluminum chamber which forces the gas to diffuse across the porous ceramic material. The setup is then immersed in water to observe the diffusion of gas as shown below:

Figure 30. Gas diffusion across porous ceramic gas diffuser

After determining that only P-3-C is capable of uniform gas diffusion across its surface, we proceeded to the next experiment. This experiment aims to determine if the porous material allows high volume flow rates close to 1000ml/min. The equipment setup is shown below:

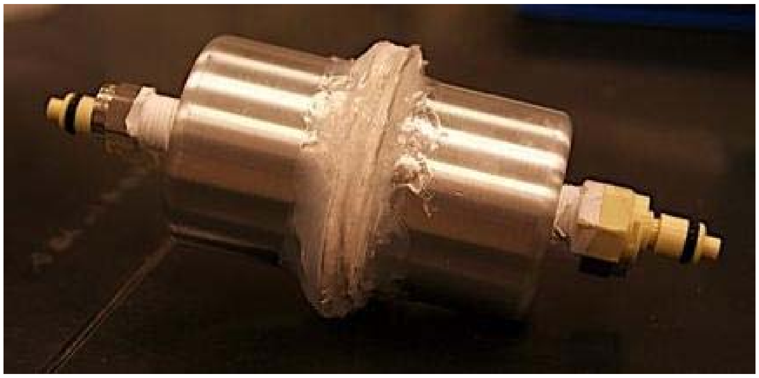


Figure 31. Mass flow rate across porous ceramic material

The device is then connected to two Mass Flow Controllers (MFCs) that show the volume flow rate across it. It is determined that the porous ceramic material is capable of flowing 1000ml/min without breaking under pressure, has a high melting temperature of 1750˚C and high flexural strength of 4000psi thus it is chosen for further machining.

HEATER WIRE

The critical requirements for the heater wire are high temperature and high flexibility. Through research and contacting suppliers, we have narrowed down our material choice to nickel-chromium alloy resistive heating wire due to its ability to attain temperatures close to 1000˚C. The chosen heater wire diameter is 24gage (0.0201in) because of its ability to thread through small complex hole patterns. From the geometry of our heater disc, we determined that approximately 15ft of heating wire will be used. We then determine the resistance per length (*R*) and the current (*I*) characteristics from the manufacturer's specifications. The value of the wire's resistance also changes with temperature. The following are values for wire parameters[2]:

- Resistance, R = 1.609 ohms/ft
- Resistance factor at 1100ºC, f = 1.078
- Current at 1100ºC, I = 9.4 A

To obtain the value of resistance at the operating temperature, we will need to scale the specified resistance by a factor (f). From these values, we then can calculate the voltage supply (V) required for the heating circuit using the following simple equation.

$$V = (R * f * \text{length}) * I \qquad \text{Eq. [1]}$$

Subsequently, we calculated the required voltage to be 244.56V which will be supplied using the wall socket coupled with a 240V transformer. Since nickel-chromium alloy resistive heating wire meets all our requirements, it is chosen for our project.

MOTOR ASSEMBLY

The main constraint in our rotational subsystem is very slow rotational speed. Three motor configurations were considered in the design of the rotational subsystem; a DC brush motor with a geared speed reducer, a miniature turbo disc stepper motor with a geared speed reducer, and a NEMA hybrid step motor. Each configuration has positive and negative attributes. Through the process of trying to incorporate each one into our design, we determined that the DC motor was not precise enough in control and the turbo stepper motor was too small to mount. Thus, we have chosen to use the NEMA 17 series step motor with a High Resolution Motion Encoder Feedback controller/step driver. This motor is capable of micro stepping which will allow us to achieve a smooth rotation.

Based on currently used CNT growth methods similar to ours, we are estimating that the nanotubes will need anywhere from 1 to 15 minutes in the growth chamber to achieve a few millimeters in length. Because of the uncertainty of CNT growth in our chamber, we wish to design for variability in the rotation speed. A range of 1 rev/min to 1 rev/hr is suitable for the desired CNT growth. Thus, rotation speeds of 2.8 E -4 rev/sec to 1.7 E -2 rev/sec are necessary (Eq. 2, 3).

$$1 \text{ rev/hr} * (1 \text{ hr}/3600 \text{ sec}) = 0.00028 \text{ rev/sec} \qquad \text{Eq. [2]}$$

$$1 \text{ rev/min} * (1 \text{ min}/60 \text{ sec}) = 0.017 \text{ rev/sec} \qquad \text{Eq. [3]}$$

The NEMA 17 series operates at 1.8 deg/step. Thus, we need a step driver that can deliver a minimum of 0.056 pulses per second (Eq. 4).

$$1.8 \text{ deg/step} * (1 \text{ rev}/360 \text{ deg}) * (200 \text{ steps/rev}) * (0.00028 \text{ rev/s}) = 0.056 \text{ steps/s} \qquad \text{Eq. [4]}$$

The High Resolution Motion Encoder Feedback controller meets this requirement, driving the step motor at 1.9 E -5 rev/s up to 385 rev/s.

Now that the speed requirement is met, we must ensure that this motor can handle the torque load applied by our system. Because the substrate is free spinning, the only torque-load contributors are the bearings and the inertia of the shaft. Using the equations shown below, calculations were performed with constants for a 303 stainless steel shaft and PTFE sleeve bearings *(steel density $\rho = 8000\ kg/m^3$, shaft radius $R = 0.0064\ m$, coefficient of friction for PTFE $\mu = 0.2$, radial load P, bearing inner diameter $D = .0127\ m$, mass m, moment of inertia for solid shaft I, shaft length L, friction torque T_f, and inertia torque T_i)*.

$$T_f = P * \mu * (D/2) \qquad \text{Eq. [5]}$$
$$T_i = I * \alpha \qquad \text{Eq. [6]}$$
$$I = 0.5 * m * R^2 \qquad \text{Eq. [7]}$$
$$m = \rho * V = \rho * pi * R^2 * L \qquad \text{Eq. [8]}$$

Assuming that the radial load is 1, the angular acceleration is 1000 rad/s^2, and a safety factor of 3 on the torque load;

$m = 0.154\ kg$, $I = 3\ E\ {-6}\ kgm^2$
$T_f = 0.00127\ Nm$, $T_i = 0.003\ Nm$
➔ $T_{total} = 3 * (.00127 + .003) =$ **12.8 mNm**

Since the holding torque of the NEMA 17 motor is rated at 280 mNm, it is suitable for our application.

MAGNET

The critical requirements for magnets are high strength and high temperature tolerance. This is because the magnet is expected to prevent slippage by the silicon disc while spinning under high temperature conditions. Several magnets have been identified to suit our requirements. The first is Alnico magnet which has a low pull of 3 pounds but high temperature tolerance of 500 ºC. Second is Neodymium magnet which has an extremely high pull of 19 pounds but low temperature tolerance of 148 ºC. Lastly is Samarium-Cobalt magnet which has a medium pull of 11 pounds and a medium temperature tolerance of 260 ºC. Samples of each magnet group have been ordered and experiments will be performed to determine their suitability in future.

PIPE FITTING

The critical requirement for pipe fitting is air-tight. Air-tight conditions are crucial in the design of our device due to the sensitivity of the process to the gases introduced. Also the flammable nature of the gases used in the process makes it essential that no gas leakage is allowed in our design as this could be a potential threat to the user's safety.

We have decided to use pipe fittings with ¼ NPT threading from Swagelok and polypropylene quick-disconnect fittings with ¼ NPT threading currently being used in the lab. These have been proven to provide an air-tight seal during experiments (with thread-lock tape) and are highly reliable.

PROJECT CONTROL SYSTEM

The critical requirement for temperature controller is its ability to provide independent temperature control over each chamber. This is achieved through a close loop control design using controllers, relays, thermocouples and a LabView program. The controller unit selected is CNI3242-C24 from Omega. This controller unit accepts signals from type-K thermocouples which allow us to utilize thermocouples currently available in the lab. Furthermore the unit also provides output signals to solid state relays which act as gates that supply power to the heater wires. The chosen relay is SSRDIN660DC25 solid state relay from Omega with a 25 ampere rating and 660 Vac line. This satisfies the current rating needed for the heater wires to reach 1000 ºC which is 9.4A. The system will then be controlled by a LabView program. Since a similar system has been constructed and tested in the lab, we have decided to use the above configuration.

The critical requirement for mass flow controller is its ability to provide independent flow control over each chamber. This is because the exact relationship between gas concentration and carbon nanotube growth has not been identified, therefore by providing independent controls in each chamber the professor will be able to vary these parameters and perform experiments. This is achieved through mass flow controllers that are connected to gas reservoirs and controlled using LabView. As the lab has already explored and perfected this area of control, we have decided to utilize their system.

The motor assembly is currently being controlled by a simple serial command program provided by its vendor. However plans are made to utilize LabView instead to provide control which allows us to link the motor control to other parameter controls such as temperature. Similarly the control programs for temperature and gas flow will be controlled using LabView and linked up together to form a single control unit in future.

FINAL DESIGN

Upon finalizing the details of our selected design, we reviewed our three dimensional CAD model of this design based on the parameters determined through our previous engineering design parameter analysis. After which, engineering drawings for each part were made in preparation for the fabrication phase of our project. Our design product, once fabricated and assembled, is shown in Figure 32 (a), below. In addition Figure 32 (b) shows our design product with the top assembly removed to enable view of the internal components.

Figure 32. (a) Assembled design product and (b) Separated top and bottom assemblies

The following sections will present the main engineering drawings for each designed part and will outline the major dimensions of each part. For clearer views and more detailed dimensions and features on each individual part, refer to the complete detailed engineering drawings attached in Appendix B.

In addition, a detailed parts list of all major and minor components is attached in Appendix D.

TOP SECTION

The top section consists of three parts- the outer wall casing, the firebrick insulator, and the heater element.

OUTER WALL CASING

The outer wall casing was made of Alloy 6013 Aluminum. This material was chosen since it has a relatively high resistance to heat, and has a lower cost than other possible materials such as stainless steel. This part will be 10.5” in outer diameter and 1.55” in height, as shown in Figure 33, below. In addition, all holes in this part are 6-32 tapped holes.

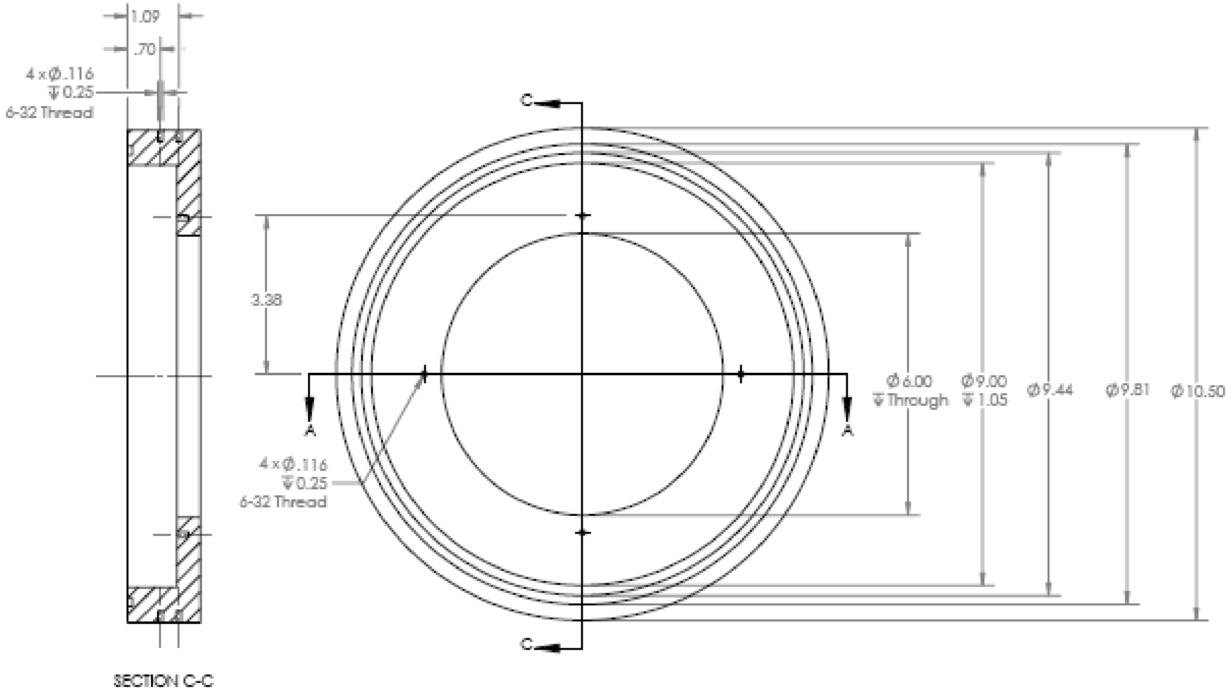


Figure 33. Engineering drawing of Outer Wall Casing

FIREBRICK INSULATOR

The firebrick insulator was machined from high temperature Insulating Fire Brick Material (K-26 type) with very low thermal conductivity of 0.19W/mK. This part is 9” in outer diameter, with walls that will be 0.9” thick. Four clearance holes of 0.144” diameter are located around the periphery of the part, all other holes will be ¼” in diameter, as shown in Figure 34.

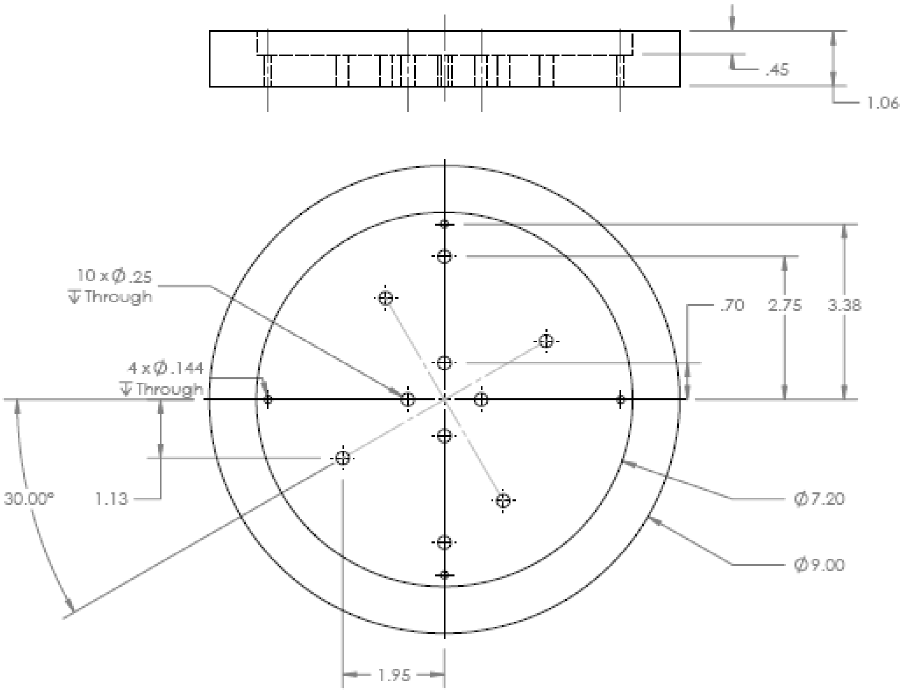


Figure 34. Engineering drawing of firebrick insulator part

HEATER ELEMENT

The heater element was fabricated out of Alumina 99.5 machinable ceramic with eight pie-wedged segments. The disc will have an outer diameter of 7” and will have an overall thickness of 0.25”. The pattern of the holes for threading the heater wire includes two staggered rows of 13 1/16” holes spaced 0.2” apart adjacently. The dimensions of the parts and hole details are shown in the engineering drawing as shown in Figure 35, below.

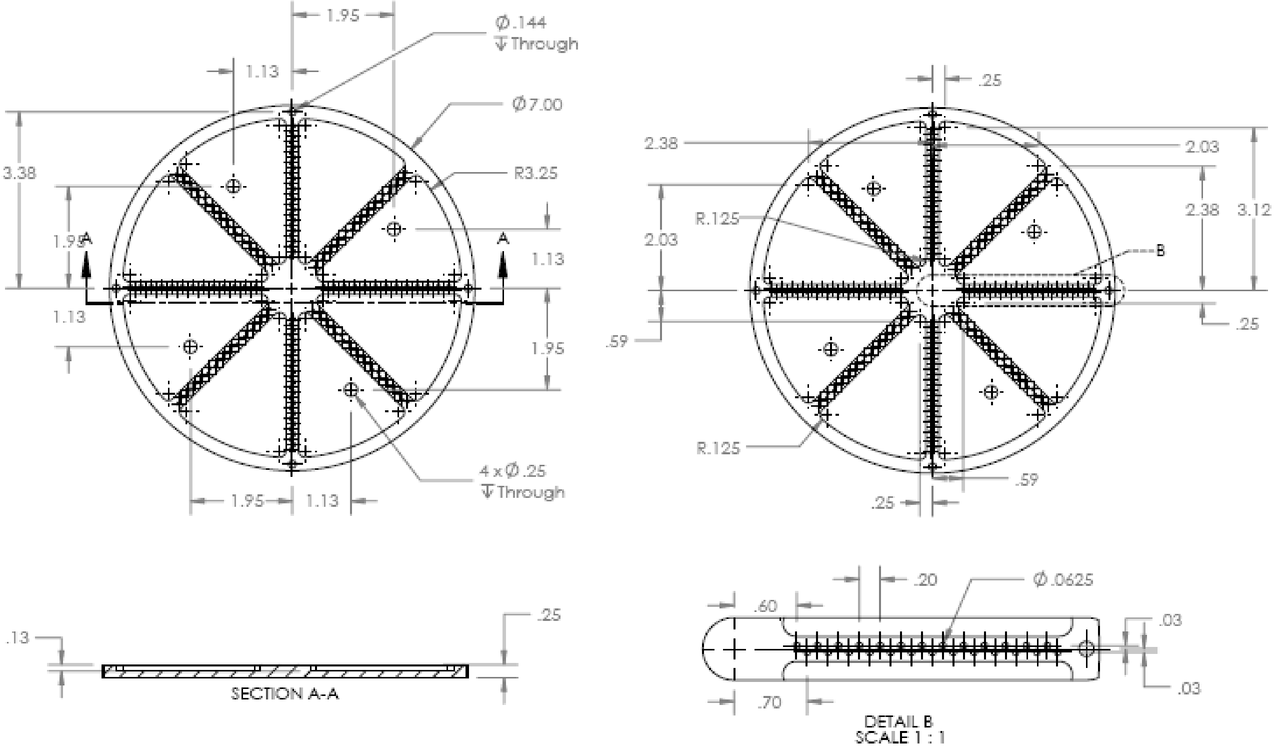


Figure 35. Engineering drawing of heating element

BOTTOM SECTION

The components in the bottom section include the fake wafer, showerheads and ceramic top layer (porous ceramic gas diffuser), stainless steel insert, and main processing chamber.

FAKE WAFER

The fake wafer was fabricated out of Alumina 99.5 machinable ceramic. Both 6” and 4” fake wafers will have an outer diameter of 9.1” and a thickness of 0.1”, which is very close to the thickness of the actual substrate wafer. The inner diameter will vary according to the size of substrate disc it was designed for, being 4.1” and 6” for the 4” and 6” substrate discs respectively. These dimensions have taken into account clearance between the actual wafer and the fake wafer for rotational motion. The fake wafer will feature 4 countersunk 6/32” clearance holes (0.144” diameter holes) and 4 pairs of 1/8” holes as shown in Figure 36, below.

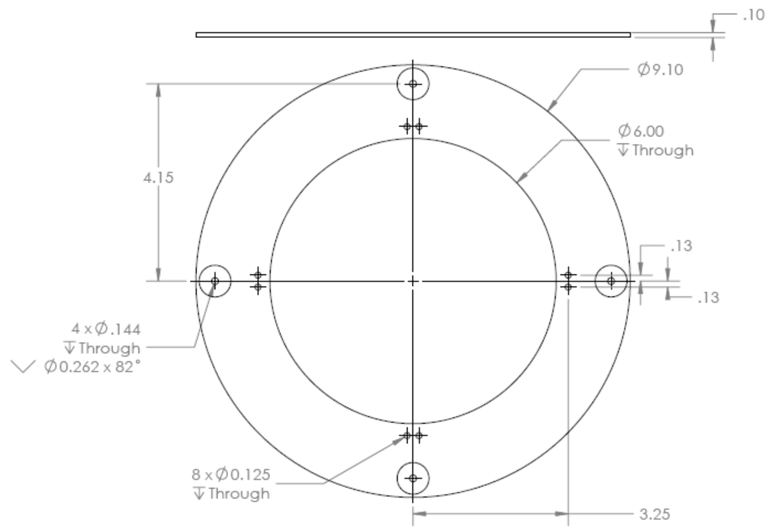
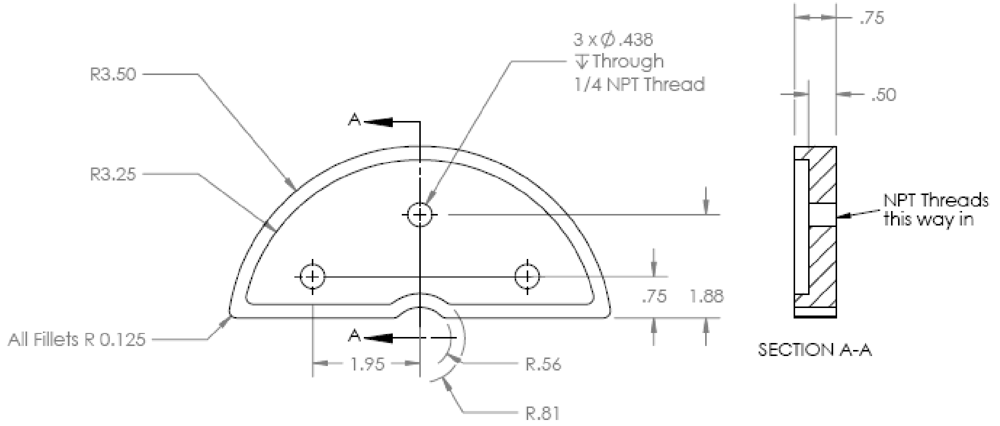


Figure 36. Engineering drawing of 6" fake wafer

SHOWERHEADS

The showerheads were made out of Type 303 grade machinable stainless steel to withstand the high temperatures in the chambers. These parts have a 3.5" outer radius and 0.25" thick side walls. The height of the parts is 0.75" with 0.5" thick bottom floors required for the ultra-torr vacuum pipe fittings to be installed as shown in Figures 37 and 38 below.



(a) **(b)**

Figure 37. Engineering drawing of half showerhead part

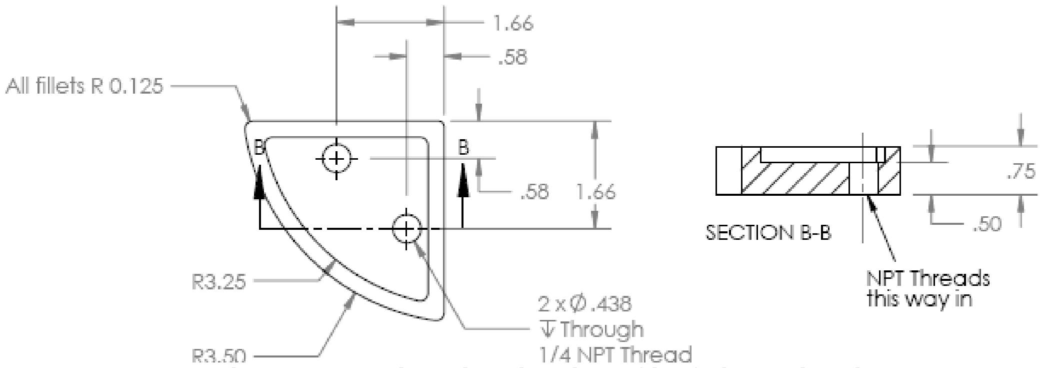
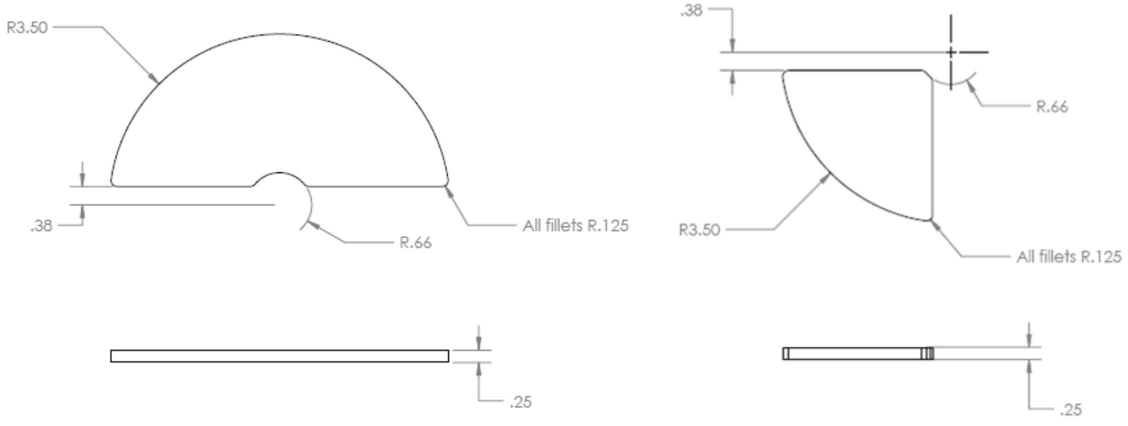


Figure 38. Engineering drawing of half showerhead part

The ceramic top layers were machined out of Alumina 99.5 porous ceramic material and have shapes corresponding to the outline of the showerhead cavity parts. These layers are 0.25” in thickness with dimensions as shown in Figure 39 below.



(a) (b)

Figure 39. Engineering drawing for (a) half showerhead ceramic layer, and (b) quarter showerhead ceramic layer

STAINLESS STEEL INSERT

The stainless steel insert was manufactured from Type 303 grade machinable stainless steel. This insert will have the same geometry as the internal vacuum walls and will have a thickness of 0.25”. The center hole for the magnet holder will be 0.85” in diameter and the slots will be 0.25” wide. Three 6-32” clearance holes on the ends of each “leg” will serve to secure this piece to the main processing chambers, as shown in the engineering drawing in Figure 40, below.

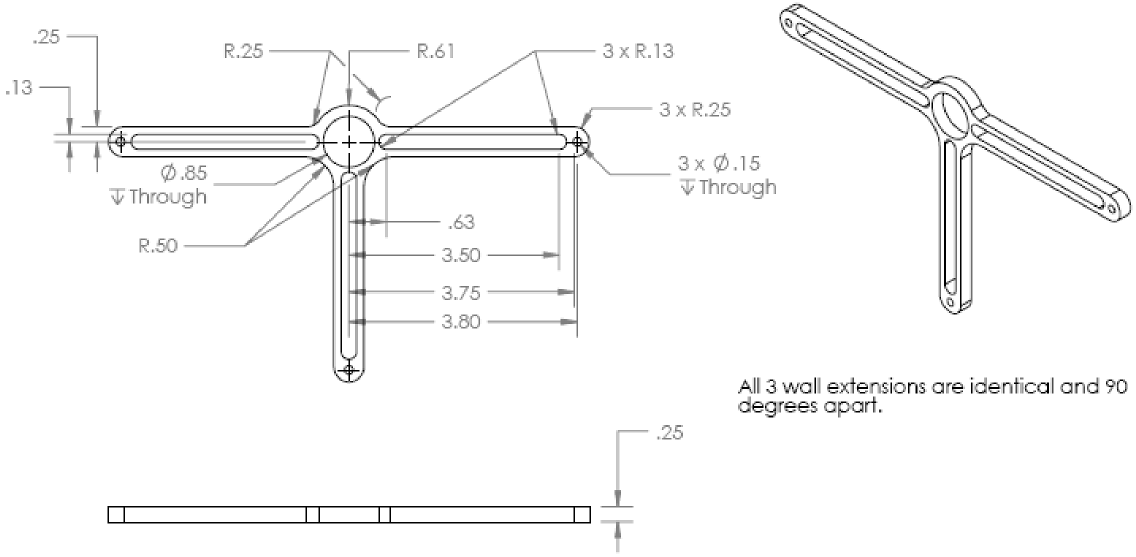


Figure 40. Engineering drawing of Stainless steel insert

MAIN PROCESSING CHAMBER

The processing chambers will be made out of Alloy 6013 aluminum, again to withstand the high temperatures involved with the CNT growth process. It will have an outer diameter of 10.5” and 1.25” thick side walls. The total height of this part will be 3.6” with a bottom floor of 1” thickness. The internal separating walls rise to a height of 2” above the bottom floor of the chambers. The fake wafer will be secured at 2.4” above the bottom floor of the chambers, leaving 0.1” clearance between the top of the fake wafer/substrate wafer disc and the glass plate above the bottom section assembly. These dimensions are also shown in Figure 41, below. For clearer enlarged views, refer to Appendix C.

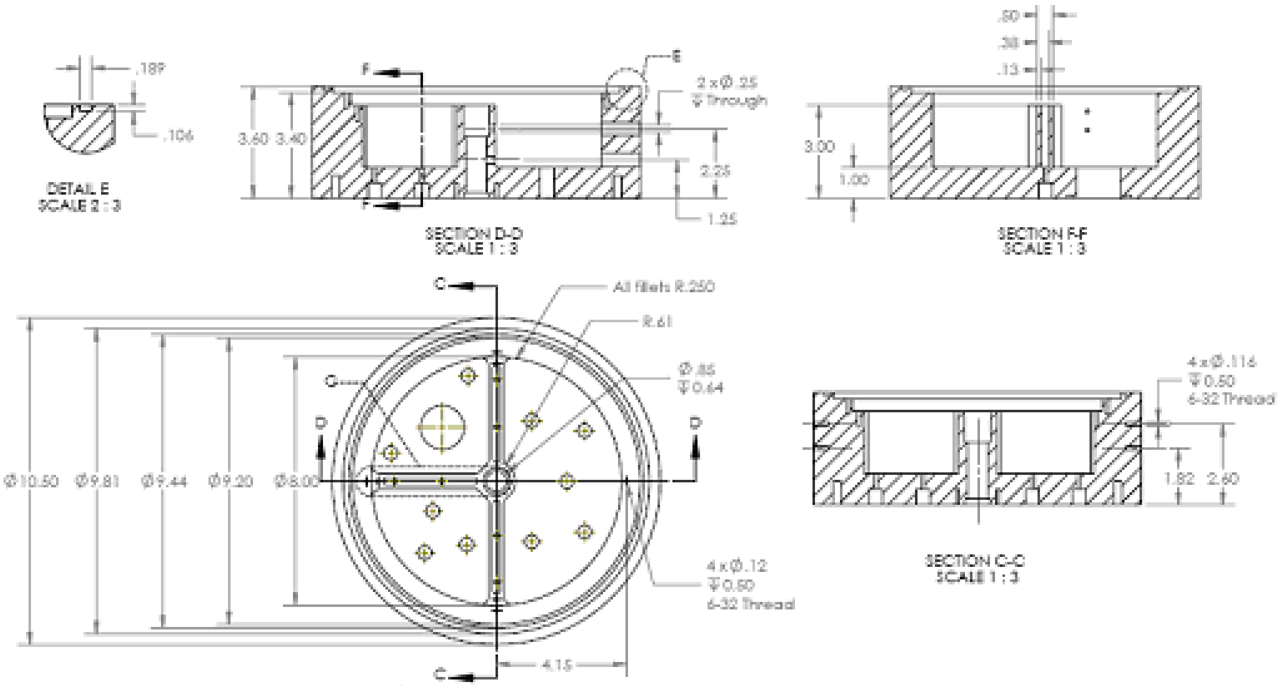


Figure 41. Engineering drawing of main processing chamber (top views and cross section)

Holes for the inflow and out flow of gases are situated at the bottom of the chambers. A cutout for the viewport in the cutting chamber is also included. In addition, four 5/16-28 threaded holes were designed around the outer periphery of the chamber. These were incorporated for stainless steel legs to be attached to the bottom of the chamber, which act as a stand for the whole assembly. The dimensions and locations of the various holes are shown in Figure 42, below. For clearer enlarged views, refer to Appendix C.

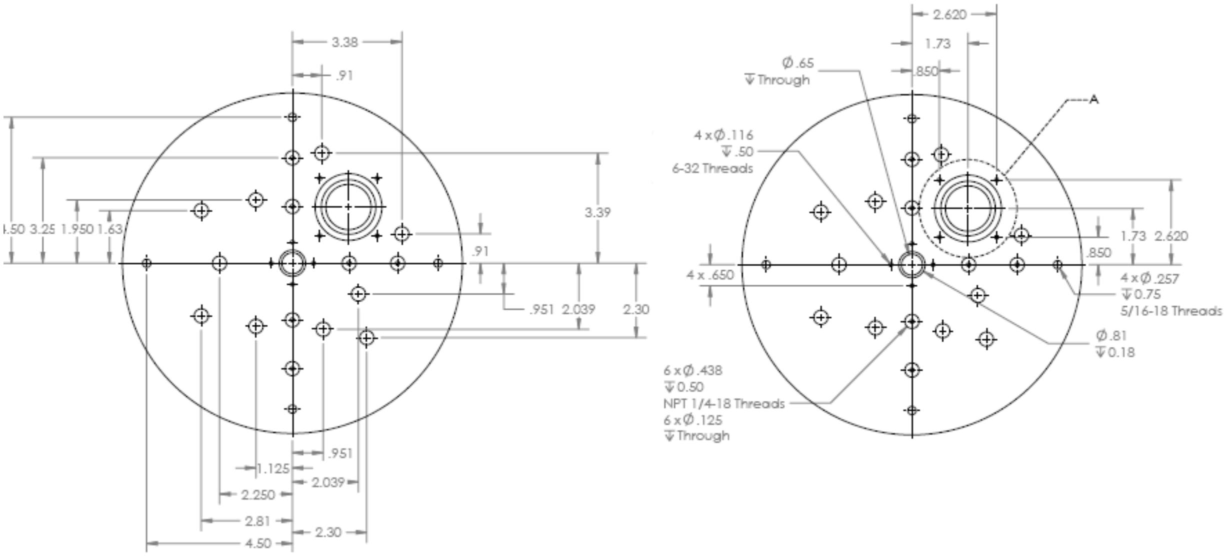


Figure 42. Engineering drawing of main processing chambers (bottom view)

MAGNET HOLDER AND SHAFT

The magnet holder and shaft will be made of Type 303 grade machinable stainless steel. The magnet holder has an outer diameter of 0.8” and an inner diameter of 0.520”. The length of the entire part is 6”. Both holes in the magnet holder portion are sized and tapped for 4-40 set screws. All the dimensions of the magnet holder are shown in the engineering drawing in Figure 43, below.

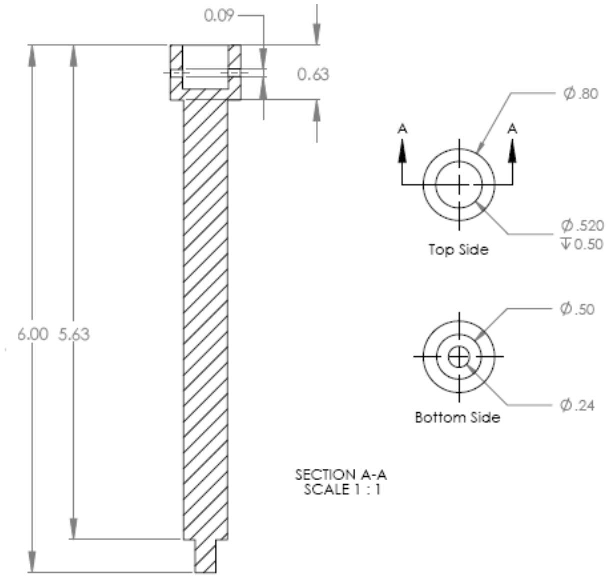


Figure 43. Engineering drawing of magnet holder and shaft

EXTERNAL ROTATIONAL ASSEMBLY

The bottom of the shaft attaches to the external rotational assembly, consisting of the lip seal flange, the bearing housing, a wafer-spring coupler, and a NEMA 17 Hybrid step motor. The lip seal flange and the bearing housing were the two components in this assembly that were designed by our team.

LIP SEAL FLANGE

The lip seal flange was machined out of Alloy 6013 aluminium and has an outer diameter of 1.6” and an inner diameter of 0.62”. The dimensions and features of this part are shown in Figure 44, below.

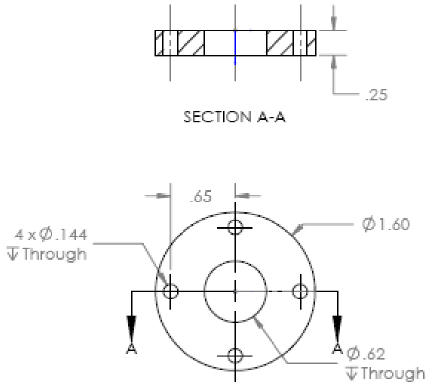


Figure 44. Engineering drawing of lip seal flange

BEARING HOUSING

The bearing housing was machined out of Alloy 6013 aluminium. The overall hieght of the part is 2”. The detailed dimensions and features of this part are shown in Figure 45, below.

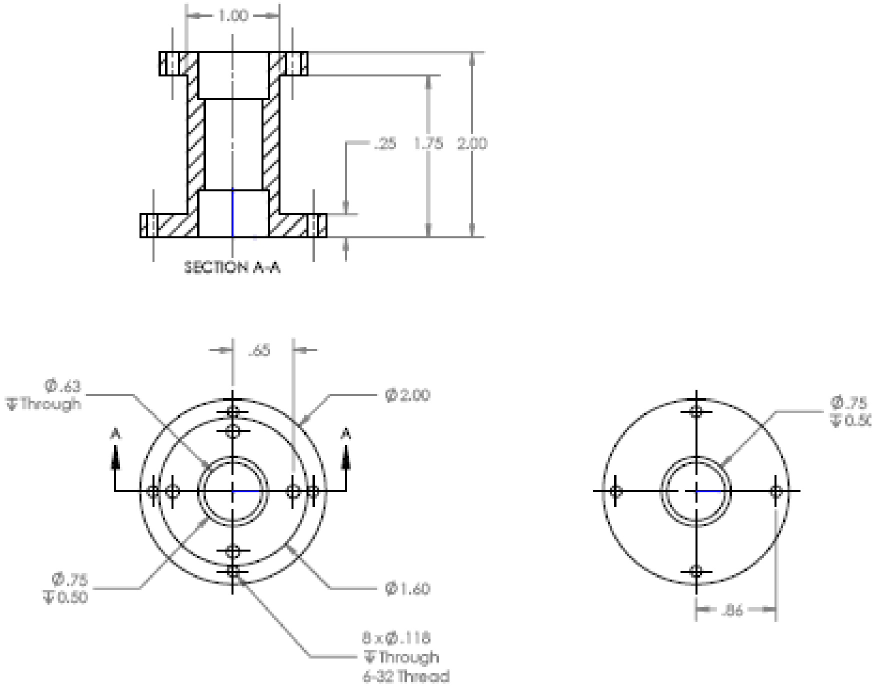


Figure 45. Engineering drawing of lip seal flange

TEMPERATURE CONTROLLER

The main components in our temperature controller include the following major internal components- a) solid state relay, (b) PID controller with RS-232 port, and (c) DIN terminal blocks. In addition the following cables linked the internal components to the external setup – (a) thermocouple extension wire, (b) power connector cable, (c) RS-232 cable with DB9 port. For a full parts list and bill of materials for the temperature controller, refer to Appendix D.

To control the temperature of each of the three heart segments incorporated in our design, we built three separately wired sets of the same temperature controller setup in one single casing. The components were wired as shown in Figure 46, below.

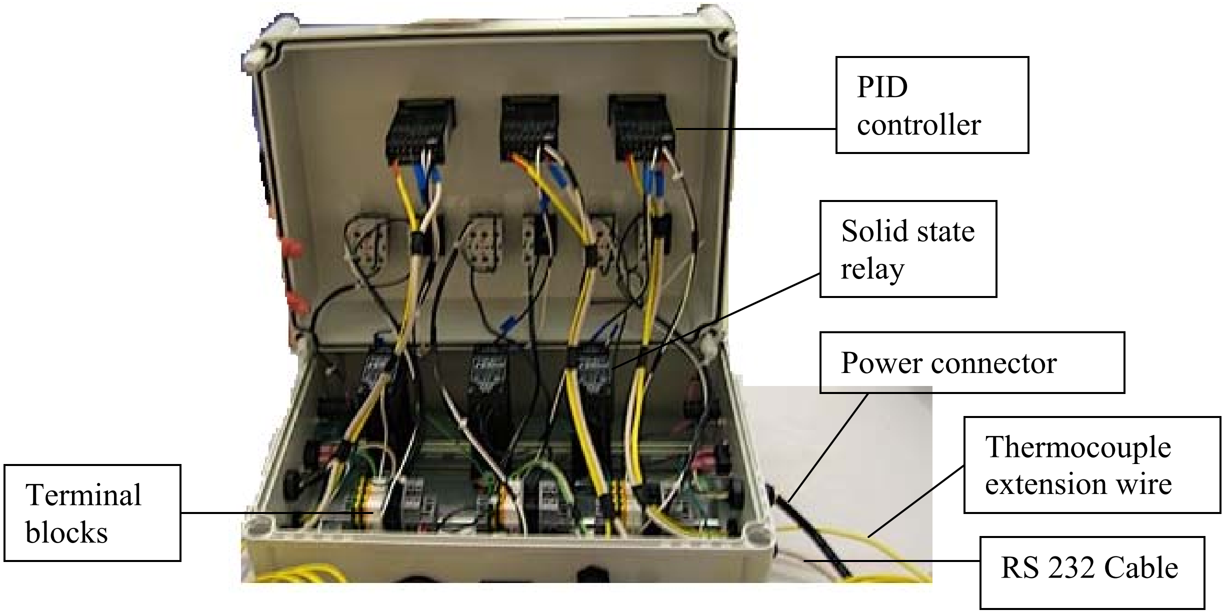


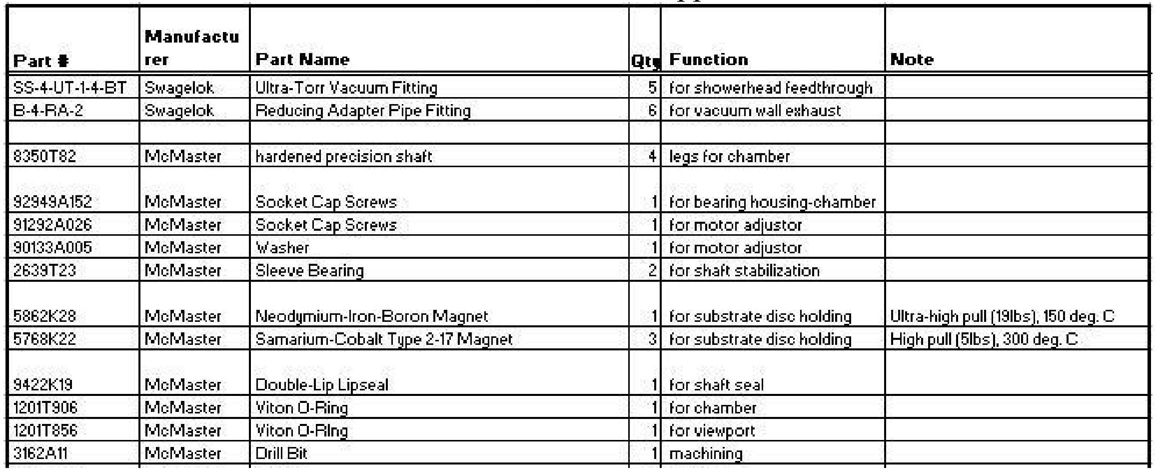
Figure 46. Temperature controller box and components

FABRICATION PLAN

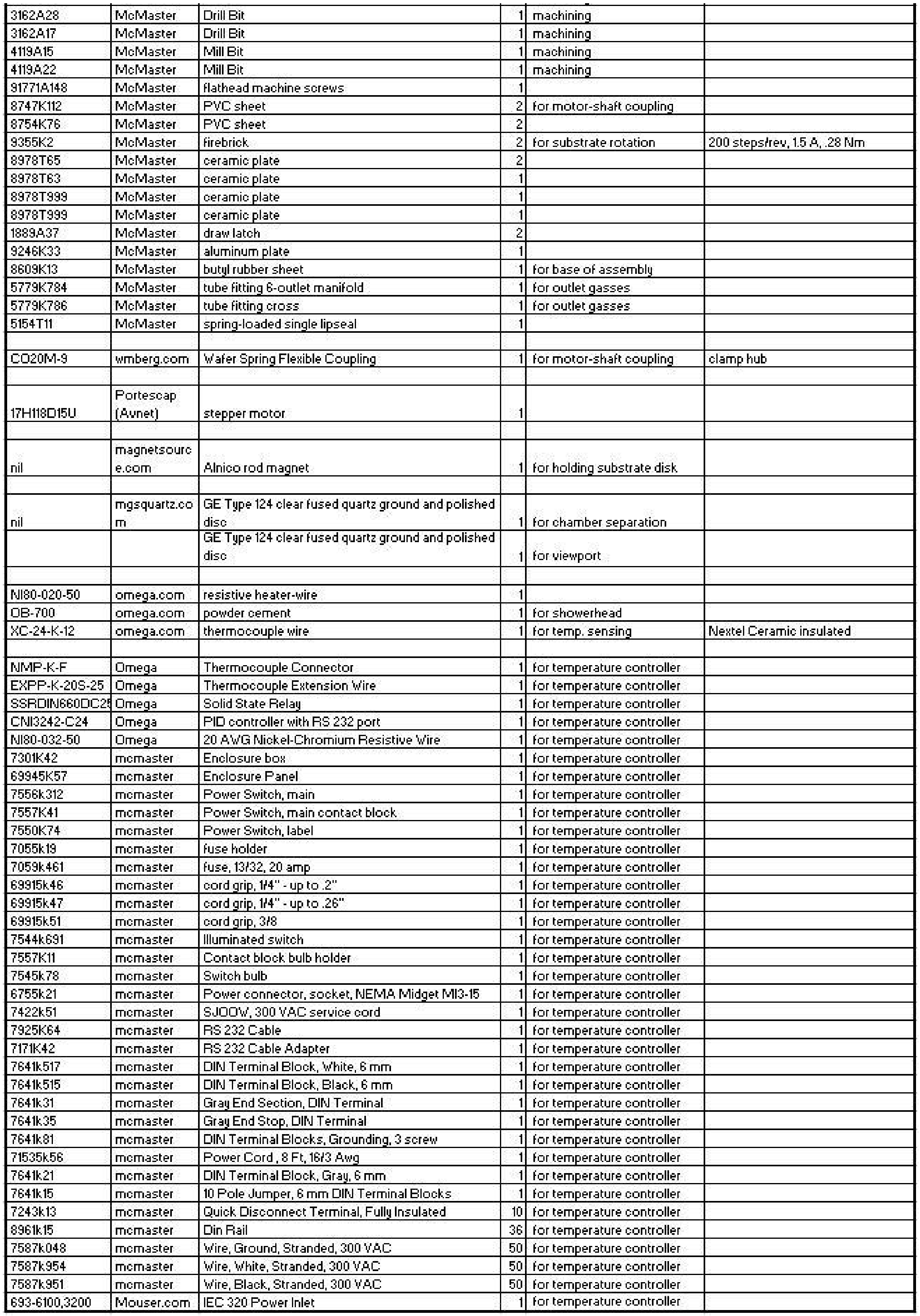
After the final design is completed, a fabrication plan was developed to machine our product. This section includes a bill of material for any parts purchased or out-sourced, a manufacturing plan for any parts machined in-house and an assembly plan for putting the product together.

OFF-THE SHELF COMPONENTS

Off-the-shelf purchases are summarized in the bill of materials as presented in Table 4, below. For a full detailed bill of materials, refer to Appendx C.



Part #	Manufacturer	Part Name	Qty	Function	Note
SS-4-UT-1-4-BT	Swagelok	Ultra-Torr Vacuum Fitting	5	for showerhead feedthrough	
B-4-RA-2	Swagelok	Reducing Adapter Pipe Fitting	6	for vacuum wall exhaust	
8350T82	McMaster	hardened precision shaft	4	legs for chamber	
92949A152	McMaster	Socket Cap Screws	1	for bearing housing-chamber	
91292A026	McMaster	Socket Cap Screws	1	for motor adjustor	
90133A005	McMaster	Washer	1	for motor adjustor	
2639T23	McMaster	Sleeve Bearing	2	for shaft stabilization	
5862K28	McMaster	Neodymium-Iron-Boron Magnet	1	for substrate disc holding	Ultra-high pull (19lbs), 150 deg. C
5768K22	McMaster	Samarium-Cobalt Type 2-17 Magnet	3	for substrate disc holding	High pull (5lbs), 300 deg. C
9422K19	McMaster	Double-Lip Lipseal	1	for shaft seal	
1201T906	McMaster	Viton O-Ring	1	for chamber	
1201T856	McMaster	Viton O-Ring	1	for viewport	
3162A11	McMaster	Drill Bit	1	machining	



3162A28	McMaster	Drill Bit	1	machining	
3162A17	McMaster	Drill Bit	1	machining	
4119A15	McMaster	Mill Bit	1	machining	
4119A22	McMaster	Mill Bit	1	machining	
91771A148	McMaster	flathead machine screws	1		
8747K112	McMaster	PVC sheet	2	for motor-shaft coupling	
8754K76	McMaster	PVC sheet	2		
9355K2	McMaster	firebrick	2	for substrate rotation	200 steps/rev, 1.5 A, .28 Nm
8978T65	McMaster	ceramic plate	2		
8978T63	McMaster	ceramic plate	1		
8978T999	McMaster	ceramic plate	1		
8978T999	McMaster	ceramic plate	1		
1889A37	McMaster	draw latch	2		
9246K33	McMaster	aluminum plate	1		
8609K13	McMaster	butyl rubber sheet	1	for base of assembly	
5779K784	McMaster	tube fitting 6-outlet manifold	1	for outlet gasses	
5779K786	McMaster	tube fitting cross	1	for outlet gasses	
5154T11	McMaster	spring-loaded single lipseal	1		
CO20M-9	wmberg.com	Wafer Spring Flexible Coupling	1	for motor-shaft coupling	clamp hub
17H118D15U	Portescap (Avnet)	stepper motor	1		
nil	magnetsource.com	Alnico rod magnet	1	for holding substrate disk	
nil	mgsquartz.com	GE Type 124 clear fused quartz ground and polished disc	1	for chamber separation	
		GE Type 124 clear fused quartz ground and polished disc	1	for viewport	
NI80-020-50	omega.com	resistive heater-wire	1		
OB-700	omega.com	powder cement	1	for showerhead	
XC-24-K-12	omega.com	thermocouple wire	1	for temp. sensing	Nextel Ceramic insulated
NMP-K-F	Omega	Thermocouple Connector	1	for temperature controller	
EXPP-K-20S-25	Omega	Thermocouple Extension Wire	1	for temperature controller	
SSRDIN660DC2	Omega	Solid State Relay	1	for temperature controller	
CNI3242-C24	Omega	PID controller with RS 232 port	1	for temperature controller	
NI80-032-50	Omega	20 AWG Nickel-Chromium Resistive Wire	1	for temperature controller	
7301K42	mcmaster	Enclosure box	1	for temperature controller	
69945K57	mcmaster	Enclosure Panel	1	for temperature controller	
7556k312	mcmaster	Power Switch, main	1	for temperature controller	
7557K41	mcmaster	Power Switch, main contact block	1	for temperature controller	
7550K74	mcmaster	Power Switch, label	1	for temperature controller	
7055k19	mcmaster	fuse holder	1	for temperature controller	
7059k461	mcmaster	fuse, 13/32, 20 amp	1	for temperature controller	
69915k46	mcmaster	cord grip, 1/4" - up to .2"	1	for temperature controller	
69915k47	mcmaster	cord grip, 1/4" - up to .26"	1	for temperature controller	
69915k51	mcmaster	cord grip, 3/8	1	for temperature controller	
7544k691	mcmaster	Illuminated switch	1	for temperature controller	
7557K11	mcmaster	Contact block bulb holder	1	for temperature controller	
7545k78	mcmaster	Switch bulb	1	for temperature controller	
6755k21	mcmaster	Power connector, socket, NEMA Midget MI3-15	1	for temperature controller	
7422k51	mcmaster	SJOOW, 300 VAC service cord	1	for temperature controller	
7925K64	mcmaster	RS 232 Cable	1	for temperature controller	
7171K42	mcmaster	RS 232 Cable Adapter	1	for temperature controller	
7641k517	mcmaster	DIN Terminal Block, White, 6 mm	1	for temperature controller	
7641k515	mcmaster	DIN Terminal Block, Black, 6 mm	1	for temperature controller	
7641k31	mcmaster	Gray End Section, DIN Terminal	1	for temperature controller	
7641k35	mcmaster	Gray End Stop, DIN Terminal	1	for temperature controller	
7641k81	mcmaster	DIN Terminal Blocks, Grounding, 3 screw	1	for temperature controller	
71535k56	mcmaster	Power Cord , 8 Ft, 16/3 Awg	1	for temperature controller	
7641k21	mcmaster	DIN Terminal Block, Gray, 6 mm	1	for temperature controller	
7641k15	mcmaster	10 Pole Jumper, 6 mm DIN Terminal Blocks	1	for temperature controller	
7243k13	mcmaster	Quick Disconnect Terminal, Fully Insulated	10	for temperature controller	
8961k15	mcmaster	Din Rail	36	for temperature controller	
7587k048	mcmaster	Wire, Ground, Stranded, 300 VAC	50	for temperature controller	
7587k954	mcmaster	Wire, White, Stranded, 300 VAC	50	for temperature controller	
7587k951	mcmaster	Wire, Black, Stranded, 300 VAC	50	for temperature controller	
693-6100,3200	Mouser.com	IEC 320 Power Inlet	1	for temperature controller	

Table 4. Bill of Materials as of Mar 20, 2007

OUTSOURCED PARTS

Most of the major components were outsourced to Malaysia for machining due to inadequate equipments and capability in the University's machine shops to manufacture these parts as seen in Table 5. The pockets in the outer wall casing, the main processing chamber, and the showerhead body were milled out and the holes of assorted sizes were drilled. The overall T shape and the through cuts within the insert were milled and holes were drilled at the ends of each leg. Lastly, the magnet holder plus the shaft was turned to gain their cylindrical shape and holes in the magnet holder were drilled.

Part	Material	Fabrication Plan
Outer wall casing	6013 Aluminum	Mill, drill
Main processing chamber	6013 Aluminum	Mill, drill
Showerhead body	Type 303 Stainless steel	Mill, drill
Stainless steel insert	Type 303 Stainless steel	Mill, drill
Magnet holder + shaft	Type 303 Stainless Steel	Lathe, drill

Table 5. Outsourced parts

IN-HOUSE MACHINED PARTS

The ceramic and firebrick parts are scheduled for in-house machining since outsourcing is not economical. Table 6 shows the parts to be machined in-house. Machining of a test piece firebrick revealed that traditional milling produces health hazardous fine particles and therefore the alternative of water jet cutting was necessary. Water jet cutting is a process that combines water under high pressure with abrasive substances to cut through materials. This method provides precise and accurate cuts of different shapes, dimensions, and materials. The benefit of using the water jet over a mill is the slurry-like byproduct from the cut, which creates a healthier work environment. The water jet cutting machine also needs minimal fixture and tooling and yields highly accurate, clean cuts. The disadvantages of water jetting include its inability to machine cavities and cut small holes on brittle material. The thermal insulator, fake wafer, showerhead ceramic contours along with their holes will all be water jetted while the heater disc will be milled using CNC in Bob's shop due to its complex hole pattern.

Part	Material	Mach. Index	Fabrication Plan
Thermal insulator	Firebrick	1000	Water jet
Fake wafer	Alumina 99.5	3	Water jet
Showerhead ceramic	Alumina 99.5	3	Water jet

Table 6. In-house machined parts

However in order to water jet a part, a standard procedure as shown below has to be followed.

1. Draw an outline of the desired shape using AutoCAD and save the file as a .dxf file.
2. Verify accuracy of the part drawing using OMAX layout
3. Determine machinability index of material as specified in OMAX material database
4. Determine desired cut quality

5. Create toolpath using OMAX
6. Secure stock material onto the water jet machine and determine toolpath origin
7. Start water jet

Milling of the ceramic heater disc required careful planning and Table 7 summarizes the problems and solutions we encountered.

Material Properties	Problem	Action taken
Hard and brittle	Normal tools are not capable of machining ceramic	Purchase diamond coated carbide tools designed for ceramic machining
Hard and brittle	High temperature experienced by tool during machining	Drench part and tool with coolant during machining
Powdery	Produce fine particles during machining which pose health hazard	Build water bath to submerge ceramic part during machining

Table 7. Safety precautions taken before milling ceramics

After taking all necessary precautions, an equipment setup as shown below is adopted. This is followed by CNC programming and machining by Bob Coury at speeds ranging from 500 RPM to 700 RPM.

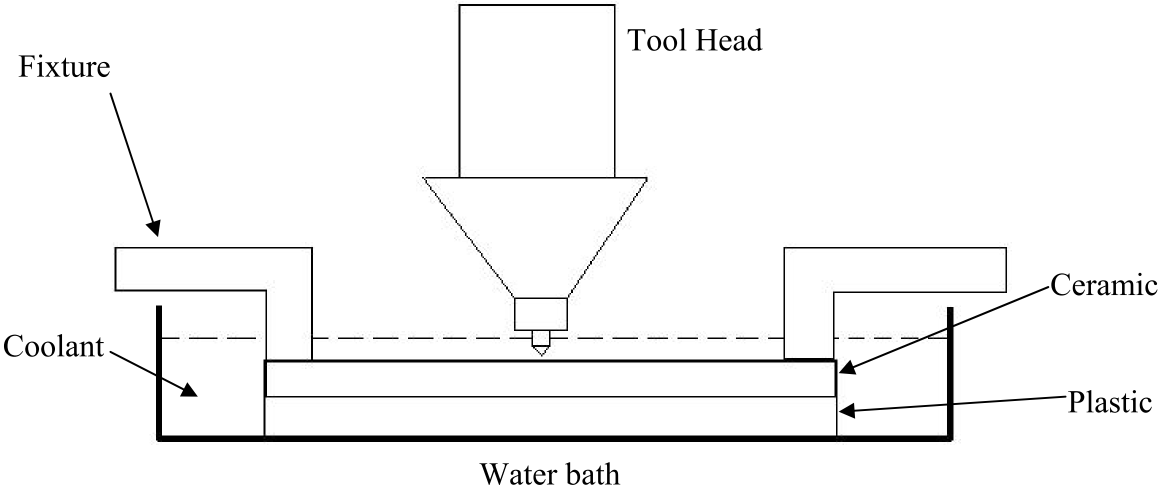


Figure 47. Schematic diagram of water bath and CNC setup

ASSEMBLY PROCESS

The assembly plan will be divided into 3 separate sections. The first two sections will cover the top chamber and the bottom chamber respectively while the third section will cover all miscellaneous fittings.

The top chamber consists of 5 main components which are the heater roof, heater disc, heater wires, washers, and insulation roof. The order of assembly is shown in Figure. 48 below:

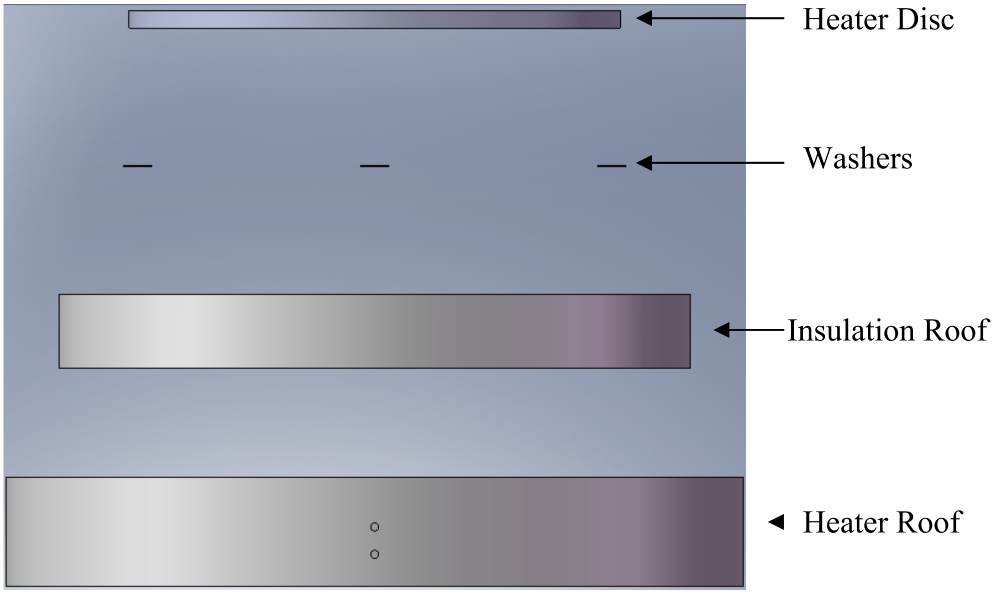


Figure 48. Order of assembly for top chamber

The first step to assembling the top chamber is to thread the heater wire through the complex hole pattern on the heater disc. After this, the four components shown above will be secured using 4 ½ inch long 6-32 thread screws from the heater disc.

Next is the bottom chamber which consists of 2 sub assemblies (motor assembly and shower head assembly), which then makes up the main assembly along with other parts. The overall order of the bottom assembly is shown below in Figure 49 and Figure 50

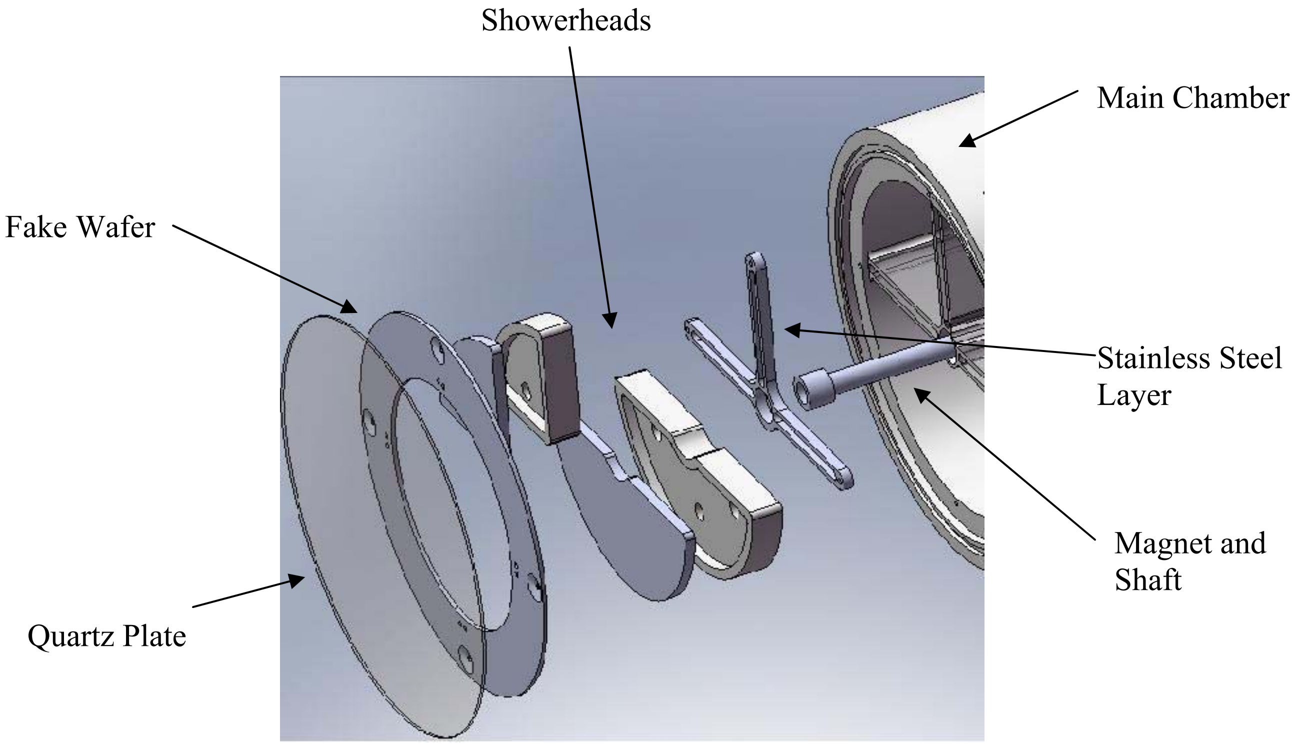


Figure 49. Order of assembly for bottom chamber

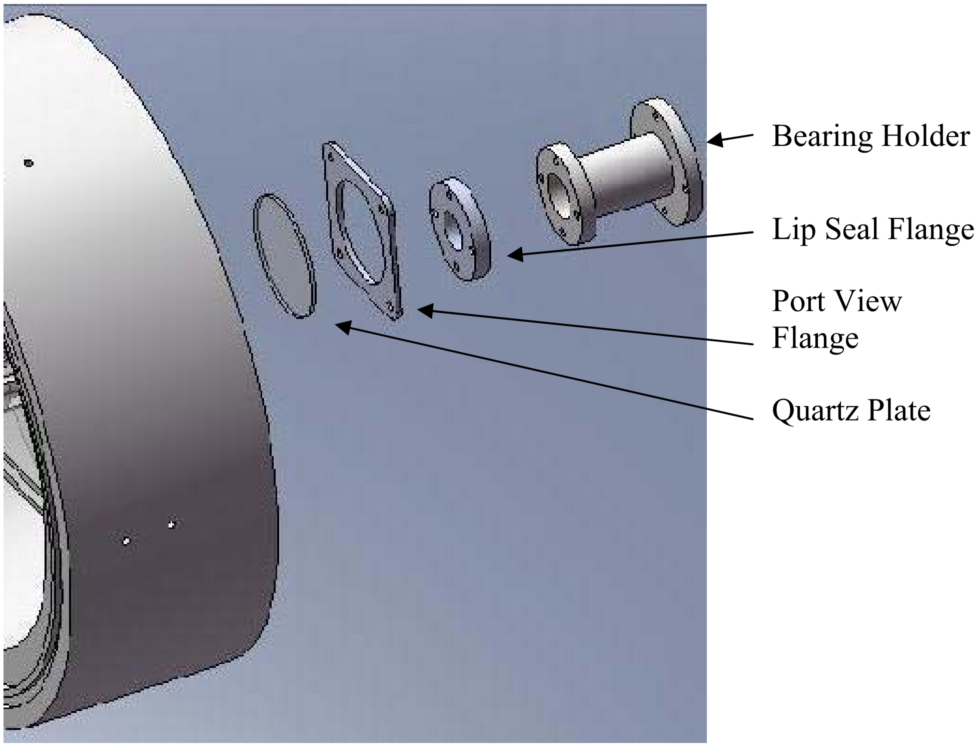


Figure 50. Order of assembly for bottom chamber

The showerhead assembly is shown in figure 51 below where the ceramic piece is cemented to the stainless steel showerhead.

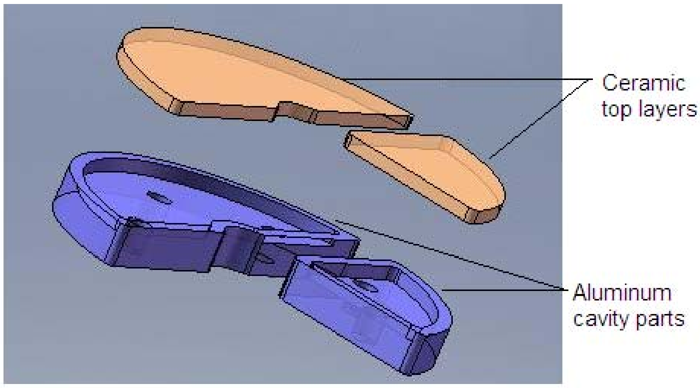


Figure 51. Showerhead assembly

After the cement dries, ¼ inch NPT pipe fittings will be fitted to the bottom of the shower heads. Bored-through Ultra-Torr fittings on the bottom of the chamber will allow steel pipes to pass through a vacuum seal and be connected to Tygon tubes outside of the main chamber for gas supply. Besides acting as a supply route, the steel pipes also act as support structures that keep the showerheads suspended near to the substrate disc. All securing screws used in the bottom chamber are ¼ inch long 6-32 thread screws.

Finally the upper chamber and the lower chamber will be secured together using two draw latches that will be mounted on both sides of the main chamber. After this, the heater wires will be connected to the temperature controller box, the motor will be secured to the bearing holder, and the steel pipes will be connected to the mass flow controller.

VALIDATION PLAN

Upon completion of our prototype, we will undergo a systematic approach to demonstrate that the engineering specifications have been met. A summary of the customer requirements, engineering specifications, and validation plans are included in Table 8, below.

	Customer Requirements	**Engineering Specifications**	**Validation Plans**
1) Top priority			
a)	Fluid separation between different chambers	Partition walls with low pressured outlet points to allow fluid separation	-Too complex for CFD -Use MFCs at vacuum wall outlet -Create plastic model w/ working fluid = water
b)	High temperature tolerance material	Heating elements capable of attaining temperatures up to 1000 ºC	-Temperature controller feedback
		Materials and parts that withstand high temperatures up to 1000 ºC (alumina/quartz/silicon)	-Testing with high temperature environment

c)	Rotating mechanism to allow continuous growth	Step motor with speeds ranging from 0.02RPM to 4 RPM	-Motor controller/Labview feedback
d)	Uniform gas flow over surface of substrate	Diffused air injection to allow uniform flow	-Results/pictures of water-bubbling test in lab
2) Second priority			
a)	Efficient gas flow through chambers	Increase number of inlet-outlet points to optimize gas flow	-Observation
b)	Separate heating zones	Localized or external heating mechanism for zones of different specified temperatures	-Demonstration that wiring configuration can be changed to accommodate desired heating zones
c)	Minimum contamination of reactants	Usage of O-rings and lip seals to provide an air-tight environment	-Observation
		Gases to be channeled to and removed from chambers separately	-Observation
d)	Continuous film of CNTs harvested	Substrate platform to be continuous without breaks	-Observation
e)	Continuous removal of CNTs	Removal of CNTs by mechanical, thermal, chemical means.(eg, gas treatment/gentle mechanical action)	-Cannot be validated until growth is possible -Compatible for “removal-aiding” gas delivery in the event of blade failure
f)	Continuous collection of CNTs	Compartment for collecting nanotubes to be designed within chamber	-Observation
3) Last priority			
a)	Adjustable rotational speed	Controller for speed of rotation	-Observation & demonstration
b)	Adjustable temperatures	Temperature controller to be included in system	-Observation & demonstration
c)	CNT forests to be few inches in width	2 inch wide growth region	-Observation
d)	Process to be monitored externally	Viewing port to be integrated at growth region	-Observation

Table 8. Customer requirements, engineering specifications, and corresponding validation plans.

Although our team plans to see this project thorough to completion, the prototype is not fully functional yet. Because of the inability to grow CNTs with our apparatus, we cannot yet “prove” that it works. We can, however, validate that the engineering specifications with regards to the customer requirements were met in our prototype.

First, the overall design and shape of the apparatus required efficient gas flow/distribution, three heating zones, three gas zones, continuous growth/removal/collection, 2” width of CNT forest, 3mm height of CNT forest, and variable 4” to 6” silicon wafer. Efficient gas flow is provided by a cylindrical chamber with gas outlets evenly dispersed on the bottom. Heating zones are accommodated by the “pie” wedge-like sections of resistive wire which can be connected in series (for the same current), or in parallel for different currents. Gas zones are accommodated by the vacuum walls that separate the chamber into three areas under the wafer disc. Each area has its own gas inlets and outlets which are at the bottom to help prevent gas flow up and over the vacuum walls. The vacuum walls suck out gasses that attempt to cross the boundary into another chamber area, and the “fake wafer” also aids in minimizing the mixing. To achieve continuous growth, we have a spinning silicon wafer on which the CNTs will grow. CNT removal and collection occur via razor blade in the third chamber area. The “fake wafer” ceramic ring is replaceable to accommodate a 4” or 6” diameter silicon wafer. This will allow for the desired width of CNT forest growth. Also, the motor shaft assembly is adjustable (via screws from bearing housing to motor) to allow for a given height of CNTs to pass from pretreatment chamber, to growth chamber, to removal chamber undamaged by the vacuum walls.

Next, our project required controlled delivery of three different gasses to the chamber. To accomplish this, we first have the tygon tubes connecting the gas tanks to a mass flow controller box. This box contains three mass flow controllers (MFCs) calibrated specifically for each gas (Helium, Hydrogen, and Ethylene), power supplies, DAQ cards, emergency power switches, and a manifold that combines the gasses after passing through the MFCs. The DAQ cards are connected to the computer via USB cables, thus allowing us to control gas flow from labview and adjust flow rates to research the optimal growth parameters. After passing through the MFC box, tygon tubes run to another manifold and then to the chamber. The tubes connect to stainless steel pipes that enter the chamber via Ultra-Torr fittings that provide a vacuum seal. The pipes then enter the showerheads which evenly diffuse the gas over the silicon wafer via porous ceramic. Helium and Hydrogen flow to the pretreatment chamber showerhead and Ethylene flows to the growth chamber showerhead.

To ensure that the showerheads distribute the gas evenly across the surface we ran two experiments (outlined in “Porous Ceramic Gas Diffuser” section, page 25). The first was to test the transient time for backpressure inside the showerhead once the MFCs begin gas delivery. We placed a sample of ceramic between two cavities and sealed off the joints with silicone. We connected both cavities to separate MFC boxes, one to control the in-flow and the other to monitor the out-flow. We ran four tests at 100, 200, 400, and 600 mL/min in-flow. Transient time for equal flow rates on both sides of the ceramic were 5, 10, 30, and 30 sec. respectively. Next, we removed one of the cavities so that the ceramic was exposed but still sealed to the other cavity. We then placed the ceramic/cavity unit beneath the surface of a bucket of water with the ceramic surface facing up. By running the gas, we observed the distribution of the bubbles exiting the ceramic. This test was performed with three different porosity-grades of ceramic to choose the grade with the most even gas distribution.

Because CNT growth is very sensitive to gas concentration and because the gas environment is flammable, the entire chamber needs to be vacuum sealed. To accommodate this requirement, the top and bottom parts seal off to the glass disc via Viton O-Rings. Two draw latches on the outer wall of the chamber provide the sealing pressure. Also, thread-lock tape is used on all pipe fittings and threaded fittings to prevent minute leakage.

Contamination of the gas environment is prevented by using all stainless steel, aluminum, brass, and glass materials in the lower chamber. Although the ceramic and firebrick parts are compatible with the gasses in this system, we seal off the top chamber with a borosilicate glass disc as a safety factor. Most heat transfer from the heater disc occurs by radiation, allowing this transmitting glass to sit between the heater disc and the wafer. Temperature control is a requirement met by means of a thermocouple that enters the lower chamber, threads up the side, and sits above the silicon wafer. This thermocouple is connected to the temperature controller box which houses the controller, relay, switches and contact blocks. A simple diagram is shown below in figure 52 to further illustrate the connections within the temperature controller box.

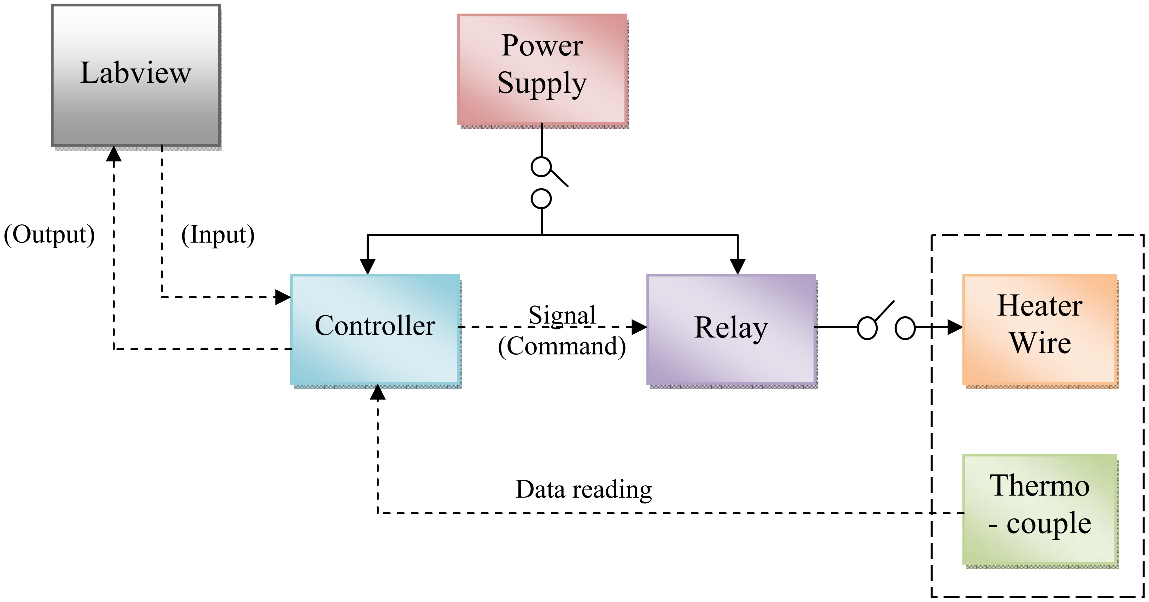


Figure 52. Temperature Controller Schematic Flow Chart

The box is connected to the computer via DB-sub cable which allows us to control the temperature from the computer and research the optimal growth parameters.

For safety and energy efficiency purposes, thermal insulation of some sort was required. To accommodate this, we added a layer of firebrick that surrounds the heater disk. This layer has a very low thermal conductivity (about 0.2 W/mK) which minimizes heat conduction to the aluminum shell and heat loss to the surroundings.

Finally, very slow rotary motion of the substrate disc was required. Since motors have maximum operating temperatures and lubricants that would contaminate the gas environment, we could not have a motor inside the chamber. Therefore, we designed a motor and stabilization bearing assembly that sits beneath the chamber. We chose a micro-stepping motor with a feedback controller to accommodate the very slow speeds needed. This motor was tested and ran smoothly for one rotation in 10 min. The shaft is stabilized by bearings, and then passes through a lipseal on the bottom of the chamber to ensure vacuum sealing. The end of the shaft has a cup that houses a magnet to hold the wafer. Two small holes were added from the shaft chamber to the growth chamber to prevent trapping of gases inside the shaft chamber. The motor controller connects to the computer via USB cable, enabling us to control the motor speed from Labview and research the optimal growth parameters.

Finally, external viewing of the growth process was desired, but not necessary for this project. Unfortunately, due to the high complexity of the system, we were not able to add this feature. We did, however, add a small viewing port on the bottom side of the removal chamber.

DISCUSSION

The current design satisfies the proposed problem in creating a machine for continuous manufacturing of CNTs with strengths and weaknesses. The major strengths of the system are discussed as follows:

i) Uniform gas delivery – this is achieved through the use of porous ceramics as the top layer of our showerheads. Testing of these ceramics as previously discussed in the Engineering Parameter Analysis section, page XX, have shown that this has successfully achieve the uniform delivery of gas.

ii) Design for interchangeable wafers- our design allows for the use of both 4” and 6” diameter silicon wafers as the substrate by incorporating different sized fake wafers. This allows the flexibility and convenience on the user’s part in operating this device for their own purposes.

iii) Design for ease of assembly - our design is easily assembled and disassembled and offers easy access to replaceable parts.

iv) Design for adjustable system parameters – our design allows for user definition and control of important parameters in the system, including temperature, rotational speed, and gas flow. This will not only allow specification of unique parameter values essential for continuous CNT growth but also aid in investigating the effects these different parameters on growth characteristics of CNTs.

v) Design for easy incorporation of future improvements – looking ahead, our team has designed our product such that there is room to incorporate additional improvements that could be made in the future as requested by our sponsor. These include the additional holes in the cutting chamber for the future use of additional gases for CNT removal, which can be plugged with NPT screws if not in use, as well as additional holes in the heater disc for future use of infrared sensors to aid in temperature sensing.

There are also some flaws and weaknesses with the existing design, some of which will require further research to develop more feasible solutions. These are discussed as follows:

(i) Insufficient motor torque – upon assembly, the motor was unable to generate sufficient torque to allow complete rotation of the rotational assembly including the coupler, shaft, magnet, and substrate wafer. Although the bearing material friction, lipseal material friction, and shaft inertia were known and accounted for in initial calculations, we were unable to predict the additional amount of pressure and force exerted on the shaft once the lipseal and bearing were pressed into place. Thus, the resistance against rotation encountered by the motor was underestimated.

(ii) Additional unnecessary parts – the stainless steel layer is an additional part that was lastly added to our design. This was due to the high cost of manufacturing the entire main processing chamber in stainless steel, due to the high cost of the material and high complexity of our part. Thus, we experienced delays in placing our order since we had to revise our design once we received the quote for our part. This additional part was added due to the high temperature requirements of our system and adds assembly time and parts to the overall assembly.

(iii) Inaccurate CNT removal – due to the large thickness of the edge of the razor blade as compared to the interface between the CNTs and the substrate, inaccurate removal of CNTs may result. Other forms of CNT removal have yet to be discovered and thus we were not able to employ any other method in achieving more precise CNT removal.

(iv) High power consumption- due to the high temperatures required in our system, the heater circuit design would draw large amounts of power and current. This results excessive energy losses through heat losses.

(v) Limited length of CNT film - due to space constraints in the CNT removal chamber, the device may only be run until the chamber is full, upon which the operation must be stopped and the CNT harvested before further growth.

(vi) Difficulty in mass production - the parts in our design were designed for single unit manufacturing in mind rather than for mass production. While some part may be easily mass produced through common processes like injection molding, some parts such as the ceramics and firebrick would be hard to manufacture at a large scale if necessary in the future due to the characteristics if the materials involved.

(VII) Inability to conduct full testing – due to the complexity of our design and incorporation of a number of systems, we were unable to test the entire design with the actual growth of CNTs given our extremely tight time constraint. With a little more than three months learn about the topics associated with our project, design, fabricate, assemble and test our final product, we were only able to conduct testing of subsystems, but were not able to test for all subsystems combined.

RECOMMENDATIONS AND FUTURE WORK

With our final design product built and assembled, there is still room for improvement and future work that would see the project to greater heights and improve the overall quality and function of our design. This is especially so since our design is a pioneer in attempting to achieve continuous growth of CNTs. We suggest that the following issues should be addressed, and we can begin addressing them in the following ways:

(i) Insufficient motor torque – the previous motor calculations (pg. 27) required 0.0128 Nm of torque, but measurements of the prototype using a torque wrench indicate a required torque of 2 Nm. For a safety factor, we will need a new motor with a torque range of 0-3 Nm. Since the use a stepper motor and the same controller are desired, we recommend the use of the Portescap NEMA 23 Hybrid Step Motor. This motor is rated at 3 Amps/phase, which provides a holding torque of 3.54 Nm. It also operates at 1.8 deg./step, so the speed calculations are still the same.

(ii) Additional unnecessary parts – given additional budget and the possible reduced cost in mass production, investigation into possibly manufacturing the whole processing chamber as one part. Although the insert is screwed into the main chamber, the effects of the interface of the insert and the chamber on gas flow pattern are unknown. To ensure complete gas seal at the interface, it would be ideal to have the bottom chamber as one piece of stainless steel.

(iii) Inaccurate CNT removal – more precise cutting methods may to be explored along with possible chemicals to aid the removal process.

(iv) High power consumption- although the current resistive wires can be used with transformers, other wires of different thicknesses should be considered to change the voltage and ampere required to heat the system to a more favorable combination. Alternatively, other sources of heating such as the use of micro-heaters may be explored.

(v) Limited length of CNT film - the physical size of the chambers was determined by the sizes of the substrate wafers to be used. If the testing of the system reveals actual growth of CNTs and proves the reusability of the catalyst, the volume of the CNT removal chamber can be increased by increasing the depth of the chamber.

(vi) Inability to conduct full testing – we strongly recommend that further testing be performed on the whole system to fine tune all details to allow smooth running of the device. Testing with actual growth of CNTs will be the next milestone in the continuation of this project, and will allows the users to continue using this device for CNT manufacturing purposes and/or research purposes to further the reach and discovery of this field of much potential.

INFORMATION SOURCES

Our team gathered information about two main areas associated with our projects, that being the properties and applications of CNTs, and the current methods that are being employed for the production of CNTs. The first area gives us some knowledge of how our project can make an impact on the industry. The latter provides some benchmarking examples from which we can gain insight into the current processes and how best to make our targeted process more efficient. However, since our project is a pioneer in making chemical vapor deposition (CVD) method a continuous process, our literature search could not be comprehensive.

Subsequently, we have also gathered information about some of the materials and components that may be incorporated into our design. The types of information obtained include pricing, method of purchase, component compatibility, material characteristics, available part sizes and dimensions.

PROPERTIES AND APPLICATIONS OF CARBON NANOTUBES

In the engineering field, CNT can form extremely strong structural composites with applications including vehicle armor, transmission line cables[3].The nanotubes also possess thermal properties that are desirable as electrodes in batteries and capacitors. Additionally, CNTs can be incorporated in fuel cell components and current collectors to further widen its applications in energy storage. Another major use of CNTs is as conductive adhesives and connectors. Moreover, carbon nanotubes are considered a very biocompatible material since the majority of a human body consists of carbon. Further studies conducted have shown that cells can grow on CNTs without attachment[3]. The immense potential of CNTs has led to biomedical applications including nerve control of prosthetics, accelerated cell migration, biosensor, neuron growth, and neuron regeneration.

CURRENT METHODS OF CNT PRODUCTION

There are currently three commonly used methods for producing CNTs: Arc discharge, laser ablation, and chemical vapor deposition (CVD)[4]. Arc-discharge requires a low voltage power supply which strikes an electrical arc between two carbon electrodes. Synthesis using arc-discharge typically yields ropy and multi-walled CNTS with carbon byproducts. The nanotubes form in the arc and are collected on the anode. The second process, laser ablation, uses a high power laser to raster across a carbon target. Single-walled nanotubes form and collect on a “cold finger” provided that the conditions are right. The last method, chemical vapor deposition, uses heat to generate reactive carbon gas molecules which attaches to the catalysts applied on the substrate. CNT will form under if the appropriate conditions are maintained. A closer look at CVD reveals that the method yields more desirable and controllable CNT traits: excellent alignment, position control, nanotube diameter, and growth rate. In addition, single-walled and multi-walled CNTs can both be produced with the use of different catalysts. However, current production using this method is extremely time consuming and inefficient, producing 1 inch of CNTs in each cycle that could require approximately 1 hour[5].

Making the production of CNTs using the CVD method continuous will make the process more efficient and cost effective. Together with the current advantages of the CVD method, the successful completion of our design presents potential benefit to many applications in the industry.

CURRENTLY UNAVAILABLE INFORMATION

Removal of CNTs from the substrate after growth is another crucial aspect of our project. However, since our project is the first attempt at making the CNT production process continuous, there is currently limited or no information about harvesting techniques available. The only method currently employed is the use of a small sharp razor to initiate the separation between the CNTs and the substrate surface. The rest of the CNT forest is then manually peeled off gently. We will thus use our knowledge of the properties of CNT growth at the interface, and attempt to explore and experiment with additional techniques of CNT removal, which may include chemical and thermal methods.

COMPONENTS AND MATERIALS FOR DESIGN FABRICATION

The components to be incorporated into our design include heating components, magnets, viewport, motor and gear box, temperature sensing devices, glass plates, pipe fittings, lip seals and bearings.

“Pie wedged” heater segments will be employed in our design to provide external local heating of the substrate discs. Since we require different heater segments of different temperature and unique geometry, we have decided to purchase resistive heating wire separately and machine our own heater casing to hold these wires in the configuration desired. The wires must be able to attain high enough temperatures for the CNT growth operations of up to 1000°C. Resistive heating wire made out of Nickel-Chromium Alloy (80% Nickel/20% Chromium – NI80) has a maximum temperature or 2100°F/ 1148°C [2], which is above our required temperature and allows for some heat loss due to gas flow, conduction, and other heat loss mechanisms. Moreover, if the configuration allows higher concentration of heating wires in an area, we will be able to attain higher temperatures. This heating wire is also affordable, costing about \$10- \$20 per 50 ft of wire. [6]

Firebrick material has high insulating properties, with a low thermal conductivity of 0.19 W/mK at a temperature of 1100ºC[6]. This is a hundred times smaller than the thermal conductivity of stainless steel, which has a value of 19 W/mK at a temperature of only 225ºC[7]. The composition of this firebrick material is primarily Alumina, Al_2O_3 (47%), and Silica, SiO_2 (38%) [6]. This material is also very machinable and thus would be appropriate for use in our design as the insulating material between the heating element and the outer casing.

Due to the high temperatures associated with the CNT growth process, we need magnets with higher operating temperature ranges. Aluminum-Nickel-Cobalt (AlNiCo) magnets and Samarium Cobalt magnets were found to have the highest temperature ranges. Cast and sintered AlNiCo is very temperature stable with maximum working temperature of 975° - 1020° F (~550°C).[8] Samarium Cobalt also has high temperature stability, however, it is more expensive is cobalt is market price sensitive.[8] The maximum operating temperature for Samarium Cobalt magnets are also lower than that of AlNiCo magnets, around 200°C. Although the operating temperature of the process might reach up to 1000°C, since the magnet is not in the direct line of heating, we do not expect the temperature at the magnet to be as high as that of the substrate at the growth region. In the case where the peripheral of the magnet exceeds the maximum operating temperature, if the magnet is sufficiently thick, the center of the magnet will still retain its magnetism. The substrate disc is also very thin and light, and thus the magnetic force needed to hold the substrate and keep it rotating will be very small.

To hold the magnet in place during the operation of our device, we found a steel cap magnet holder that holds the magnet through magnetic forces between the magnet and the steel. A hole at the bottom of the holder also allows us to attach this holder to the rotating shaft that is connected to the motor and gear box configuration[9]. For the purposes of our design, the most suitable size of the magnet holder would be one of 0.875 inches outer diameter, allowing for maximum magnet diameter of 0.75 inches and minimum magnet thickness of 0.125”[9]

To enable the user to monitor the progress and growth of the CNTs, the incorporation of a view port is desirable. Instead of creating our own view port using a borosilicate glass plate and separate air tight seals such as o-rings, there are available alternative options in the market. One such feasible alternative is a UHV series vacuum view port from MDC Vacuum. In incorporates a UV series fused silica center plate, a stainless steel flange that withstands high temperature and a Del-Seal™ CF flange [10]. This has a flange outer diameter of 2.75 in and 1.2 in diameter of viewing glass.

To ensure that the substrate is at the required temperature for the different stages of growth, monitoring the temperature is essential. We explored the use of infrared temperature sensors to measure the temperature of the substrate. These sensors have different focal lengths and must be chosen according to the distance from the surface at which sensing will occur. [11] However, these IR sensors require direct line of sight with the surface of temperature measurement. This may not be feasible in our design, and thus alternative means of temperature sensing such as the use of thermocouples may be employed in our design.

For the glass plate that separates the top section and bottom section of our device, quartz or borosilicate are two feasible materials that can be used as both are transparent and have high heat resistance. A quartz plate that is 10 inches in diameter and is 1/16” thick, ground and polished will cost $368.87 [12]. However, we may not need such high quality finishing on the quartz plate. Our requirements are simply that the plate be clear, and its surfaces be flat to enable us to use o-rings for effective sealing. Thus further research and sourcing may be conducted to explore cheaper alternatives that will still be feasible for our design.

From the geometry of our design, we decided to use an AS568A-272 O-ring made out of Viton material, which has excellent chemical and fluid resistance properties[9]. This O-ring also has high heat resistance of up to 400ºF (204ºC) and thus is ideal for our application. Using standard guidelines for groove dimensions, we determined that a groove width of 4.8mm (0.18898 in) and groove depth of 2.7mm (0.10630 in) are required [13].

In order to ensure air tight sealing at every single inlet and outlet hole, we explored the use of ultra-torr vacuum fittings from Swagelok [14]. The body, nut and sleeve of this vacuum seal is made of stainless steel which withstands high heat and corrosion. A 70 durometer fluorocarbon FKM o-ring is also incorporated into the seal, with temperature rating of -31°C to 204°C [14]. Moreover, this design has been helium leak tested and thus is suitable for use in our application. When including these seals in our design, particularly at the bottom of the processing chambers, we need to make sure that the inlet and outlet holes are spaced with sufficient clearance for the hex nuts that come with the vacuum seal. From the Swagelok catalogs[14], we determined that for ¼" NPT holes, we need to account for an 11/16" nut outer diameter, while 1/8" NPT holes will require space for 9/16" nut outer diameter.

In order to ensure air tight sealing where the rotary shaft enters the chamber, we are using a Viton lipseal. A flange will hold the lipseal tight to the chamber and the inner diameter is tight against the shaft. Also, two PTFE dry sleeve bearings enclosed in aluminum housing will act to stabilize the rotary shaft directly before it enters the lipseal. Both of these parts are ordered from McMaster-Carr.

CONCLUSIONS

Carbon nanotubes (CNTs) are long molecules having exceptional properties, including high strength, high thermal conductivity and high electrical conductivity, with a wide variety of applications. Current methods for producing CNTs do not allow for continuous processing of CNT forests as yet, and are time-consuming and inefficient. Thus, the main objective of our ME 450 project is to design a mechanism that will allow for continuous processing of CNT forests using the Chemical Vapor Deposition (CVD) method, under the sponsorship of Professor Anastasios John Hart, Mechanical Engineering, and the University of Michigan. The successful design and fabrication of such a device would allow for continuous production of larger amounts of CNT films in less time, and the potential for scaling this process up for large scale production of CNTs will be extremely valuable to the currently expanding market for CNTs.

Our final design product is a desktop-scale machine for continuous manufacturing of CNT forests on a substrate coated with growth catalyst. The process must be contained within a sealed reaction chamber, and will require heating of a flammable gas atmosphere up to 800-1200° C. In order to achieve the main project goals, the three main fundamental engineering concepts that need to be addressed are the continuous growth process, restricted gas flow within the device, and the high temperatures required for the process.

The customer requirements and engineering specifications were analyzed and prioritized using a Quality Function Deployment diagram. Subsequently, four main assemblies of our design were identified through functional decomposition to be- (1) Heater assembly,

(2) Flow assembly, (3) Rotational assembly, and (4) CNT removal assembly. With this in mind, we generated various concepts for each of the main assemblies, and integrated these to obtain five main concept ideas, with additional variations of each general idea. Using a scoring matrix, a final concept was chosen and a three-dimensional CAD model created.

To perform engineering design parameter analysis, our team employed the use of a determined set of steps in the following order- i) identify critical part requirements, (ii) identify possible failure scenarios, (iii) experimentation/analysis, (iv) contacting suppliers/manufacturers, (v) design revision, (vi) finalize parameters. These steps were performed for each critical part/ subsystem of our design. These were identified to include the upper and lower chamber casing, the insulation roof (firebrick insulator), the heater disc, porous ceramic gas diffuser (showerhead), heater wire, motor assembly, magnet, pipe fitting, and project control system.

Once the required or desired parameters were determined, we proceeded to revise our CAD models and produced the engineering drawings in preparation for fabrication. Subsequently, a fabrication plan was developed and a parts list was collated. The components were divided into three main categories- (1) off-the-shelf components, (2) parts to be outsourced to external manufacturers, and (3) parts to be machined in-house at the University of Michigan. Parts that were machined in-house involved water-jetting, milling and drilling. Assembly of our parts mostly involved standard sized screws, with additional use of cement to bond the ceramic layer to the top of the showerheads.

To demonstrate that the customer requirements and engineering specifications have been met with our final device, a validation approach was devised and performed upon completion of our design product. Although we could not demonstrate CNT growth with our prototype, the validation determined that all customer requirements were met in the design.

Our final design product has some strengths and weaknesses. The main strengths include uniform gas delivery through use of porous ceramics, design for adjustable parameters, and design for incorporation of future additions and improvements such as infrared sensors. Some main weaknesses of our design include insufficient motor torque, high power consumption, and inability to conduct full testing with growth of CNTs. Given the time constraints, our team has made considerable achievements, and gained much knowledge and invaluable experience. However, we feel there is still room for improvement and future work that would see the project to greater heights and improve the overall quality and function of our design. This is especially so since our design is a pioneer in attempting to achieve continuous growth of CNTs. Use of a higher torque rated Portescap NEMA 23 Hybrid Step Motor is suggested and testing with actual growth of CNTs is strongly recommended to allow successful operation of the device.

ACKNOWLEDGEMENTS

We would like to acknowledge the contributions of:
Anastasios John Hart, Professor - Mechanical Engineering, University of Michigan;
Jyotirmoy Mazumder, Professor - Mechanical Engineering, University of Michigan;
Guru Prasad Dinda, Intermittent lecturer - Mechanical Engineering, University of Michigan;
Steve L Ceccio, Professor - Mechanical Engineering;
Robert Coury, Senior Engineering Technician- Department of Mechanical Engineering, University of Michigan;
Marve Cressey, Senior Engineering Technician- Department of Mechanical Engineering, University of Michigan;
Kent Pruss, Senior Engineering Technician- Department of Mechanical Engineering, University of Michigan; Steve Erskine, IMS Lab Res Spec, University of Michigan;
Sameh Tawfik, PhD Pre-candidate – Mechanical Engineering, University of Michigan
Eric Meshot, PhD Pre-candidate – Mechanical Engineering, University of Michigan

REFERENCES

[1] Kevin Otto, http://www.kevinotto.com/RSS/templates/QFD Template.xls, 2005

[2] Newport Electronics, Inc. http://www.newportus.com/Products/Wire/NI80.htm, 2003. California, USA

[3] Azonano.com Pty Ltd. www.azonano.com, 2006. New South Wales, Australia.

[4] Maria Letizia Terranova, Vito Sessa, and Marco Rossi. "The World of Carbon Nanotubes: An Overview of CVD Growth Methodologies" Wiley InterScience (2006): 315-325.

[5] John Hart, Anastasios, Lucas Van Laake, and Alexander H. Slocum. "Desktop Growth of Carbon-Nanotube Monoliths with in Situ Optical Imaging." Small (2007): 772-777.

[6] Thermal Ceramics, http://www.thermalceramics.com/upload/features/Lphyproperties.jpg, 2000. Gerogia, USA

[7] The Engineering Toolbox http://www.engineeringtoolbox.com/thermal-conductivity-d_429.html, 2005.

[8] The Magnet Source, Master Magnetics, Inc. http://www.magnetsource.com/Solutions_Pages/whichmaterial.html, 2007. Colorado, California, Florida, Ohio, USA.

[9] McMaster-Carr. http://www.mcmaster.com/, 2008. USA

[10] MDC Vacuum Products, LLC. http://www.mdcvacuum.com/urd/uniface.urd/ecf0070w.display?5.1.2.1, 2006 California, USA.

[11] Exergen Corporation, http://www.exergen.com/industrl/irtc/index.htm, 2005. Massachusetts, USA

[12] Prism Research Glass, http://www.prismresearchglass.com/product.aspx?productID=1031&quartz-disc-1/16-in.-ground-an, 2008. North Carolina, USA

[13] EPM, Inc. "The Seal Man's O-ring Handbook" http://www.thesealman.com/pages/oring_handbook/pdf_files/epm_oring_hbpt3.pdf

[14] Swagelok, http://www.swagelok.com/downloads/webcatalogs/EN/MS-01-32.pdf, 2008. USA

[15] "Bearings 101." http://www.bearings.machinedesign.com/guiEdits/Content/BDE_6_1/bdemech6_3.aspx Machine Design. 2008. Penton Media, Inc, & Machine Design Magazine. Feb. 2008

[16] "Nonmetallic Bearings." http://www.sdp-si.com/D790/HTML2/D790C05023_1.html Stock Drive Products / Sterling Instrument. 2007. Feb. 2008

APPENDIX A: CONCEPT GENERATION

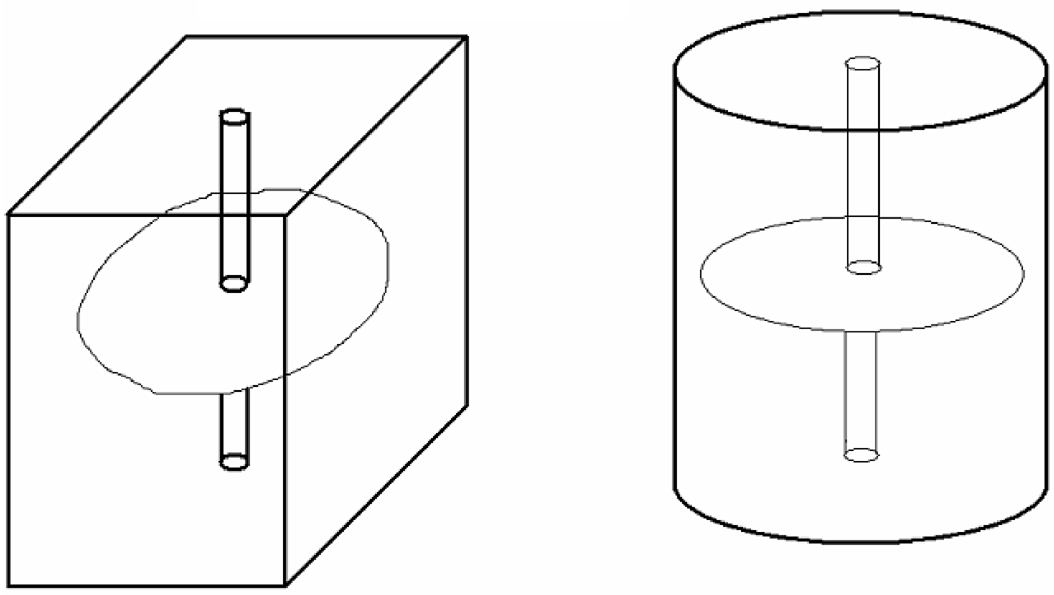


Figure 53. Chamber shape

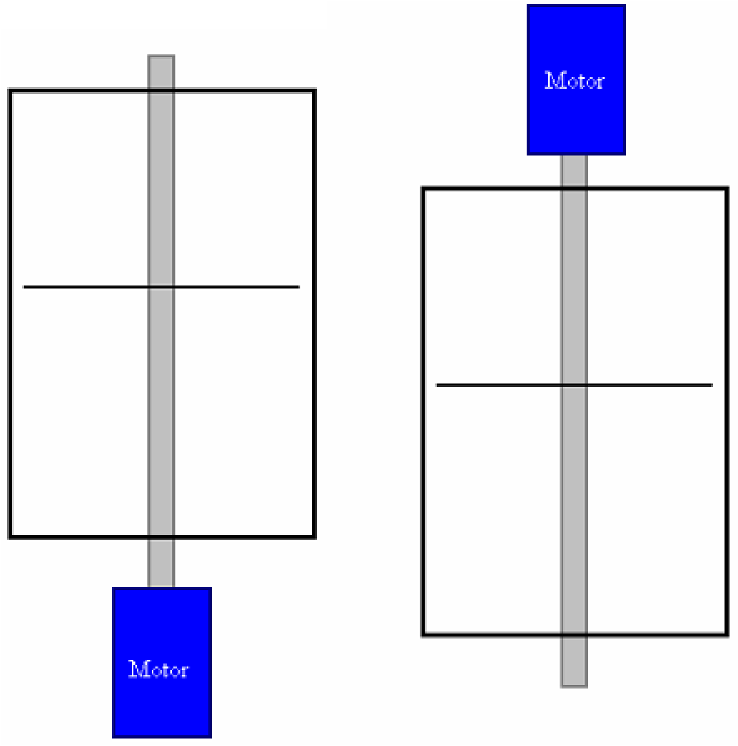


Figure 54. Motor position

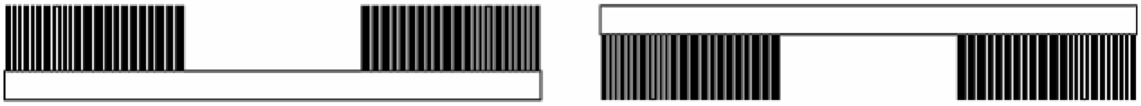


Figure 55. CNT growth position

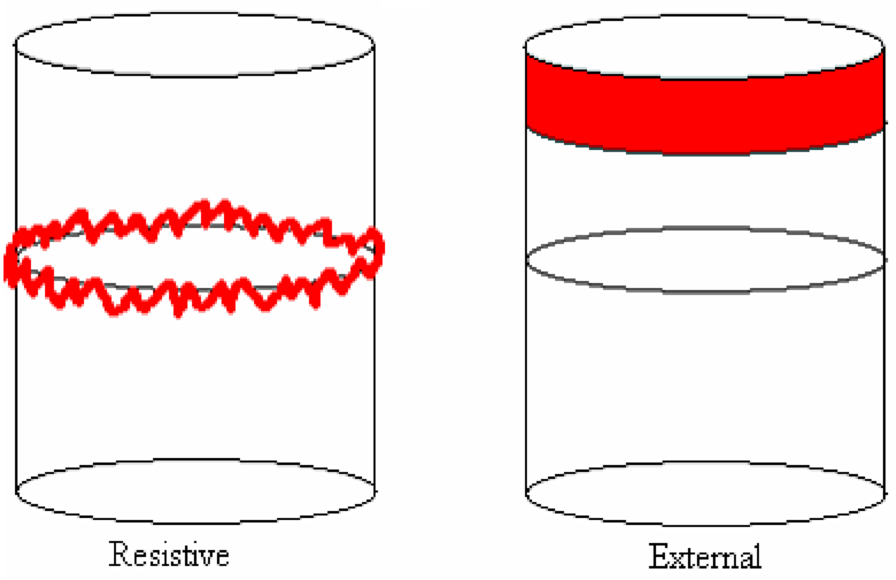


Figure 56. Heating method

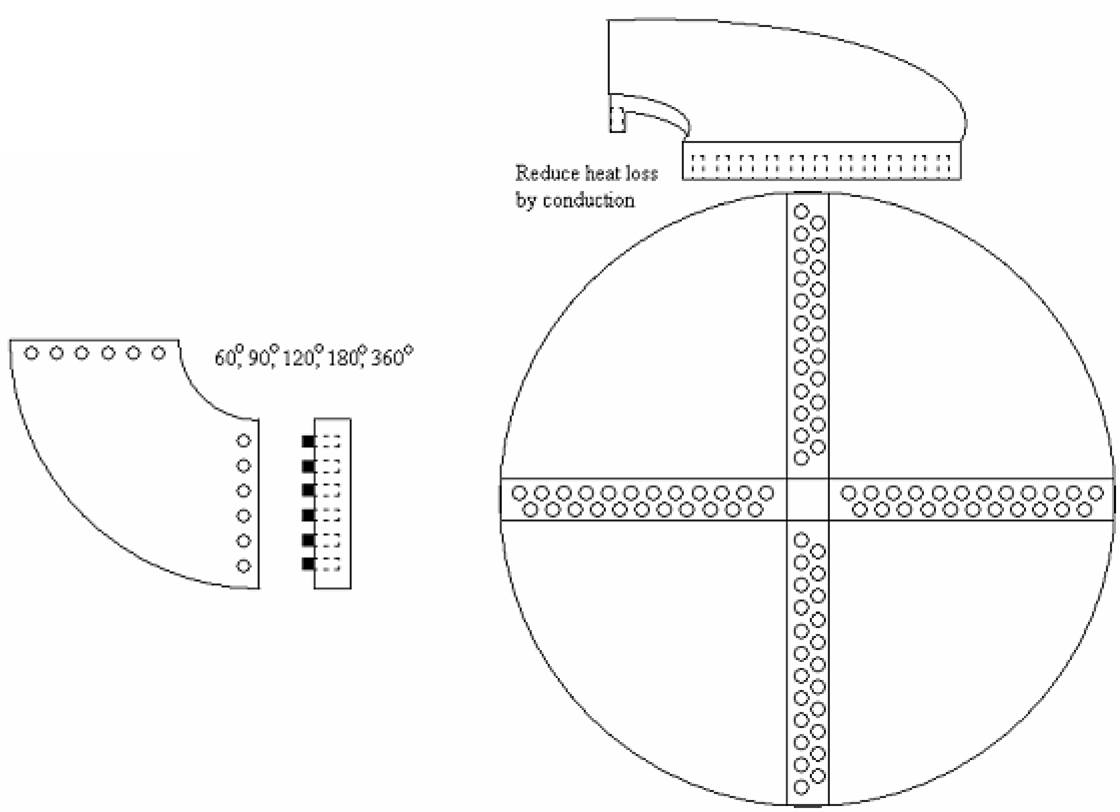


Figure 57. Heater configuration

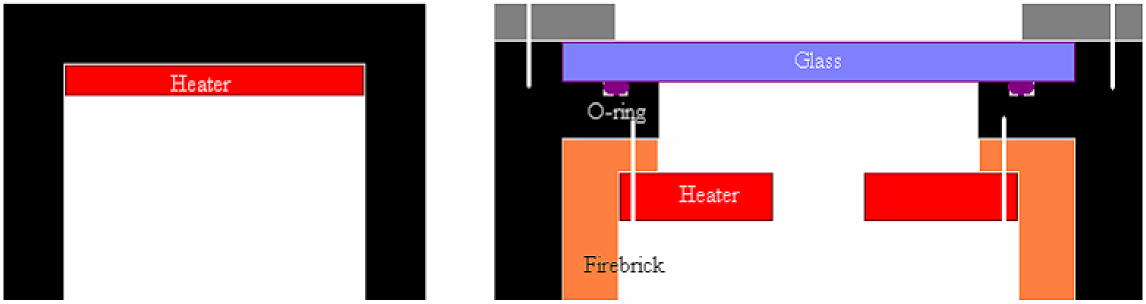


Figure 58. Top chamber configuration

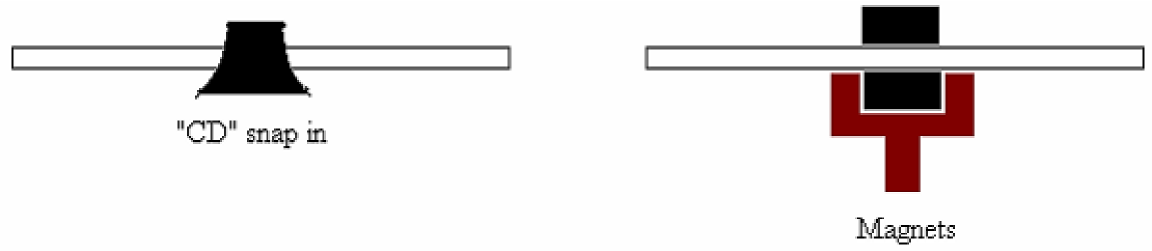


Figure 59. Substrate wafer holder

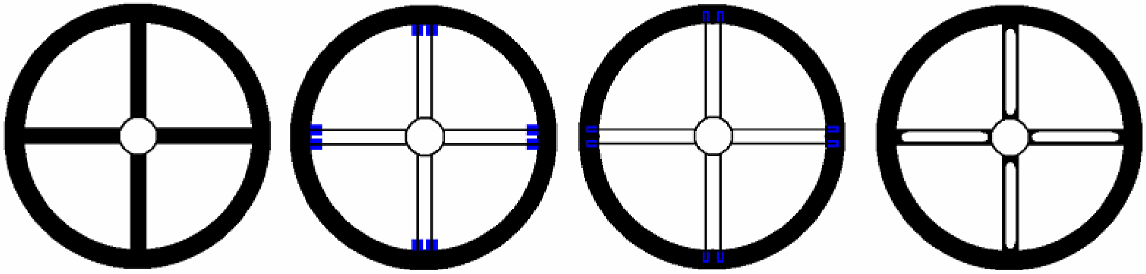


Figure 60. Gas separation method

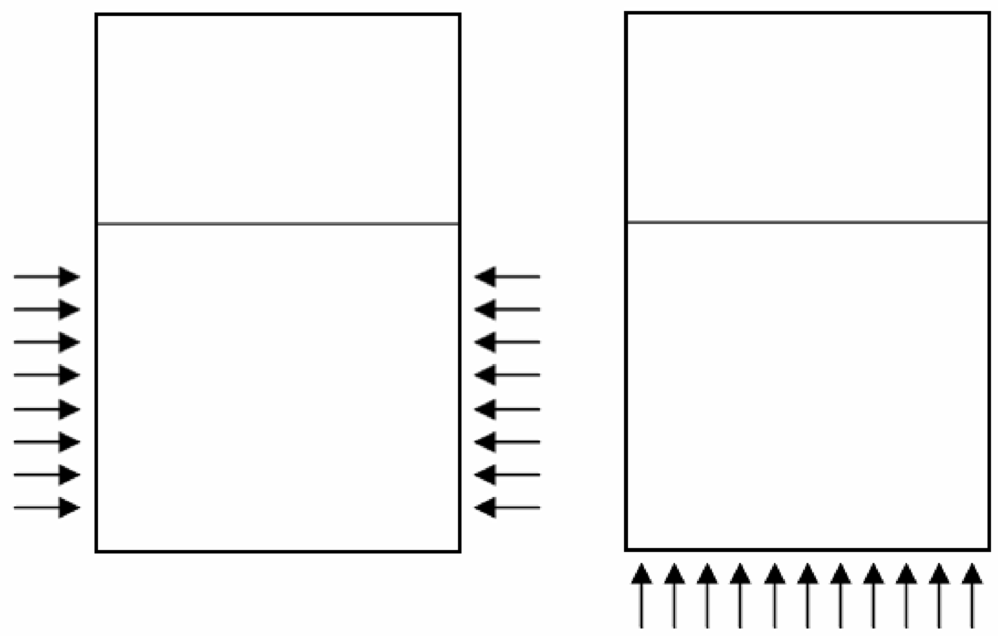


Figure 61. Gas inlet position

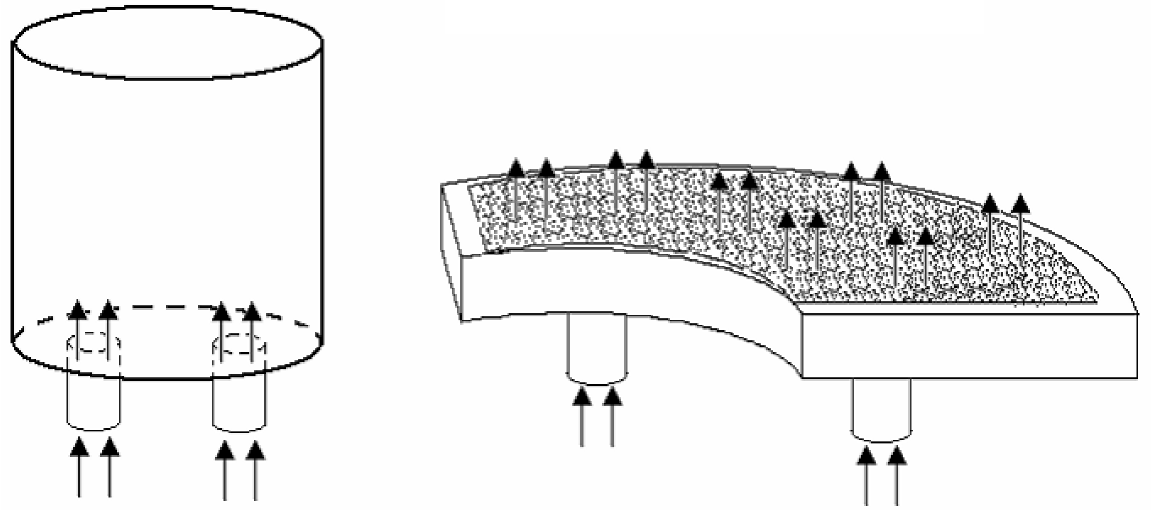
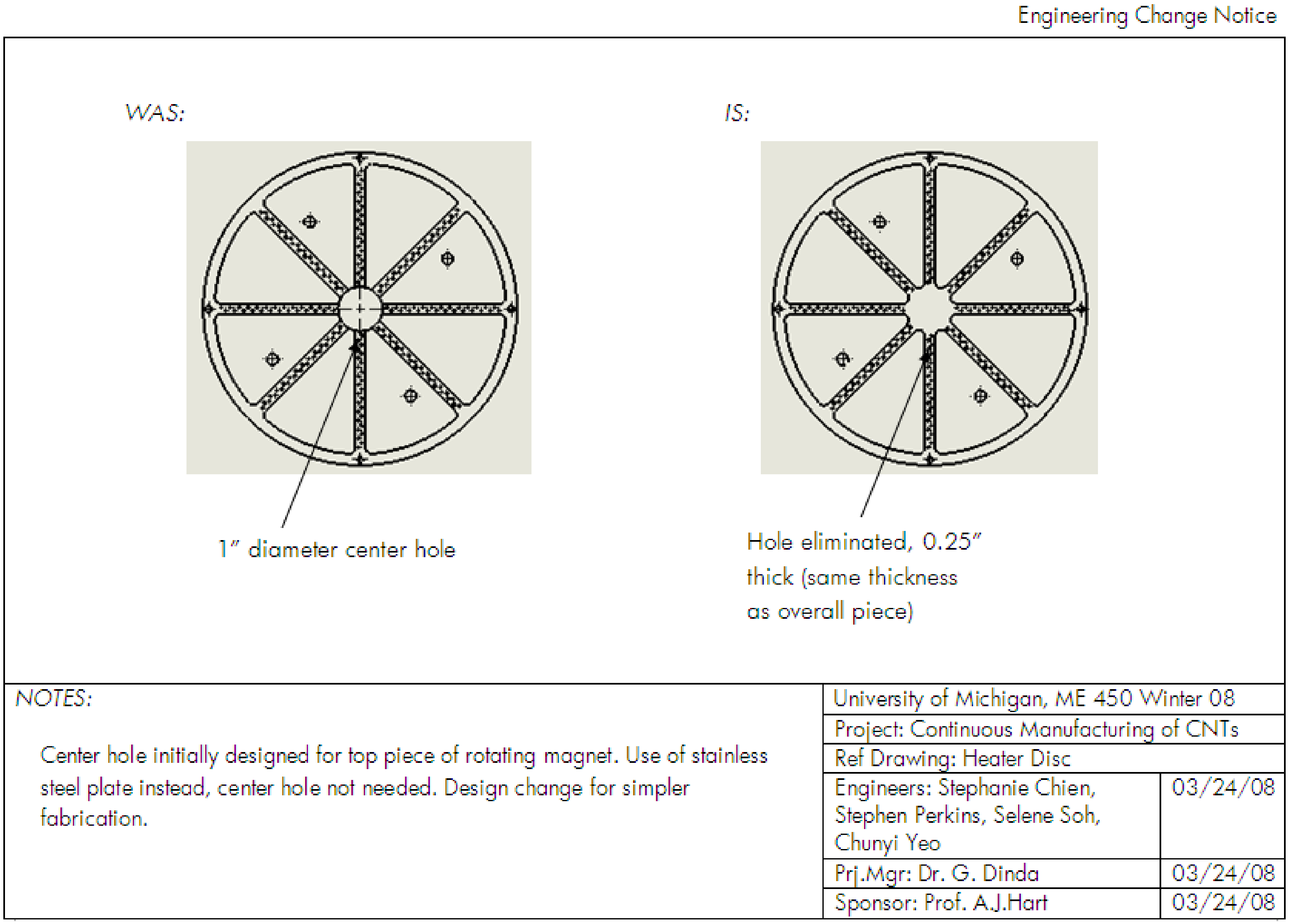


Figure 62. Gas delivery method

APPENDIX B: ENGINEERING CHANGE NOTICES



Engineering Change Notice

WAS:

1" diameter center hole

IS:

Hole eliminated, 0.25" thick (same thickness as overall piece)

NOTES:

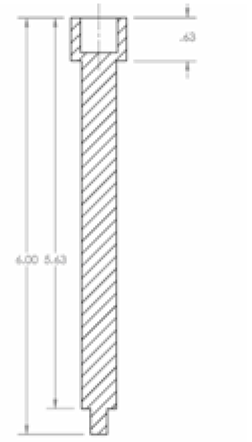
Center hole initially designed for top piece of rotating magnet. Use of stainless steel plate instead, center hole not needed. Design change for simpler fabrication.

University of Michigan, ME 450 Winter 08	
Project: Continuous Manufacturing of CNTs	
Ref Drawing: Heater Disc	
Engineers: Stephanie Chien, Stephen Perkins, Selene Soh, Chunyi Yeo	03/24/08
Prj.Mgr: Dr. G. Dinda	03/24/08
Sponsor: Prof. A.J.Hart	03/24/08

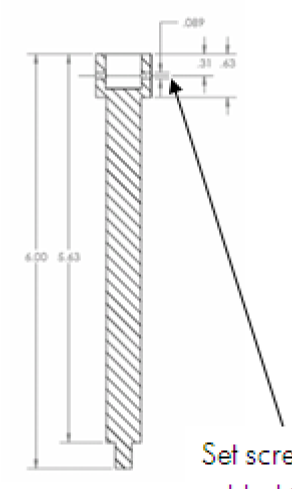
Figure 63. Engineering change notice for heater disc

Engineering Change Notice

WAS:



IS:



Set screw holes added to secure magnet

NOTES:

Initially design assuming magnetic properties of stainless steel shaft. Upon arrival, magnetic properties not sufficient to hold magnet, thus set screws are needed to secure magnet in place

University of Michigan, ME 450 Winter 08	
Project: Continuous Manufacturing of CNTs	
Ref Drawing: Magnet holder + shaft	
Engineers: Stephanie Chien, Stephen Perkins, Selene Soh, Chunyi Yeo	03/24/08
Prj.Mgr: Dr. G. Dinda	03/24/08
Sponsor: Prof. A.J.Hart	03/24/08

Figure 64. Engineering change notice for Magnet holder and shaft

APPENDIX C: ENGINEERING DRAWINGS

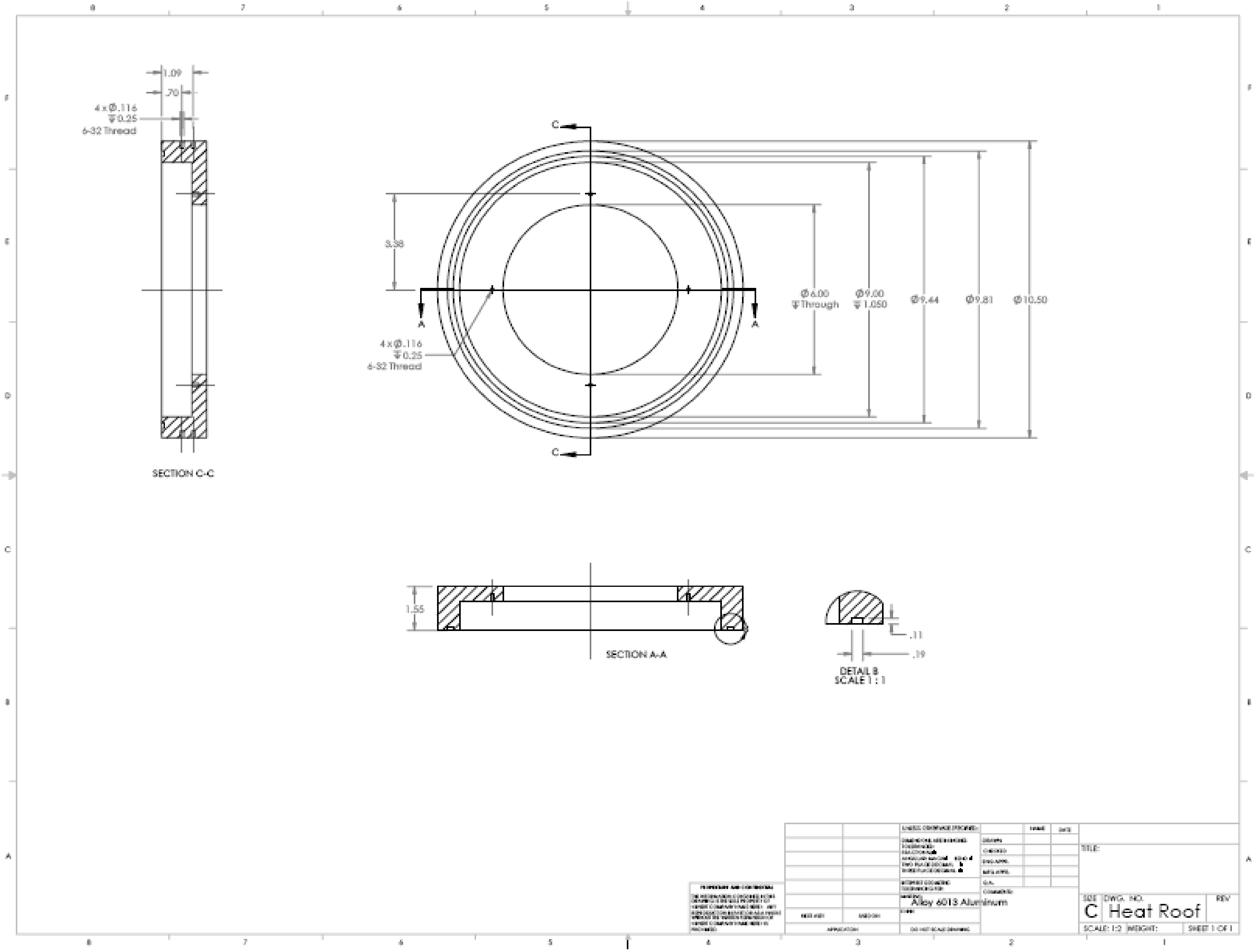


Figure 65. Engineering drawing of Outer wall casing

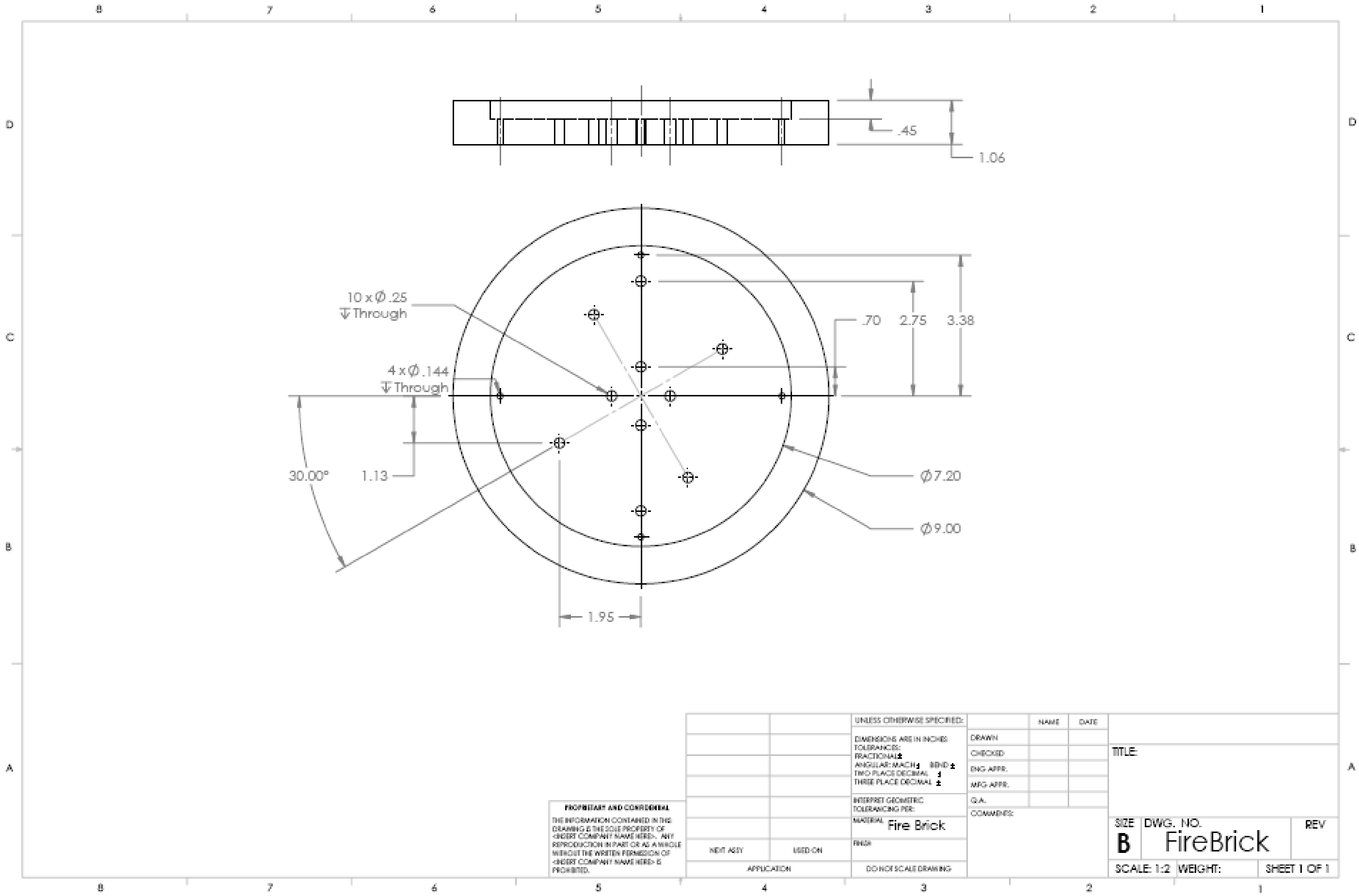


Figure 66. Engineering drawing of Firebrick Insulator

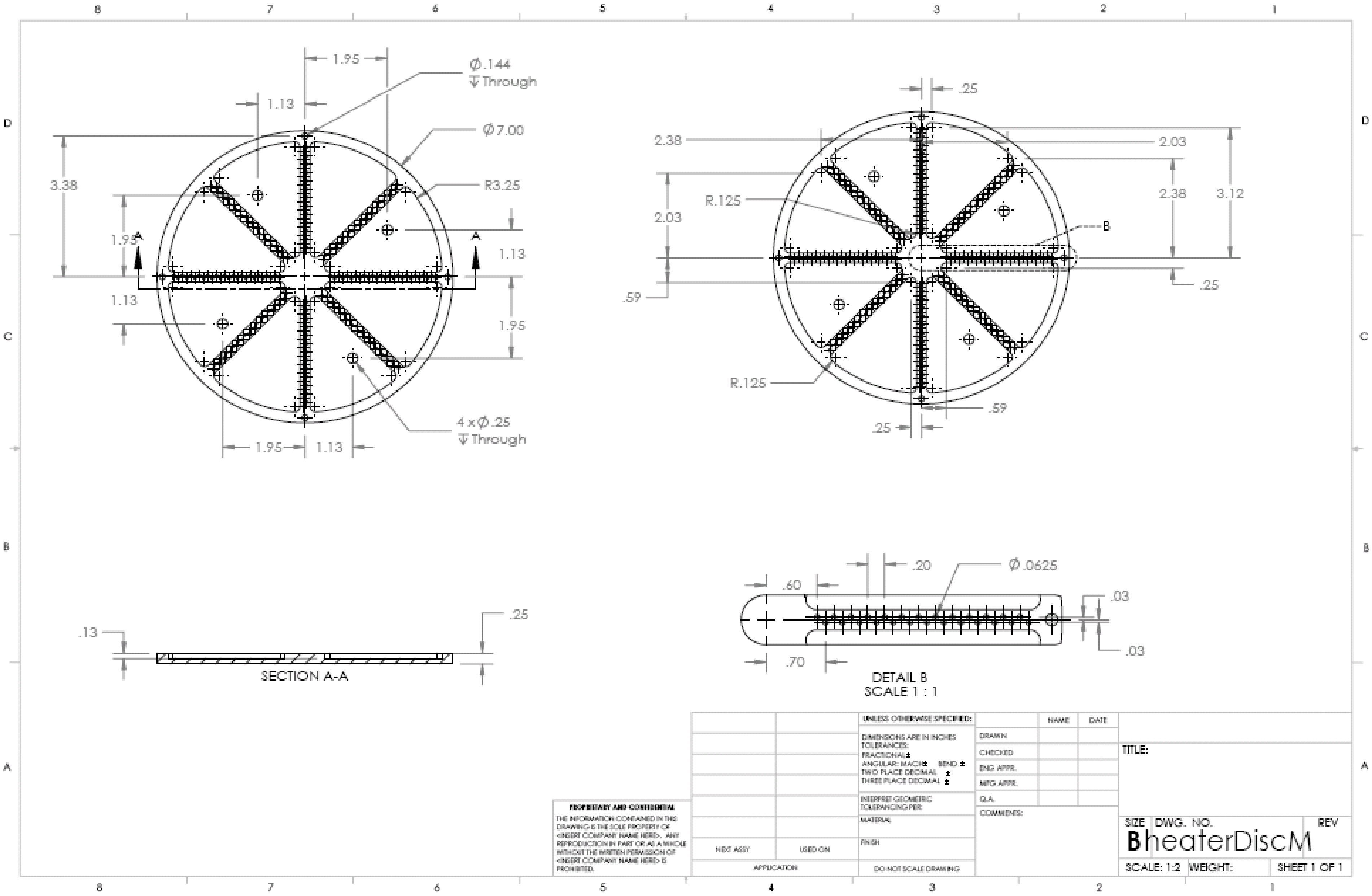


Figure 67. Engineering drawing of Heater Element

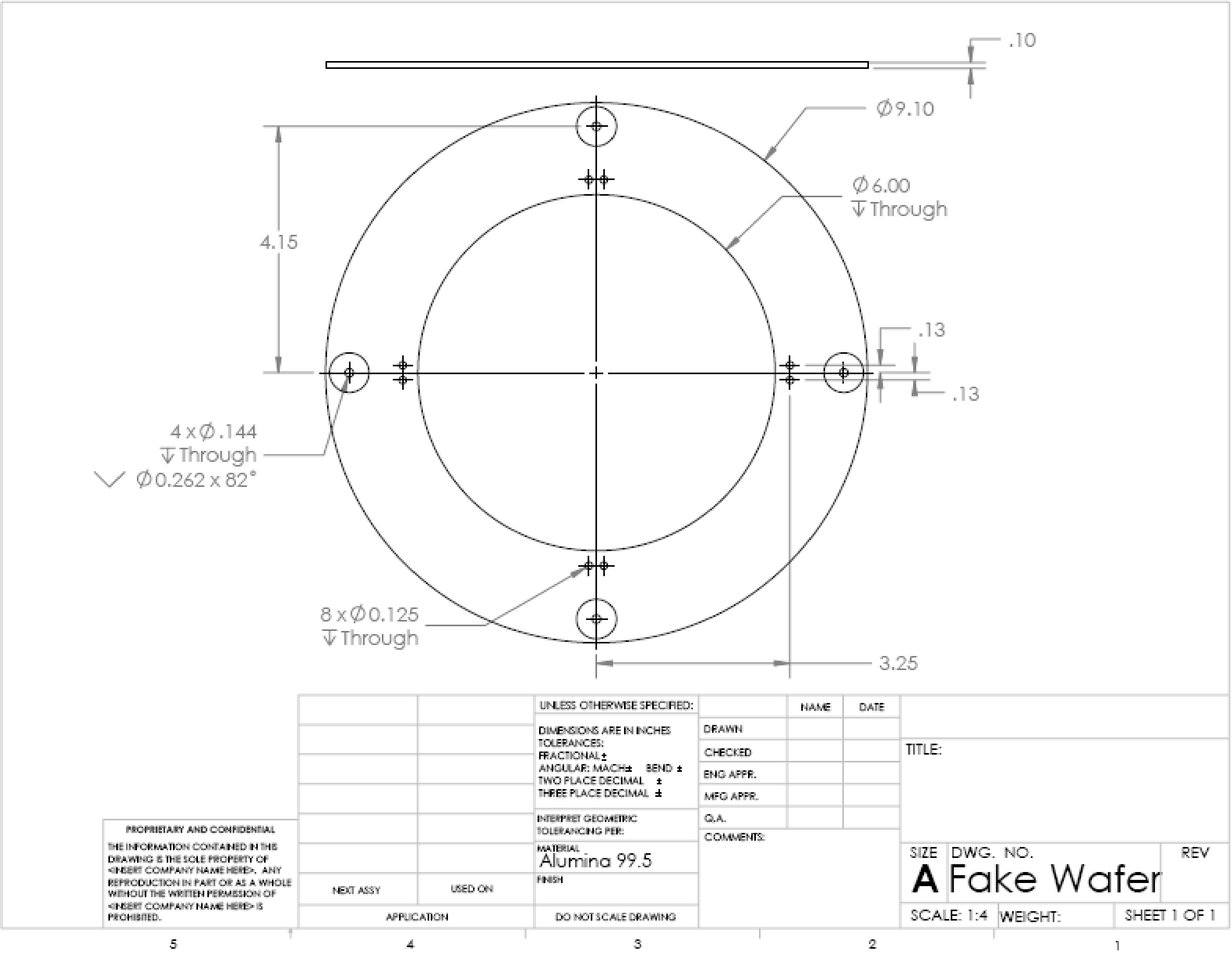


Figure 68. Engineering drawing of 6-inch Fake Wafer

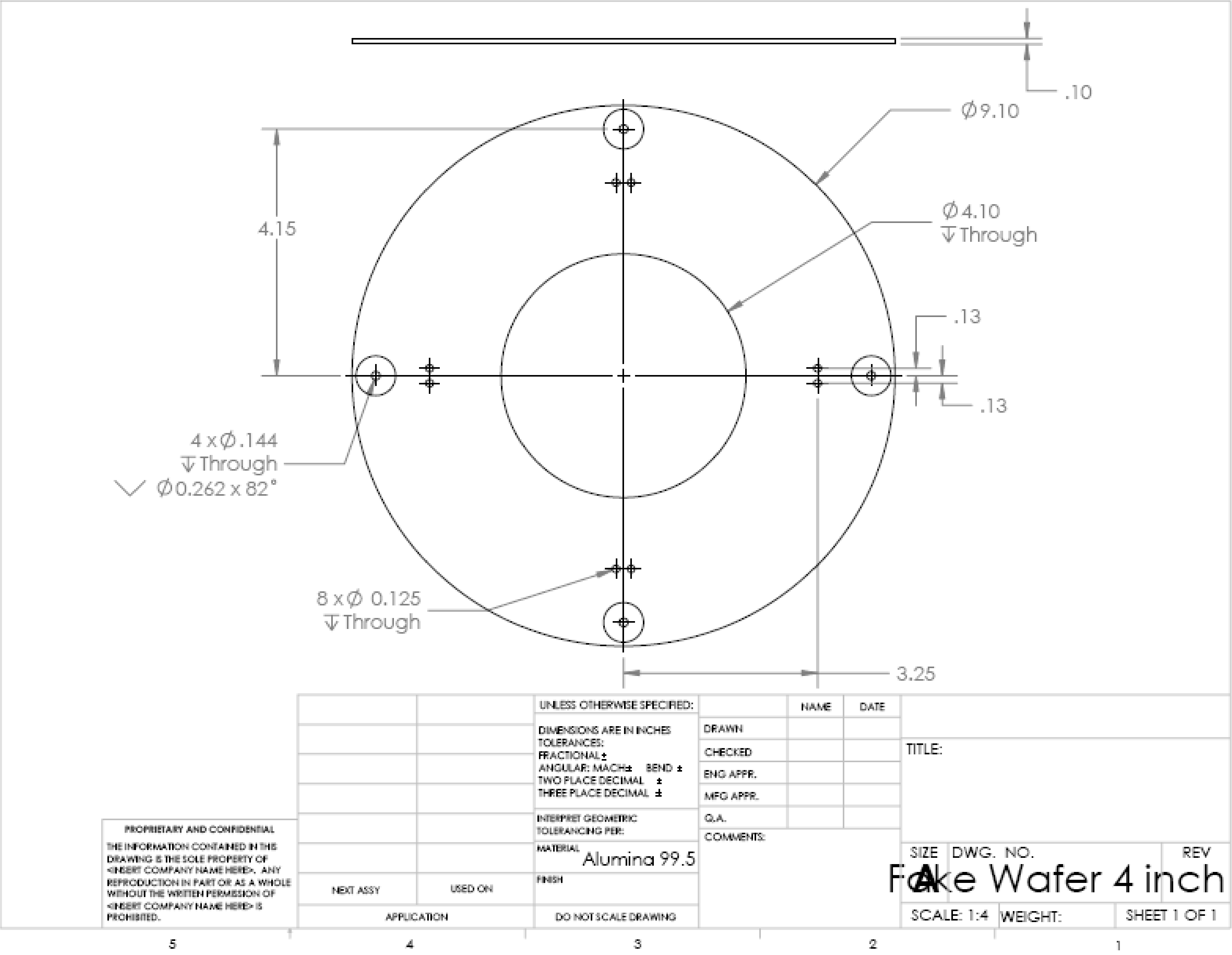


Figure 69. Engineering drawing of 4-inch Fake Wafer

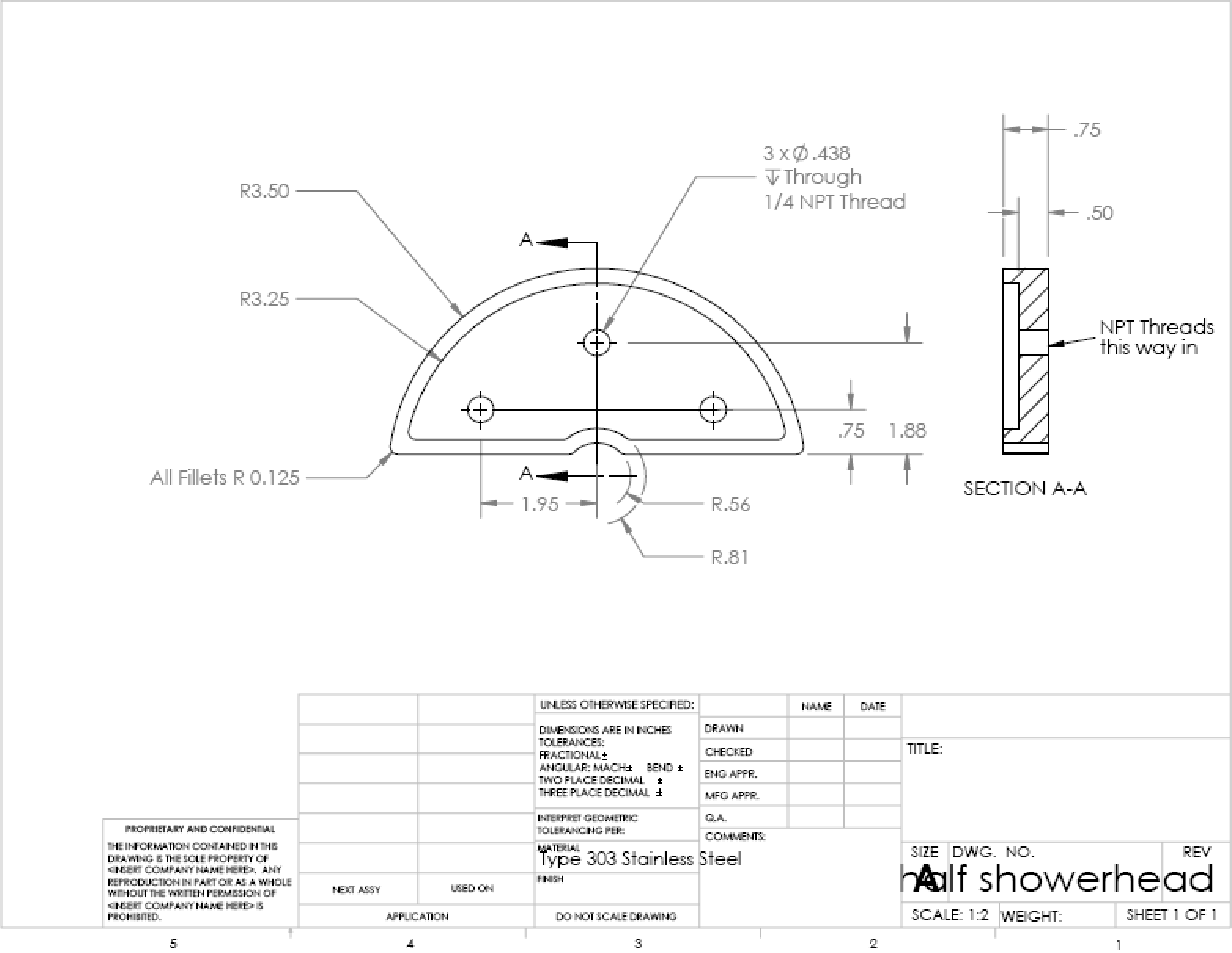


Figure 70. Engineering drawing of Half showerhead

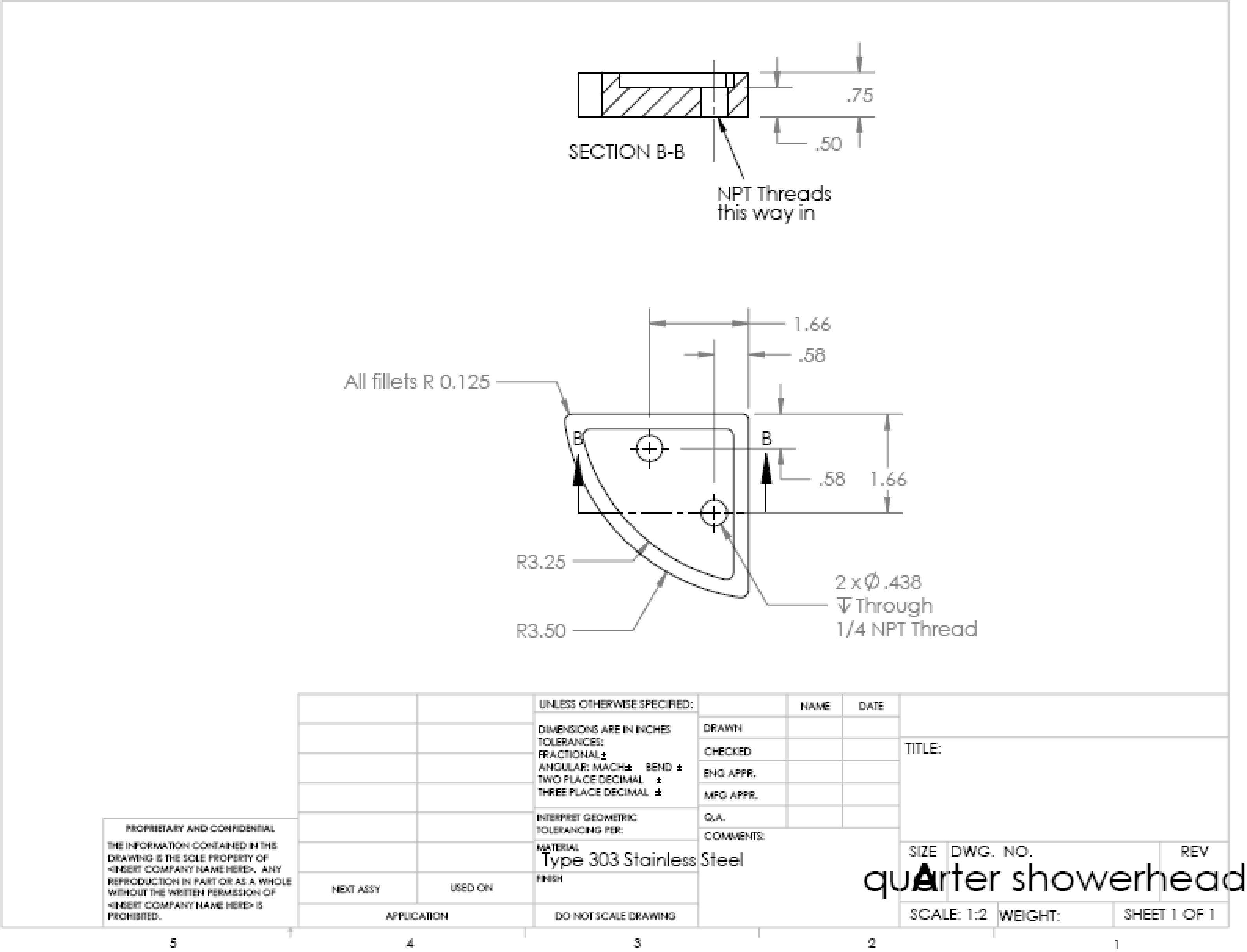


Figure 71. Engineering drawing of Quarter showerhead

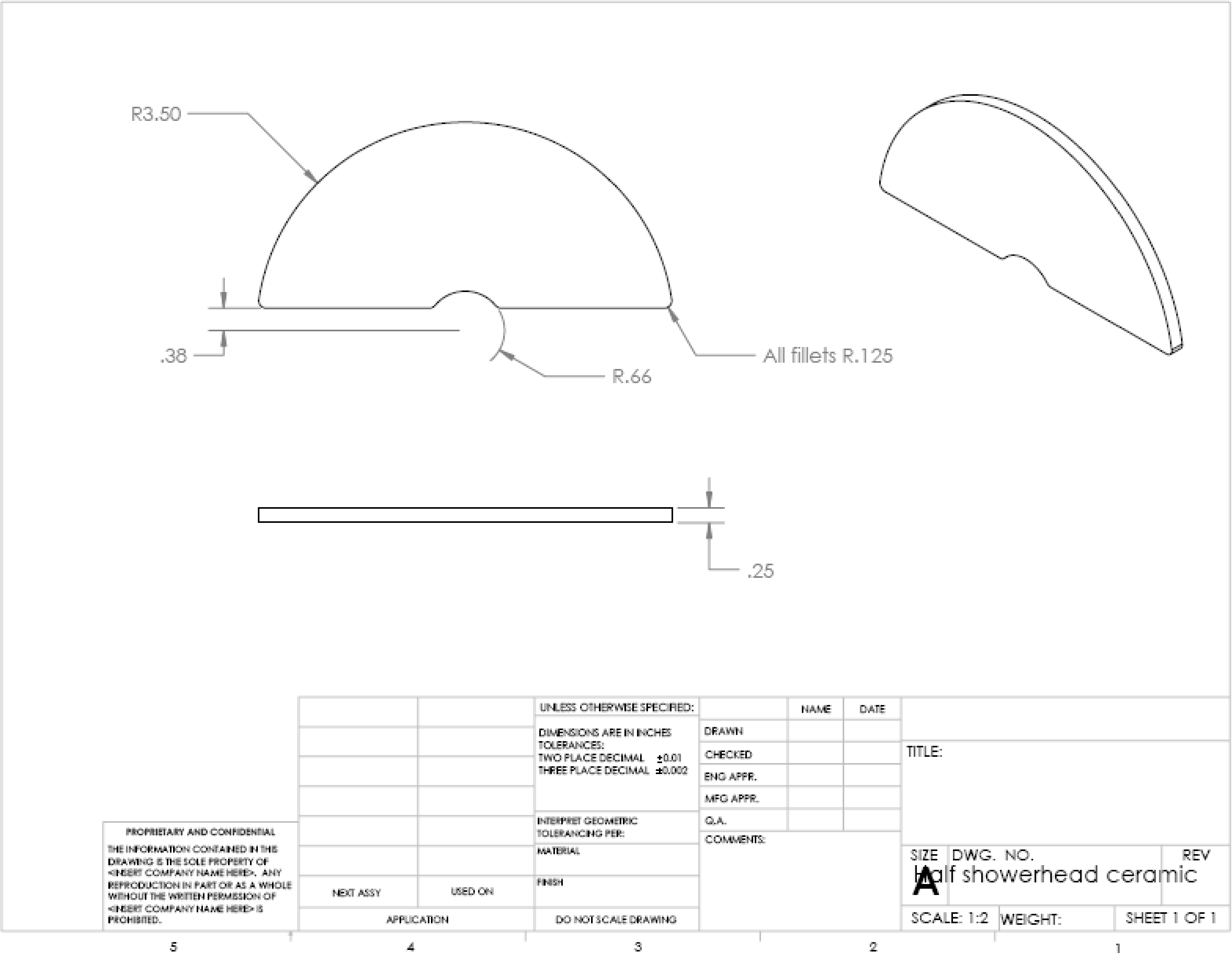


Figure 72. Engineering drawing of Half showerhead ceramic

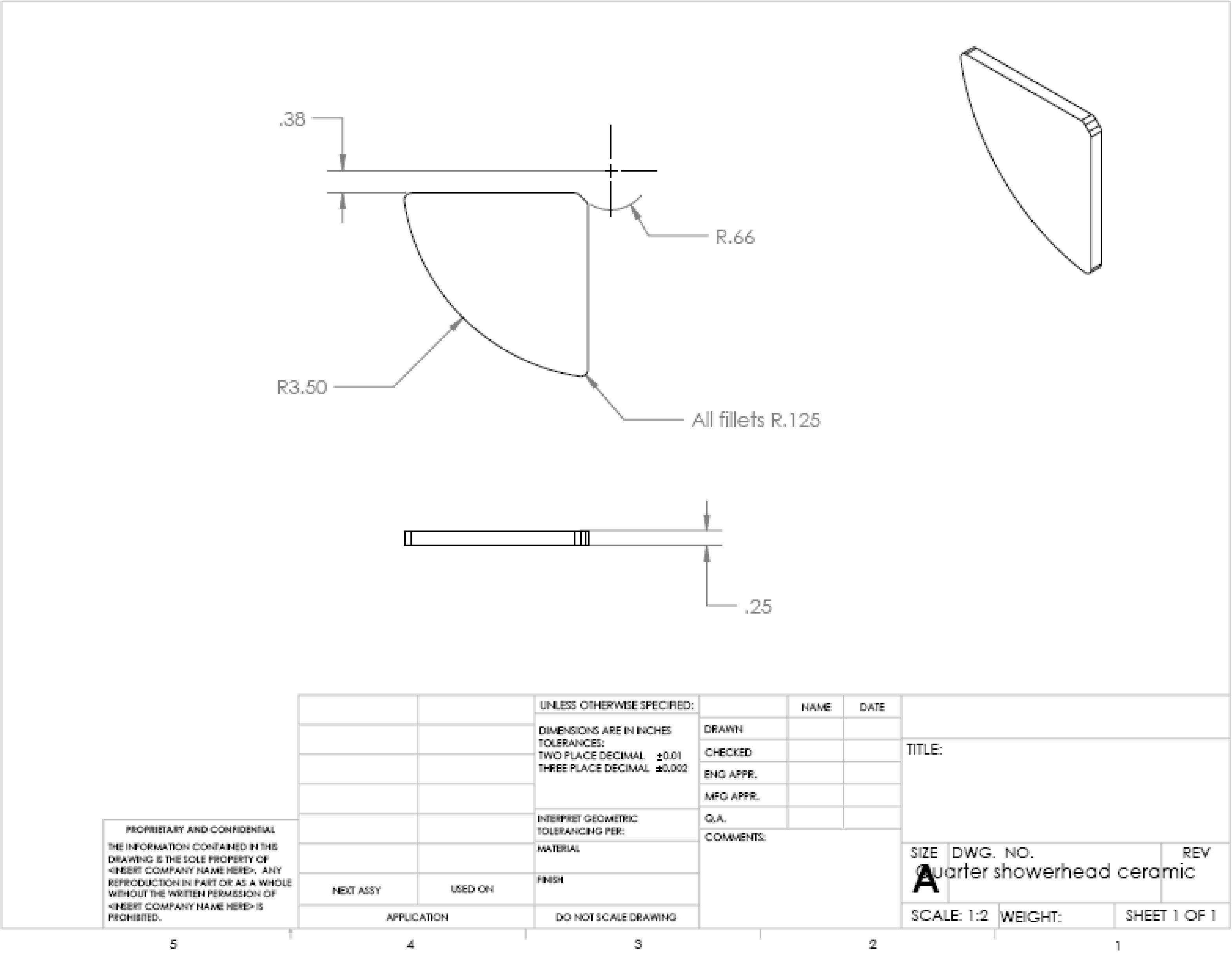


Figure 73. Engineering drawing of Quarter showerhead ceramic

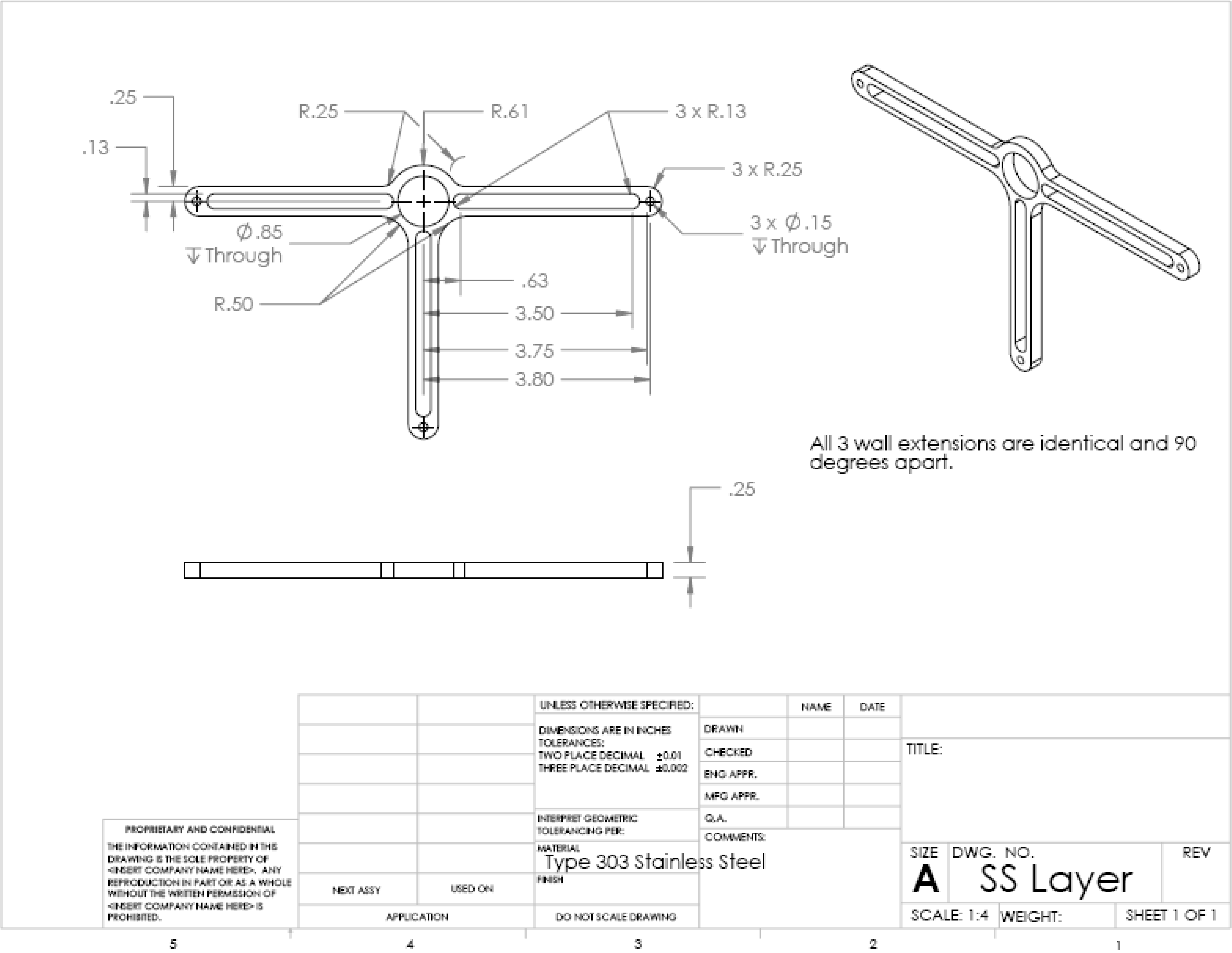


Figure 74. Engineering drawing of Stainless steel insert

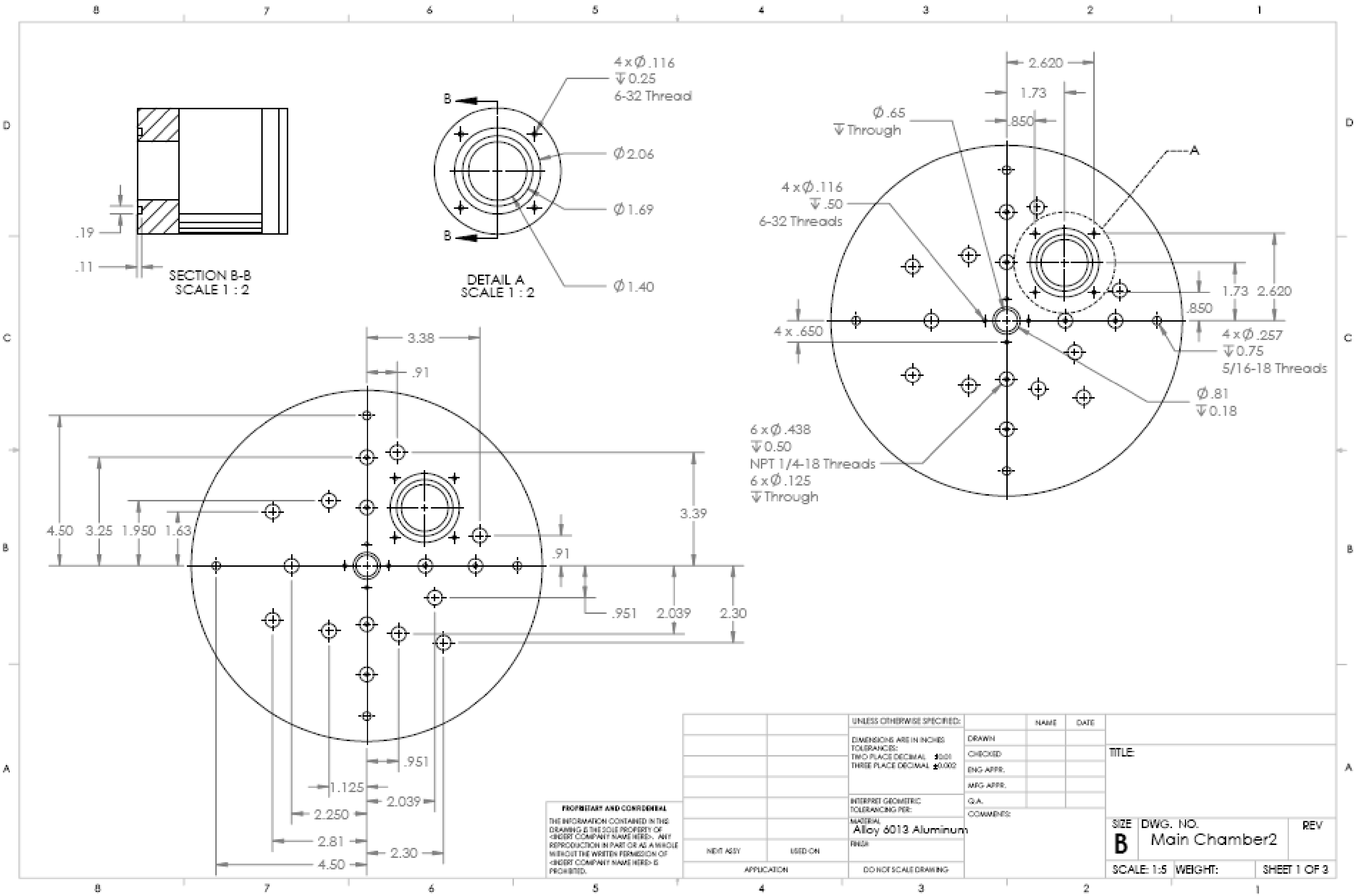


Figure 75(a). Engineering drawing of Main chamber

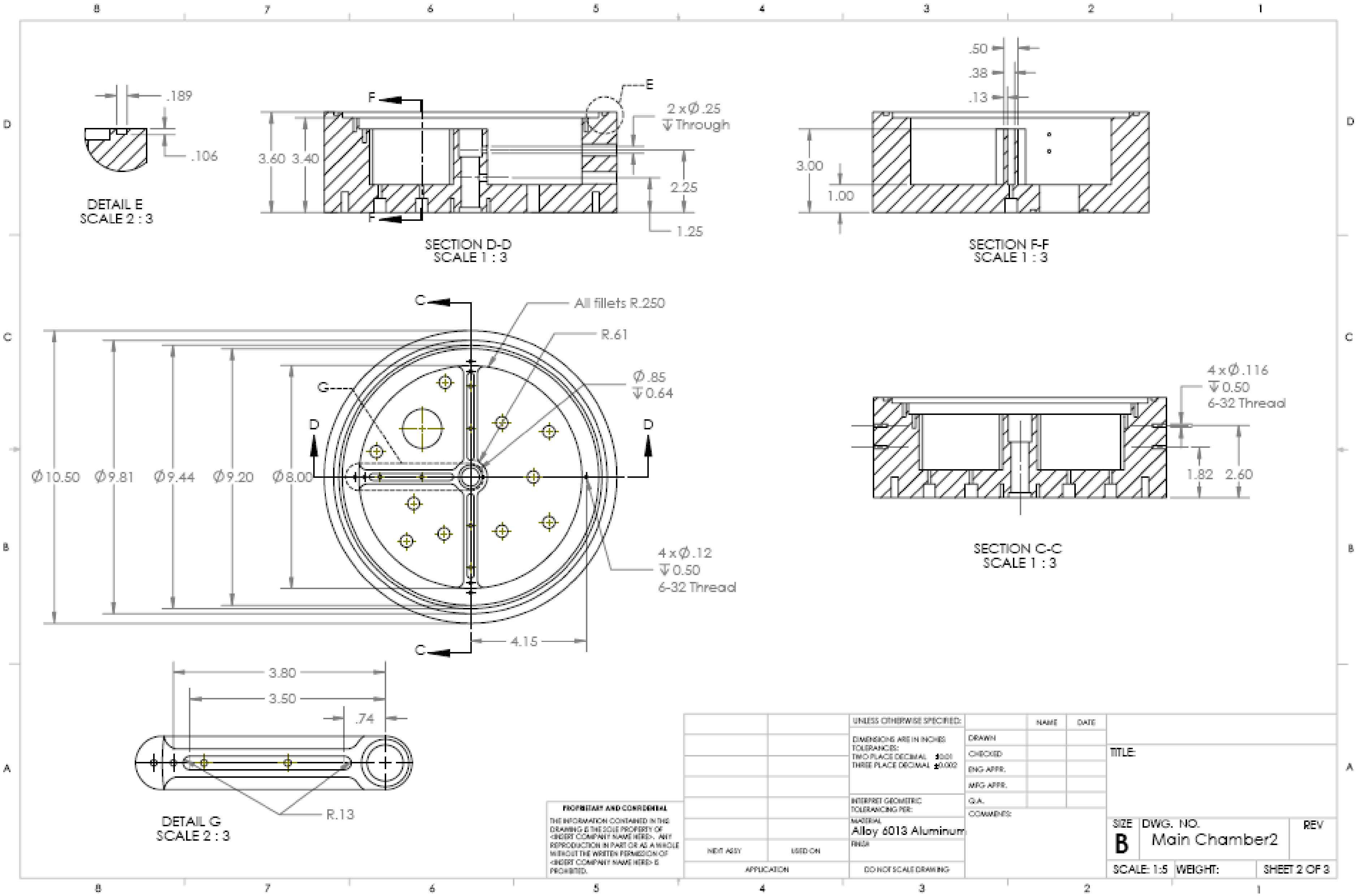


Figure 75(b). Engineering drawing of Main chamber

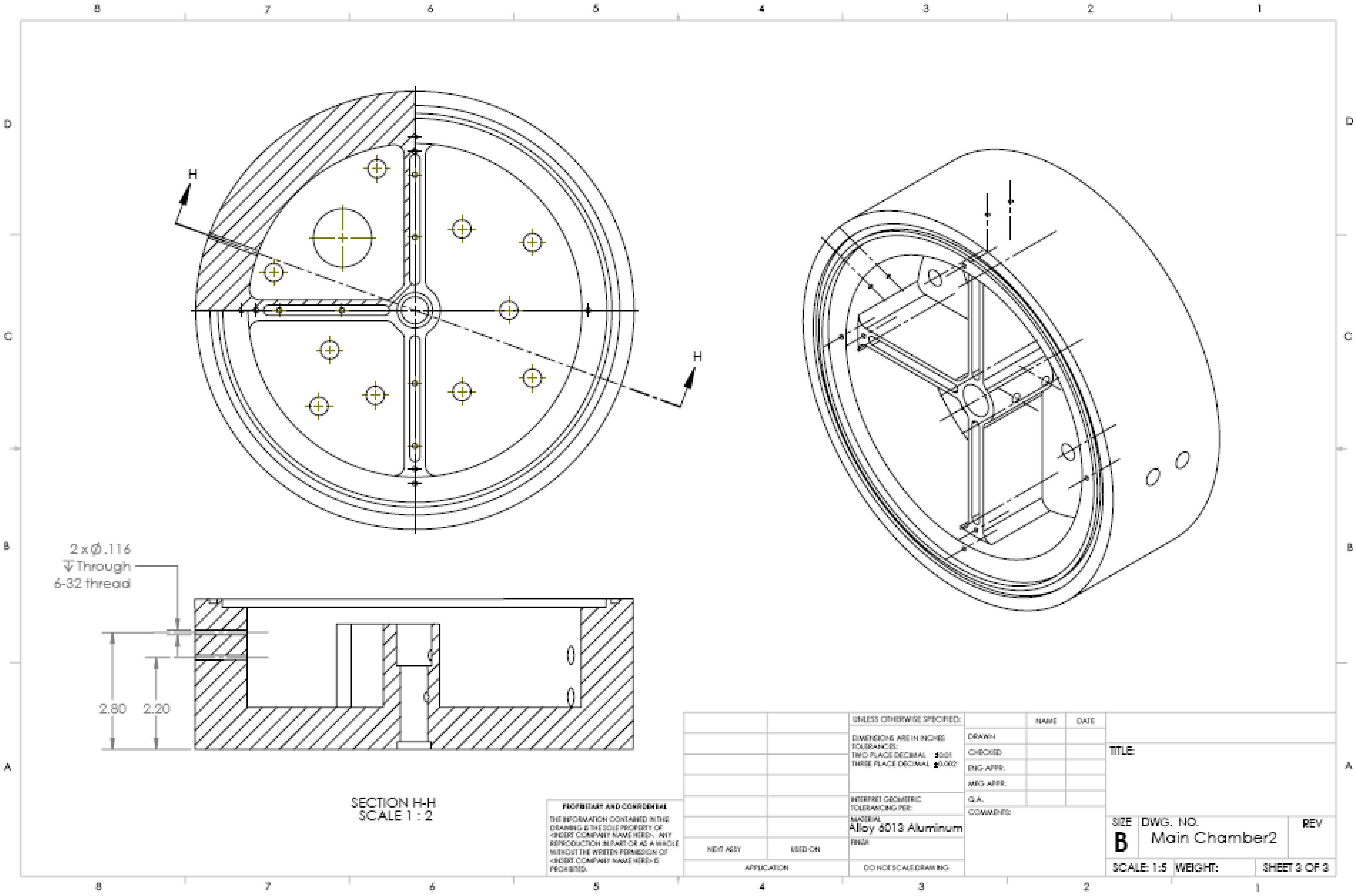


Figure 75(c). Engineering drawing of Main chamber

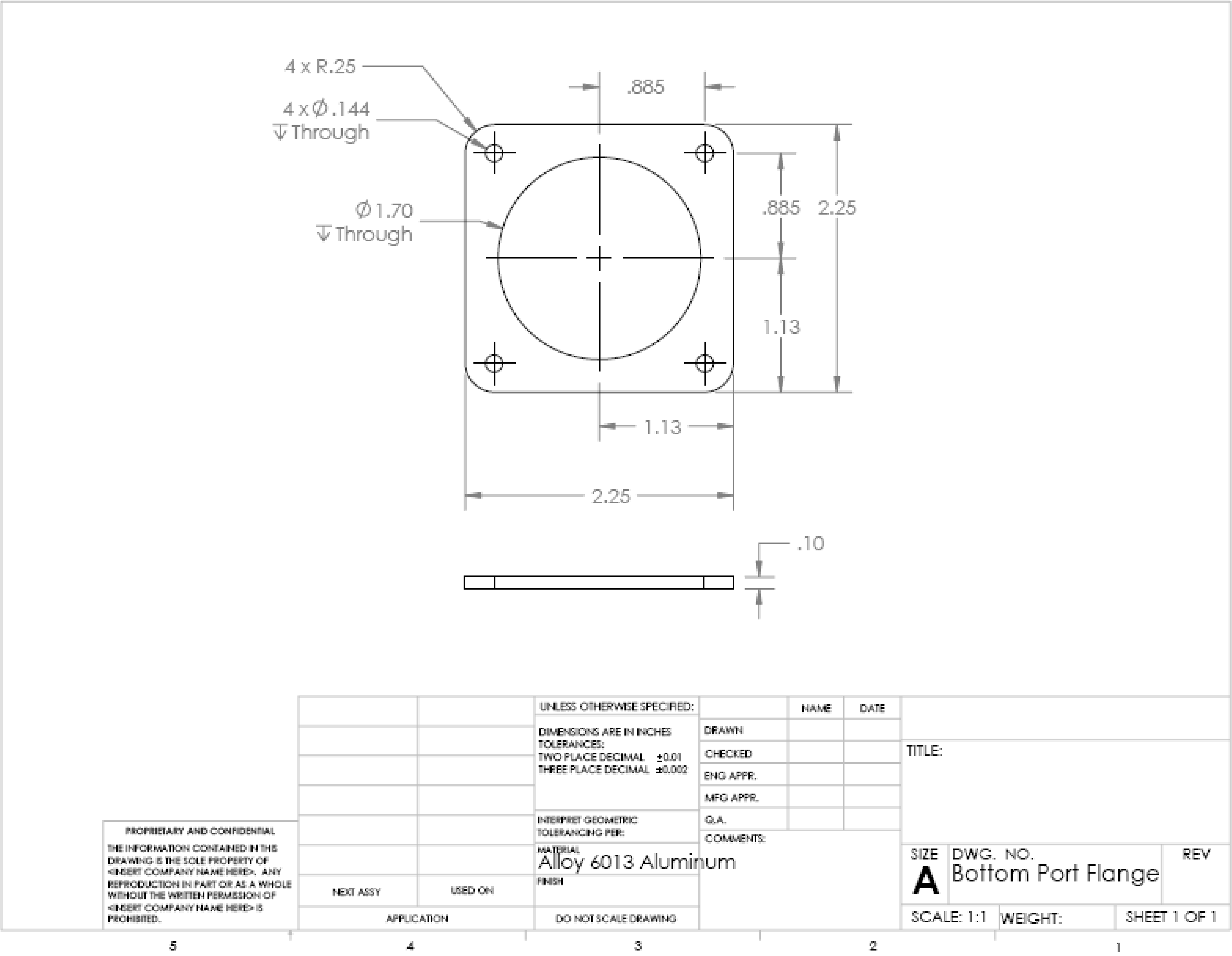


Figure 76. Engineering drawing of Bottom port flange

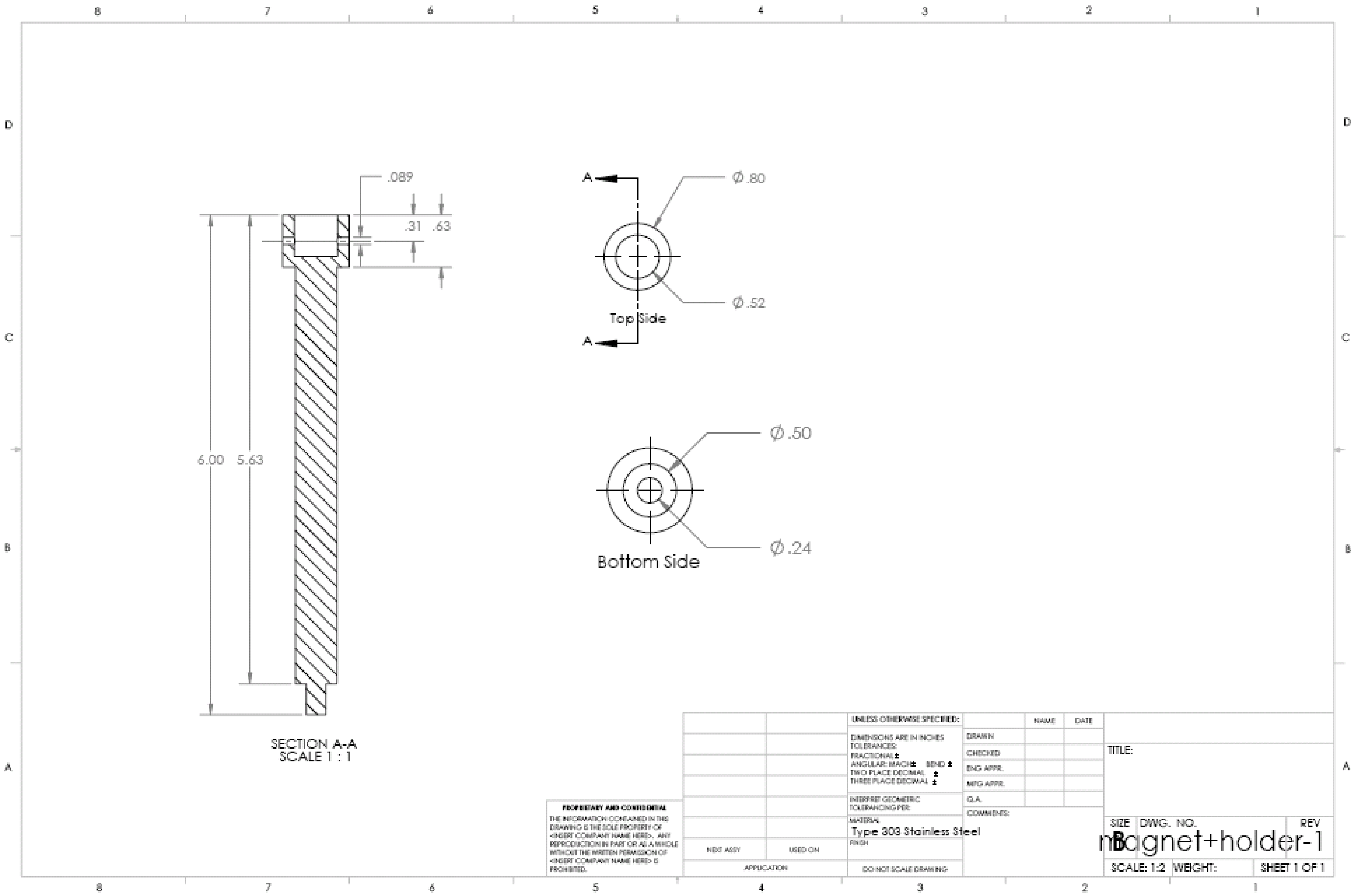


Figure 77. Engineering drawing of Magnet Holder

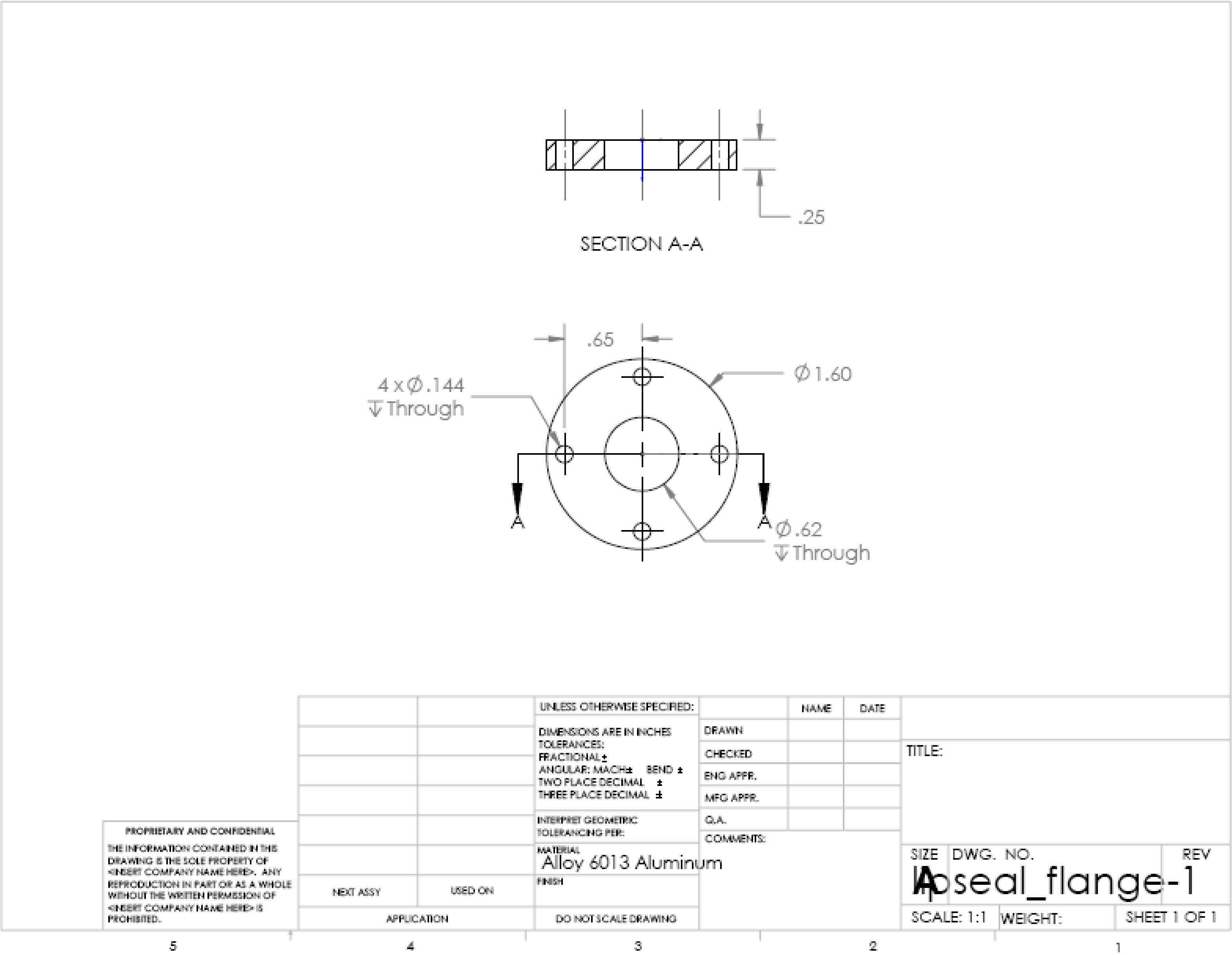


Figure 78. Engineering drawing of Lip seal flange

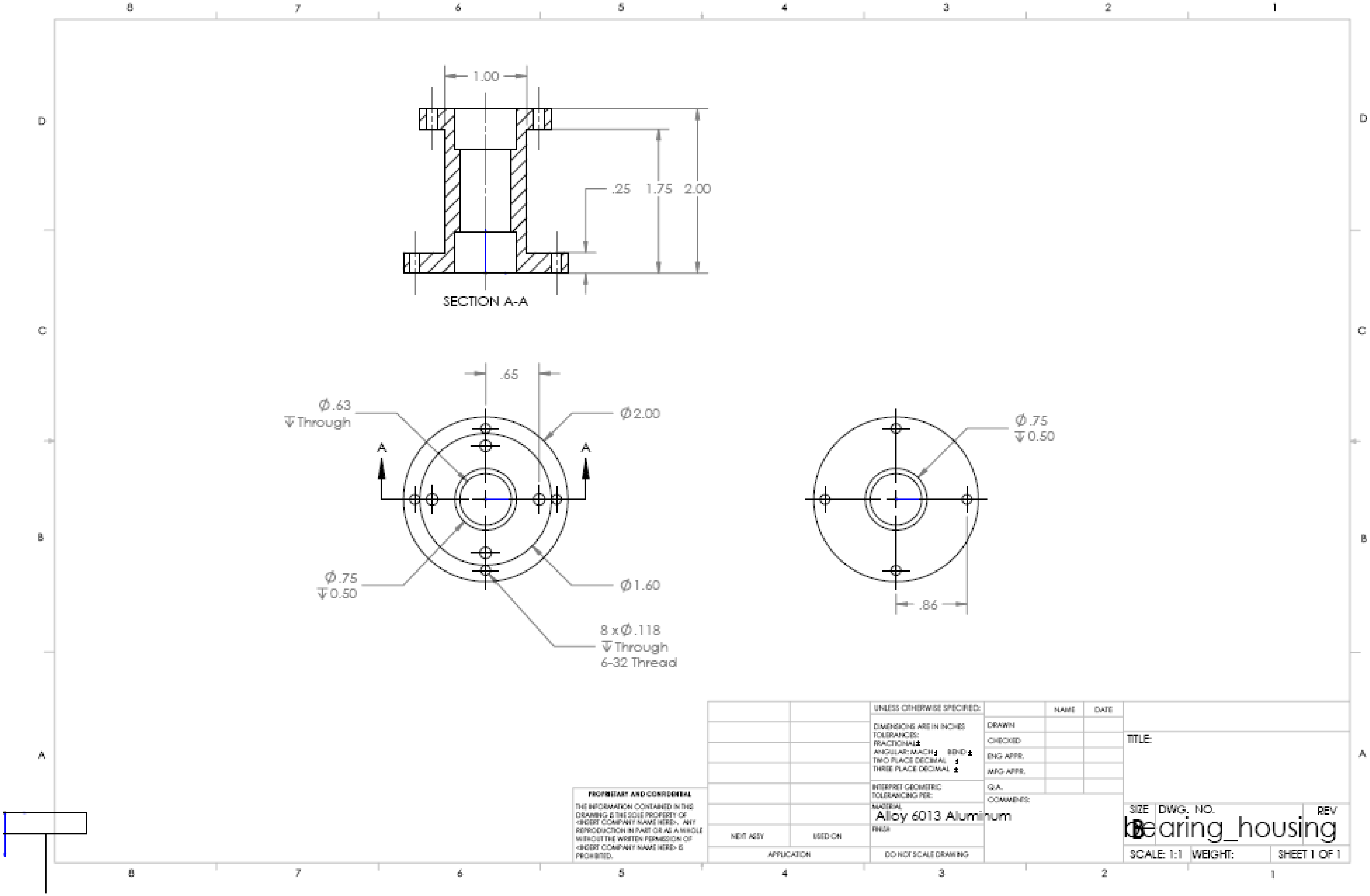


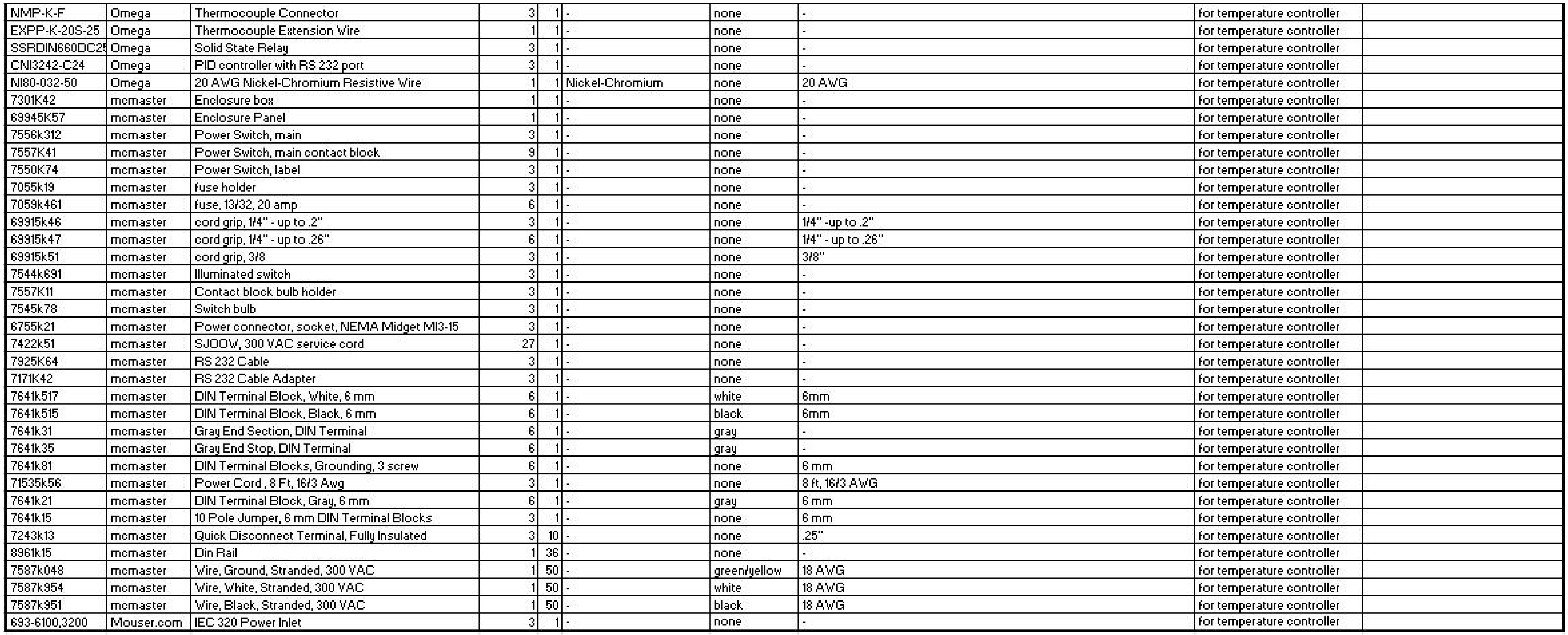
Figure 79. Engineering drawing of Bearing housing

APPENDIX D: BILL OF MATERIALS

Part #	Manufacturer	Part Name	Cost/ite	Qty	Material	Color/ Finish	Size (inches)	Function	Note
SS-4-UT-1-4-BT	Swagelok	Ultra-Torr Vacuum Fitting	18.14	5	stainless steel	silver/ gray	1/4" ultra-torr - 1/4" male NPT	for showerhead feedthrough	
B-4-RA-2	Swagelok	Reducing Adapter Pipe Fitting	3.79	6	brass	brass	1/4" female - 1/8" male NPT	for vacuum wall exhaust	
8350T82	McMaster	hardened precision shaft	36.08	4	stainless steel	silver/ gray	1/2" OD, 12" L, 5/16"-18 Thread (one end), 0.39" threaded length	legs for chamber	
92949A152	McMaster	Socket Cap Screws	9.2	1	stainless steel	silver/ gray	18-8 SS, Button Head, 6-32 thread, 7/8" L	for bearing housing-chamber	
91292A026	McMaster	Socket Cap Screws	10.17	1	stainless steel	silver/ gray	18-8 SS, Socket Head, M3 thread, 50mm L, partially threaded	for motor adjustor	
90133A005	McMaster	Washer	6.65	1	neoprene	black	for #6 screw, 0.12" ID, 1/4" OD, 0.062" thick	for motor adjustor	
2639T23	McMaster	Sleeve Bearing	3.28	2	PTFE	white	for 1/2" shaft D, 3/4" OD, 1/2" L	for shaft stabilization	
5862K28	McMaster	Neodymium-Iron-Boron Magnet	11.01	1	Neodymium-Iron-Boron	none	Disk, 1/2" D, 1/2" thick, Ultra-high pull (19lbs)	for substrate disc holding	Ultra-high pull (19lbs), 150 deg. C
5768K22	McMaster	Samarium-Cobalt Type 2-17 Magnet	10.8	3	Samarium-Cobalt	none	Disk, 1/2" D, 0.19" thick, High pull (5lbs)	for substrate disc holding	High pull (5lbs), 300 deg. C
9422K19	McMaster	Double-Lip Lipseal	3.37	1	Buna-N	black	Buna-N material, 1/2" ID shaft wiper, 13/16" OD, .203" base height	for shaft seal	
1201T906	McMaster	Viton O-Ring	14.82	1	Viton	black	MIL-Spec, AS568A-272	for chamber	
1201T856	McMaster	Viton O-RIng	11.23	1	Viton	black	MIL-Spec, AS568A-224	for viewport	
3162A11	McMaster	Drill Bit	24.67	1	Carbide	diamond	1/16"	machining	
3162A28	McMaster	Drill Bit	52.63	1	Carbide	diamond	1/4"	machining	
3162A17	McMaster	Drill Bit	36.32	1	Carbide	diamond	9/64"	machining	
4119A15	McMaster	Mill Bit	28.55	1	Carbide	diamond	1/8"	machining	
4119A22	McMaster	Mill Bit	42.73	1	Carbide	diamond	1/4"	machining	
91771A148	McMaster	flathead machine screws	4.67	1	stainless steel	none	6-32, 1/2" L, stainless steel		
8747K112	McMaster	PVC sheet	4.92	2	PVC	none	12x12x1/8"	for motor-shaft coupling	
8754K76	McMaster	PVC sheet	7.54	2	PVC	none	6x6x1/4"		
9355K2	McMaster	firebrick	8.12	2	k-26 grade	none	9x4.5x2.5"	for substrate rotation	200 steps/rev, 1.5 A, .28 Nm
8978T65	McMaster	ceramic plate	173.95	2	alumina 99.5	none	6x6x1/4"		
8978T63	McMaster	ceramic plate	110.86	1	alumina 99.5	none	6x6x1/8"		
8978T999	McMaster	ceramic plate	497.92	1	alumina 99.5	none	12x12x1/4", refer to quote #47060		
8978T999	McMaster	ceramic plate	302.08	1	alumina 99.5	none	12x12x1/8", refer to quote #47060		
1889A37	McMaster	draw latch	4.66	2	stainless steel	none			
9246K33	McMaster	aluminum plate	42.65	1	aluminum	none	12x12x1/2", T6061		
8609K13	McMaster	butyl rubber sheet	13.93	1	butyl rubber	black	adhesive, 12x12x1/8"	for base of assembly	
5779K784	McMaster	tube fitting 6-outlet manifold	18	1	brass	none	3/8" inlet, 1/4" outlet	for outlet gasses	
5779K786	McMaster	tube fitting cross	6.66	1	brass	none	1/4" tube OD	for outlet gasses	
5154T11	McMaster	spring-loaded single lipseal	4.98	1	Buna-N	none	for 1/2" shaft		
CO20M-9	wmberg.com	Wafer Spring Flexible Coupling	65.32	1	-	none	5mm-6mm,8 ang. Misal't, 0.4 parallel misal't, 14.3mm D, 23.9mm L	for motor-shaft coupling	clamp hub
17H118D15U	Portescap (Avnet)	stepper motor	160	1	-	none	NEMA 17, 200 steps/rev, 1.5 A, .28 Nm, 1 stack		
nil	magnetsource.com	Alnico rod magnet		1	Alnico	none	1/2" D, 1/2" L	for holding substrate disk	
nil	mgsquartz.com	GE Type 124 clear fused quartz ground and polished disc	223	1	Borosilicate	ground/ polished	10" D, 1/16" thick	for chamber separation	
		GE Type 124 clear fused quartz ground and polished disc		1	Borosilicate	ground/ polished	2.25" D, 1.125" thick	for viewport	
NI80-020-50	omega.com	resistive heater-wire	16	1	Nickel-Chromium	none	24-gage (.0201" D), 50 ft. L		
OB-700	omega.com	powder cement	36	1	-	none	for metal-ceramic, 8 oz	for showerhead	
XC-24-K-12	omega.com	thermocouple wire	20	1		none	type K, 24 awg, temp range -185-1250 C	for temp. sensing	Nextel Ceramic insulated

Table 9. Summary of bill of materials

APPENDIX D: BILL OF MATERIALS (CONTINUED)



NMP-K-F	Omega	Thermocouple Connector	3	1	-	none	-	for temperature controller	
EXPP-K-20S-25	Omega	Thermocouple Extension Wire	1	1	-	none	-	for temperature controller	
SSRDIN660DC2	Omega	Solid State Relay	3	1	-	none	-	for temperature controller	
CNI3242-C24	Omega	PID controller with RS 232 port	3	1	-	none	-	for temperature controller	
NI80-032-50	Omega	20 AWG Nickel-Chromium Resistive Wire	1	1	Nickel-Chromium	none	20 AWG	for temperature controller	
7301K42	mcmaster	Enclosure box	1	1	-	none	-	for temperature controller	
69945K57	mcmaster	Enclosure Panel	1	1	-	none	-	for temperature controller	
7556k312	mcmaster	Power Switch, main	3	1	-	none	-	for temperature controller	
7557K41	mcmaster	Power Switch, main contact block	9	1	-	none	-	for temperature controller	
7550K74	mcmaster	Power Switch, label	3	1	-	none	-	for temperature controller	
7055k19	mcmaster	fuse holder	3	1	-	none	-	for temperature controller	
7059k461	mcmaster	fuse, 13/32, 20 amp	6	1	-	none	-	for temperature controller	
69915k46	mcmaster	cord grip, 1/4" - up to .2"	3	1	-	none	1/4" -up to .2"	for temperature controller	
69915k47	mcmaster	cord grip, 1/4" - up to .26"	6	1	-	none	1/4" - up to .26"	for temperature controller	
69915k51	mcmaster	cord grip, 3/8	3	1	-	none	3/8"	for temperature controller	
7544k691	mcmaster	Illuminated switch	3	1	-	none	-	for temperature controller	
7557K11	mcmaster	Contact block bulb holder	3	1	-	none	-	for temperature controller	
7545k78	mcmaster	Switch bulb	3	1	-	none	-	for temperature controller	
6755k21	mcmaster	Power connector, socket, NEMA Midget MI3-15	3	1	-	none	-	for temperature controller	
7422k51	mcmaster	SJOOW, 300 VAC service cord	27	1	-	none	-	for temperature controller	
7925K64	mcmaster	RS 232 Cable	3	1	-	none	-	for temperature controller	
7171K42	mcmaster	RS 232 Cable Adapter	3	1	-	none	-	for temperature controller	
7641k517	mcmaster	DIN Terminal Block, White, 6 mm	6	1	-	white	6mm	for temperature controller	
7641k515	mcmaster	DIN Terminal Block, Black, 6 mm	6	1	-	black	6mm	for temperature controller	
7641k31	mcmaster	Gray End Section, DIN Terminal	6	1	-	gray	-	for temperature controller	
7641k35	mcmaster	Gray End Stop, DIN Terminal	6	1	-	gray	-	for temperature controller	
7641k81	mcmaster	DIN Terminal Blocks, Grounding, 3 screw	6	1	-	none	6 mm	for temperature controller	
71535k56	mcmaster	Power Cord , 8 Ft, 16/3 Awg	3	1	-	none	8 ft, 16/3 AWG	for temperature controller	
7641k21	mcmaster	DIN Terminal Block, Gray, 6 mm	6	1	-	gray	6 mm	for temperature controller	
7641k15	mcmaster	10 Pole Jumper, 6 mm DIN Terminal Blocks	3	1	-	none	6 mm	for temperature controller	
7243k13	mcmaster	Quick Disconnect Terminal, Fully Insulated	3	10	-	none	.25"	for temperature controller	
8961k15	mcmaster	Din Rail	1	36	-	none	-	for temperature controller	
7587k048	mcmaster	Wire, Ground, Stranded, 300 VAC	1	50	-	green/yellow	18 AWG	for temperature controller	
7587k954	mcmaster	Wire, White, Stranded, 300 VAC	1	50	-	white	18 AWG	for temperature controller	
7587k951	mcmaster	Wire, Black, Stranded, 300 VAC	1	50	-	black	18 AWG	for temperature controller	
693-6100,3200	Mouser.com	IEC 320 Power Inlet	3	1	-	none	-	for temperature controller	

Table 9. Summary of bill of materials (continued)

APPENDIX E: DESIGN ANAYLSIS ASSIGNMENT

(1) Material Selection

The two major components that utilized the CES software for the material selection process are the main chamber and the insert. The function, objective, and constraints of each of the components is summarized in Table 10 below.

	Main Chambers	Insert
Function	(1) House subsystems (2) Separate gases	(1) Support resistive heating wires
Objective	(1) Withstand high heat (2) Machinable at low cost	(1) Withstand high heat (2) Low thermal conductivity
Constraints	(1) Melting temperature ~500°C (2) Cost < 3 USD/lb	(1) Melting temperature ~1000°C (2) Thermal conductivity ~ 9 BTU ft/h ft^2 F (3) Cost <3 USD/lb

Table 10. Function, objective, and constraints on main chamber and insert

In order to keep the cost down, maximum price is set at 3 USD/lb for both components. For the main chamber, the melting temperature needs to be around 500°C while the insert needs to have melting temperature around 1000°C. Materials of both parts will be chosen from the metal group for durability purposes.

Figure 80 below was generated by the CES software when the relevant parameters were entered for the main chambers. The top five materials are wrought magnesium alloy AZ61, wrought aluminum alloy 6013, cast magnesium alloy EZ33A, cast aluminum pure S150, and cast aluminum allow S520. The main selection criteria from this pool were then based on machinability and availability of the material. Therefore we chose wrought aluminum alloy 6013 as our final material for the main chamber.

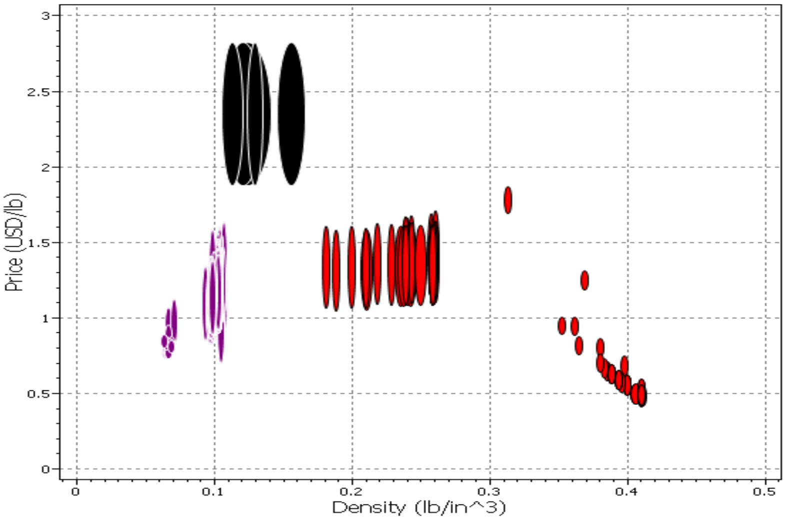


Figure 80. CES graph of appropriate materials for main chambers

The insert's constraints were inputted into the CES software and Figure 81 below shows the possible materials. Since the design calls for the use of a magnet, we decided to use a non-ferric material for the main chamber to prevent any magnetic force that might cause friction in the rotational shaft. The top five materials from CES are wrought austenitic stainless steel: AISI 347, AISI 340 (annealed), AISI

329 (annealed), AISI 302 (annealed), and AISI 304L. The system aided us in narrowing the material search. However, since machinability is a major concern in our design, we decided to go with stainless steel 303 which was the most machinable stainless steel compared to the top five materials generated by the CES program.

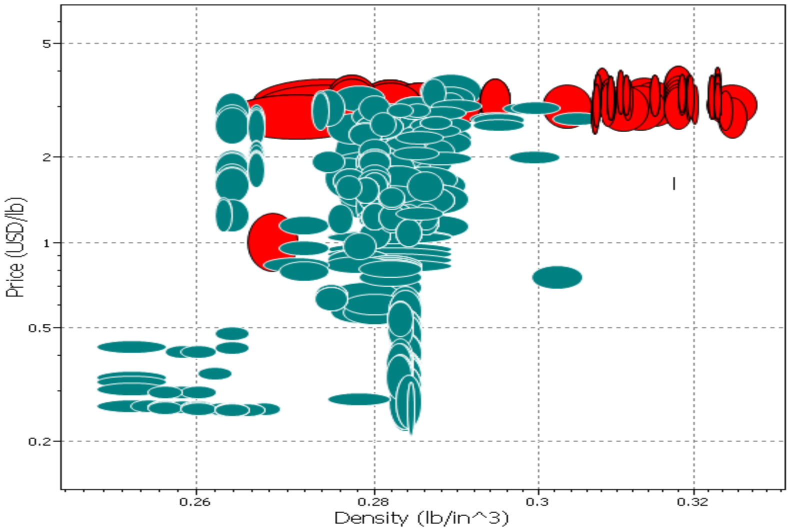


Figure 81. CES graph of appropriate materials for insert

APPENDIX E: DESIGN ANAYLSIS ASSIGNMENT

(2) Design for Assembly

To design for greater efficiency and ease of assembly, the Boothroyd-Dewhurst DFA method was employed. The original assembly design and the revised assembly design are shown in Figure 82 (a) and (b) respectively below.

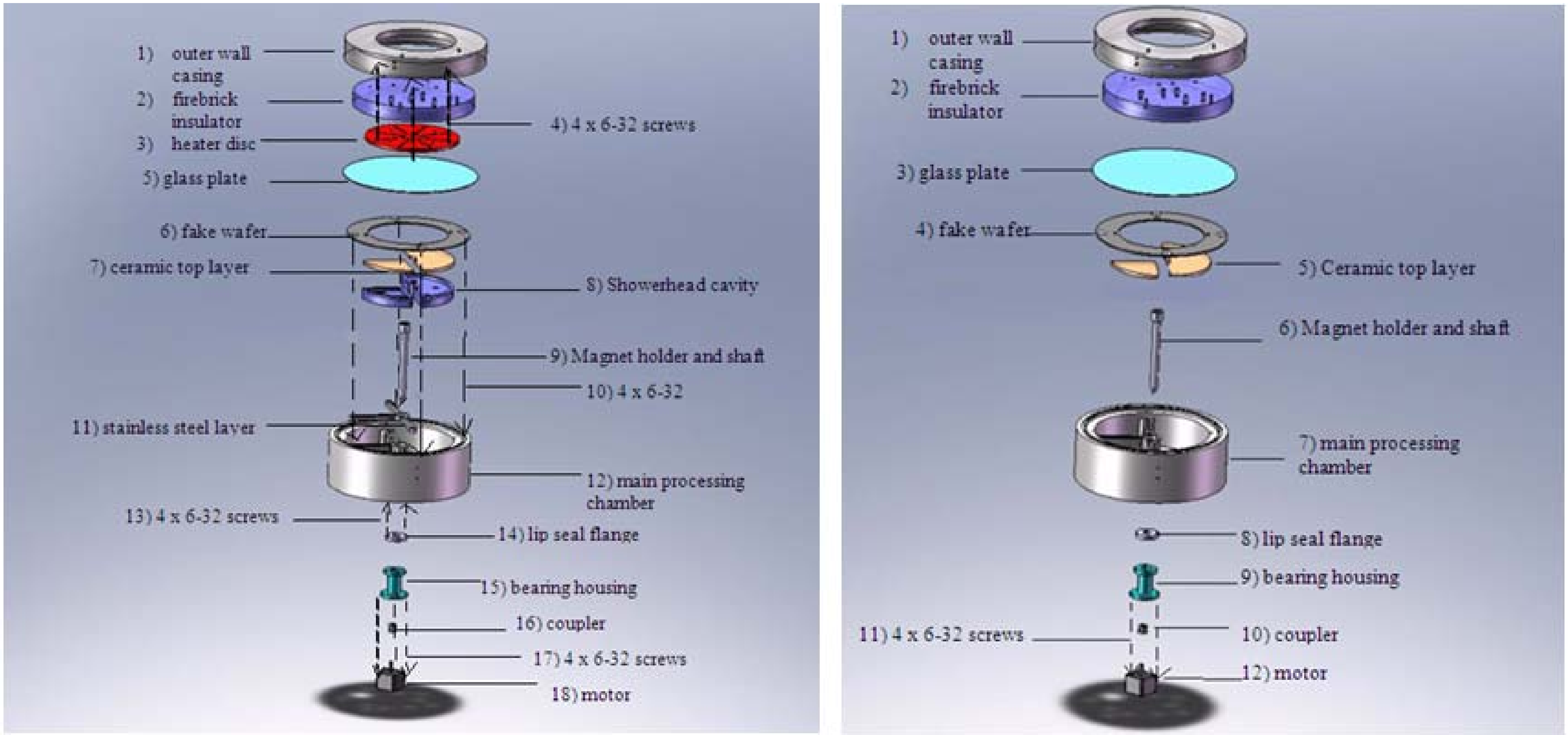
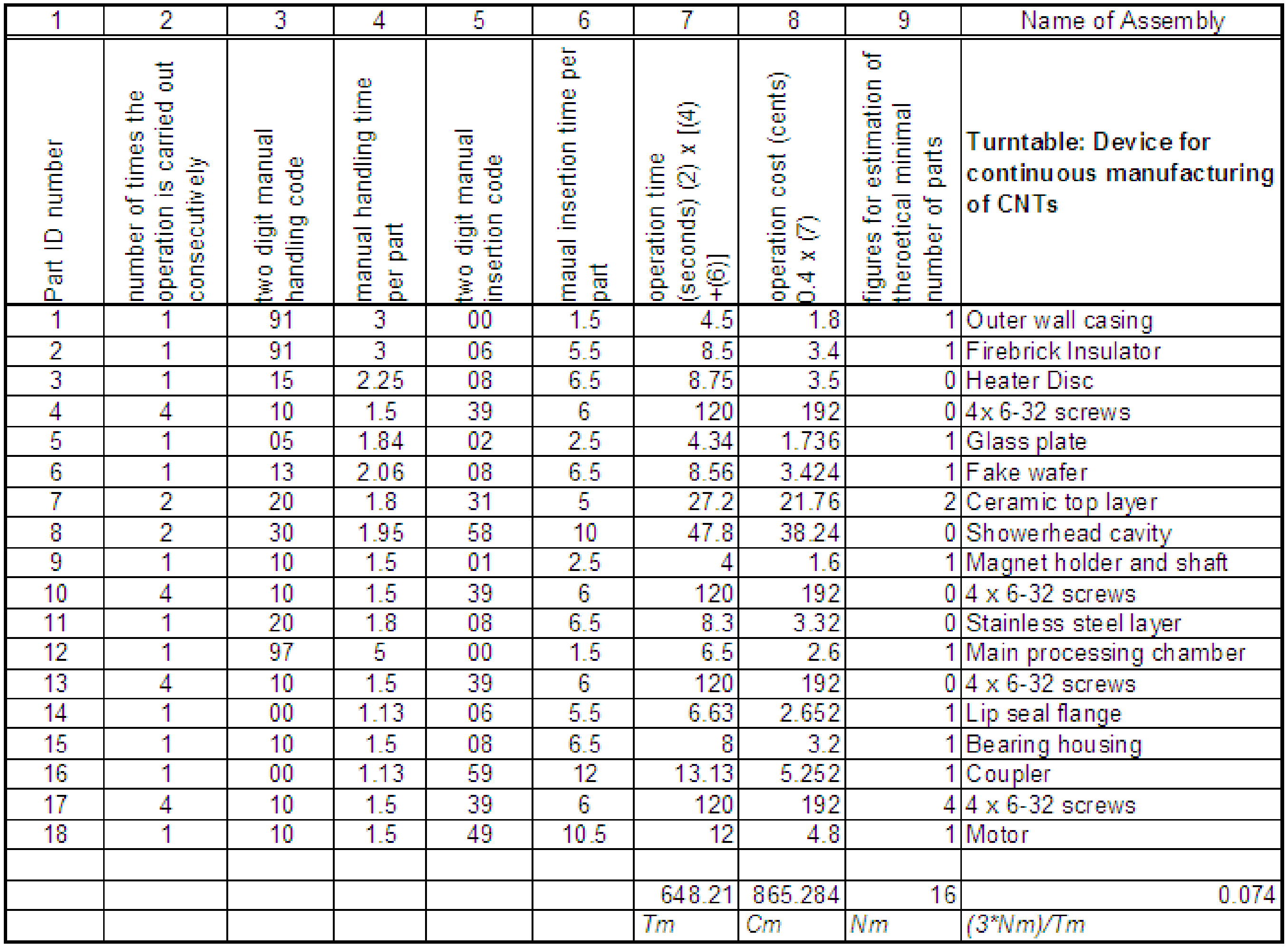


Figure 82. (a) Original assembly design and (b) Revised assembly design for continuous manufacturing of CNTs

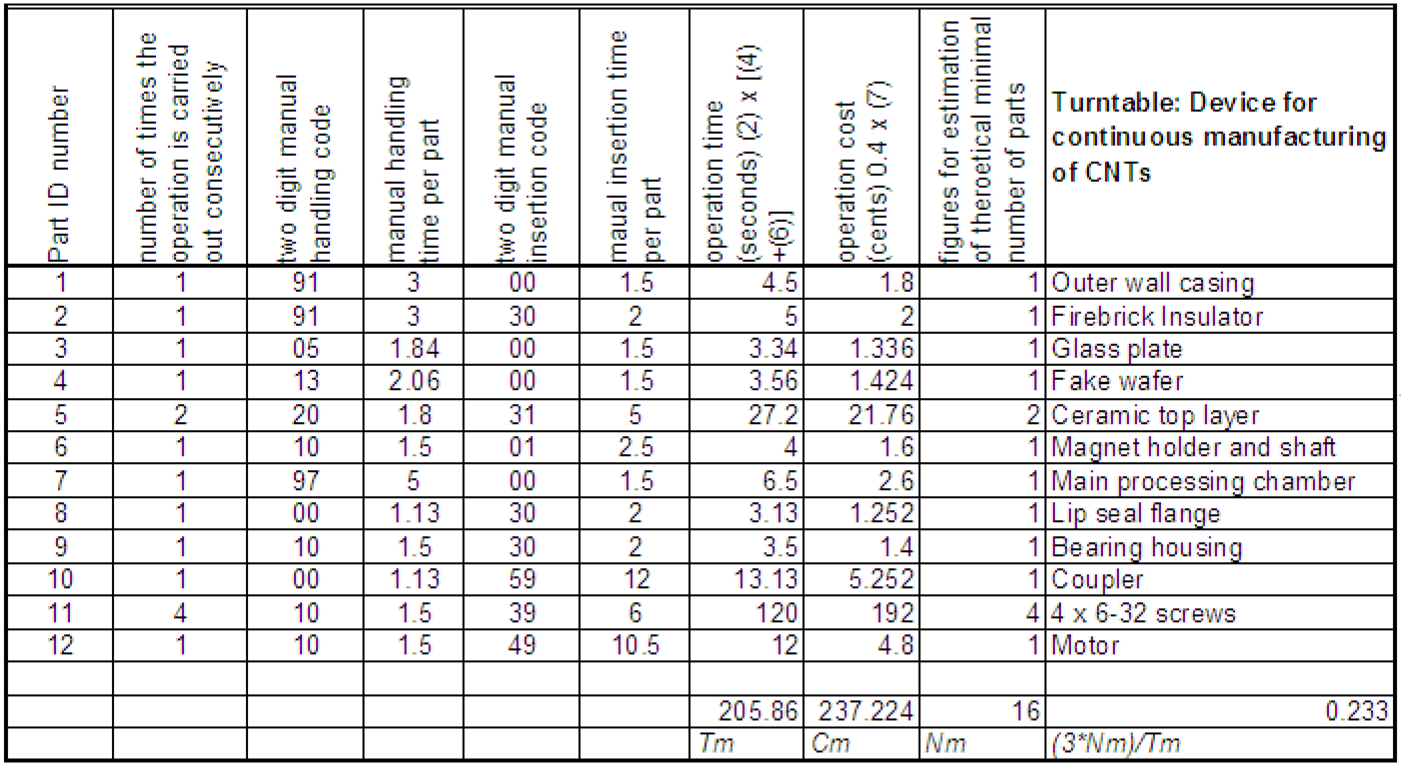
Firstly, the original assembly of the design was analyzed, breaking down the assembly into numbered parts as shown in Figure 81(a) above. According to the DFA charts as provided, two digit manual handling and insertion codes were identified. Corresponding times for manual handling and insertion were then identified, and the total time taken for assembly (T_m) was calculated. Through the test for part elimination for each part, we then determined the theoretical minimum number of parts (N_m) for our system. The assembly efficiency was also calculated using the following formula- efficiency = (3 x T_m)/N_m. These values are tabulated in Table 11.



1	2	3	4	5	6	7	8	9	Name of Assembly
Part ID number	number of times the operation is carried out consecutively	two digit manual handling code	manual handling time per part	two digit manual insertion code	maual insertion time per part	operation time (seconds) (2) x [(4)+(6)]	operation cost (cents) 0.4 x (7)	figures for estimation of theoretical minimal number of parts	**Turntable: Device for continuous manufacturing of CNTs**
1	1	91	3	00	1.5	4.5	1.8	1	Outer wall casing
2	1	91	3	06	5.5	8.5	3.4	1	Firebrick Insulator
3	1	15	2.25	08	6.5	8.75	3.5	0	Heater Disc
4	4	10	1.5	39	6	120	192	0	4x 6-32 screws
5	1	05	1.84	02	2.5	4.34	1.736	1	Glass plate
6	1	13	2.06	08	6.5	8.56	3.424	1	Fake wafer
7	2	20	1.8	31	5	27.2	21.76	2	Ceramic top layer
8	2	30	1.95	58	10	47.8	38.24	0	Showerhead cavity
9	1	10	1.5	01	2.5	4	1.6	1	Magnet holder and shaft
10	4	10	1.5	39	6	120	192	0	4 x 6-32 screws
11	1	20	1.8	08	6.5	8.3	3.32	0	Stainless steel layer
12	1	97	5	00	1.5	6.5	2.6	1	Main processing chamber
13	4	10	1.5	39	6	120	192	0	4 x 6-32 screws
14	1	00	1.13	06	5.5	6.63	2.652	1	Lip seal flange
15	1	10	1.5	08	6.5	8	3.2	1	Bearing housing
16	1	00	1.13	59	12	13.13	5.252	1	Coupler
17	4	10	1.5	39	6	120	192	4	4 x 6-32 screws
18	1	10	1.5	49	10.5	12	4.8	1	Motor
						648.21	865.284	16	0.074
						Tm	*Cm*	*Nm*	*(3*Nm)/Tm*

Table 11. DFA chart for original assembly design

Following this, we considered means by which unnecessary parts could be eliminated, as well as improving the ease of assembly for existing parts. The DFA chart was correspondingly revised and a new efficiency of 0.352 was obtained as compared to the original 0.074 of the original assembly design, as shown in Table 12, below.



Part ID number	number of times the operation is carried out consecutively	two digit manual handling code	manual handling time per part	two digit manual insertion code	maual insertion time per part	operation time (seconds) (2) x [(4)+(6)]	operation cost (cents) 0.4 x (7)	figures for estimation of theoretical minimal number of parts	**Turntable: Device for continuous manufacturing of CNTs**
1	1	91	3	00	1.5	4.5	1.8	1	Outer wall casing
2	1	91	3	30	2	5	2	1	Firebrick Insulator
3	1	05	1.84	00	1.5	3.34	1.336	1	Glass plate
4	1	13	2.06	00	1.5	3.56	1.424	1	Fake wafer
5	2	20	1.8	31	5	27.2	21.76	2	Ceramic top layer
6	1	10	1.5	01	2.5	4	1.6	1	Magnet holder and shaft
7	1	97	5	00	1.5	6.5	2.6	1	Main processing chamber
8	1	00	1.13	30	2	3.13	1.252	1	Lip seal flange
9	1	10	1.5	30	2	3.5	1.4	1	Bearing housing
10	1	00	1.13	59	12	13.13	5.252	1	Coupler
11	4	10	1.5	39	6	120	192	4	4 x 6-32 screws
12	1	10	1.5	49	10.5	12	4.8	1	Motor
						205.86	237.224	16	0.233
						Tm	*Cm*	*Nm*	*(3*Nm)/Tm*

Table 12. DFA chart for revised assembly design

The DFA chart was correspondingly revised and a new efficiency of 0.233 was obtained as compared to the original 0.144 of the original assembly design. The main revisions are listed as follows:

(i) Elimination of the heater plate to allow for one firebrick piece with embedded heater wire instead. This will be press fit to the outer wall casing to eliminate the use of screws and allow for easier assembly

(ii) A groove or slight depression to be made in the main processing chambers at the location of the glass plate so as to enable easy alignment of the glass plate with its adjacent parts.

(iii) Instead of screwing the wafer to the main processing chamber, the depression for the fake wafer will be made with less clearance. Since the fake wafer need not be held down and the primary roles of the securing screws is to hold the wafer in place, by having a distinct depression for where the fake wafer is located allows this part to be quickly located and assembled without the use of screws.

(iv) Since the stainless steel layer serves only as a material of higher melting temperature, it can be incorporated into the main chamber if the whole main chamber were made of stainless steel or another material of high melting point for the purposes of our application. However, this might not be feasible since the whole reason for the design of the stainless steel layer was due to the higher cost of stainless steel, and thus higher cost of manufacturing the whole assembly. Hence, cost of the materials and overall product should be considered in addition to these suggested modifications from applying this DFA method.

(v) Instead of having separate showerhead parts, these could be inbuilt into the main processing chambers and eliminate the need for these two additional parts.

(vi) For the lip seal flange and bearing housing, snap fits could be used instead of the additional screws to secure these in place.

APPENDIX E: DESIGN ANAYLSIS ASSIGNMENT

(3) Design for Environmental Sustainability

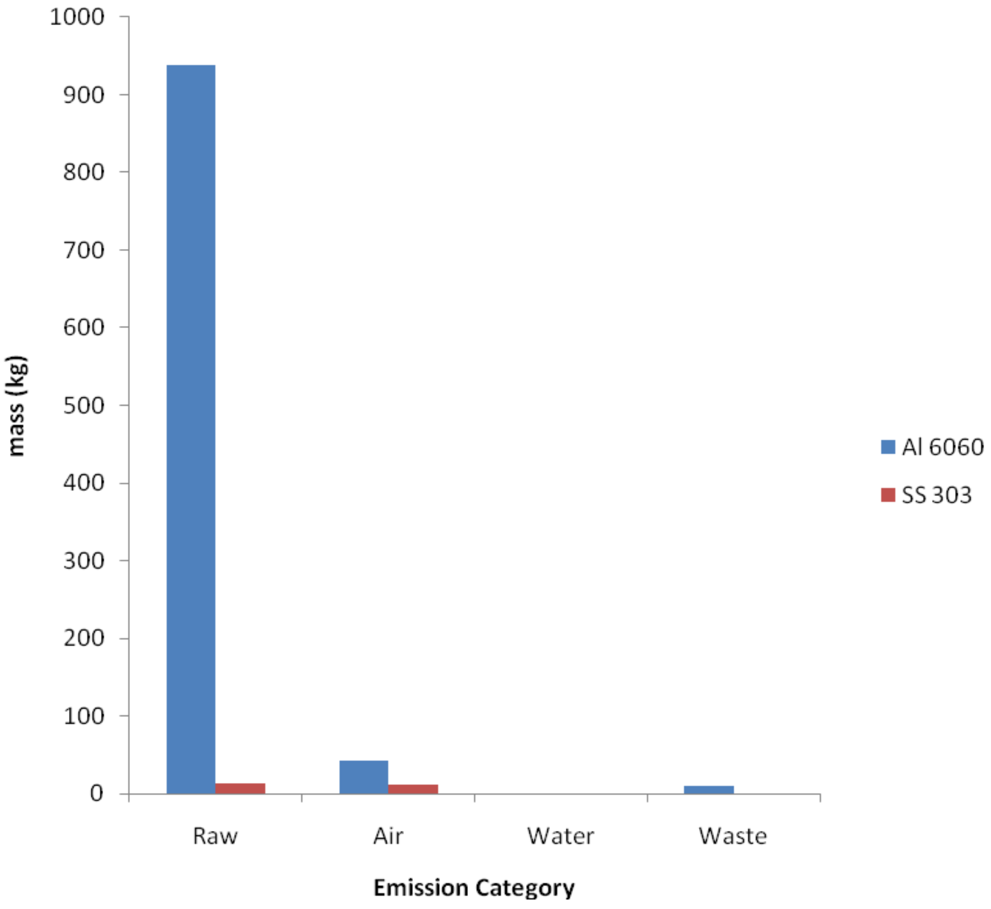


Figure 83. Total Emissions for Aluminum vs. Stainless Steel

Two of our materials for the project are Aluminum 6013 and Stainless Steel Type 303. By using SimaPro 7 software, we compared Al 6060 and SS Type 303 which are the closest materials in the software to what we actually used. The Eco-Indicator 99 (I) test yielded results shown in Figures 83, 84, 85, and 86.

From Figure 83, we see that the aluminum has a greater environmental impact by 76%, 4%, 147%, and 281% for raw, air, water, and waste emission categories. From Figure 84, we see that aluminum far outweighs stainless steel in every damage classification. From Figure 85, the “Resources” damage meta-category wins out for the most important, based on EI99 point values (being about 32 times greater than the “Human Health” and “Ecosystem Quality” categories). Yet, in all three categories, aluminum is about twice as great as stainless steel. Overall, aluminum has a higher EI99 point value, as seen in Figure 86 below. Beating out stainless steel by about 4 points, the aluminum alloy will have a greater environmental impact over its entire lifecycle.

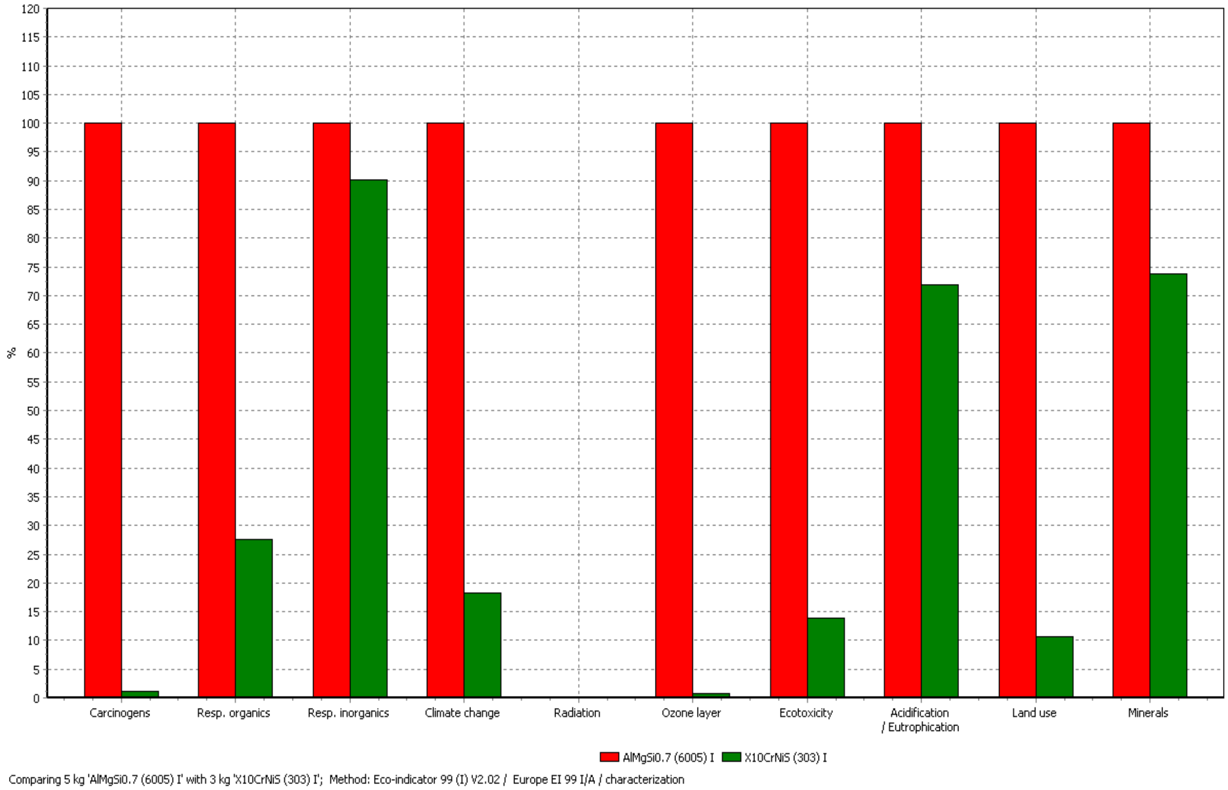


Figure 84. Relative Impacts in Disaggregated Damage Categories

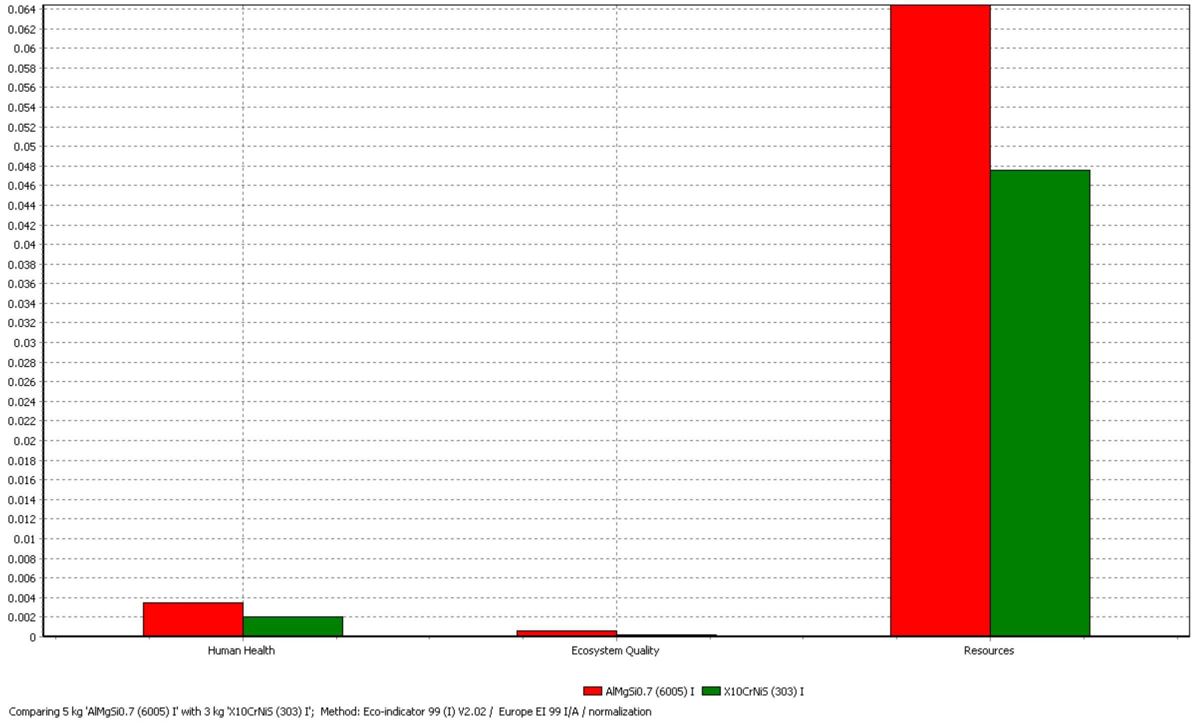
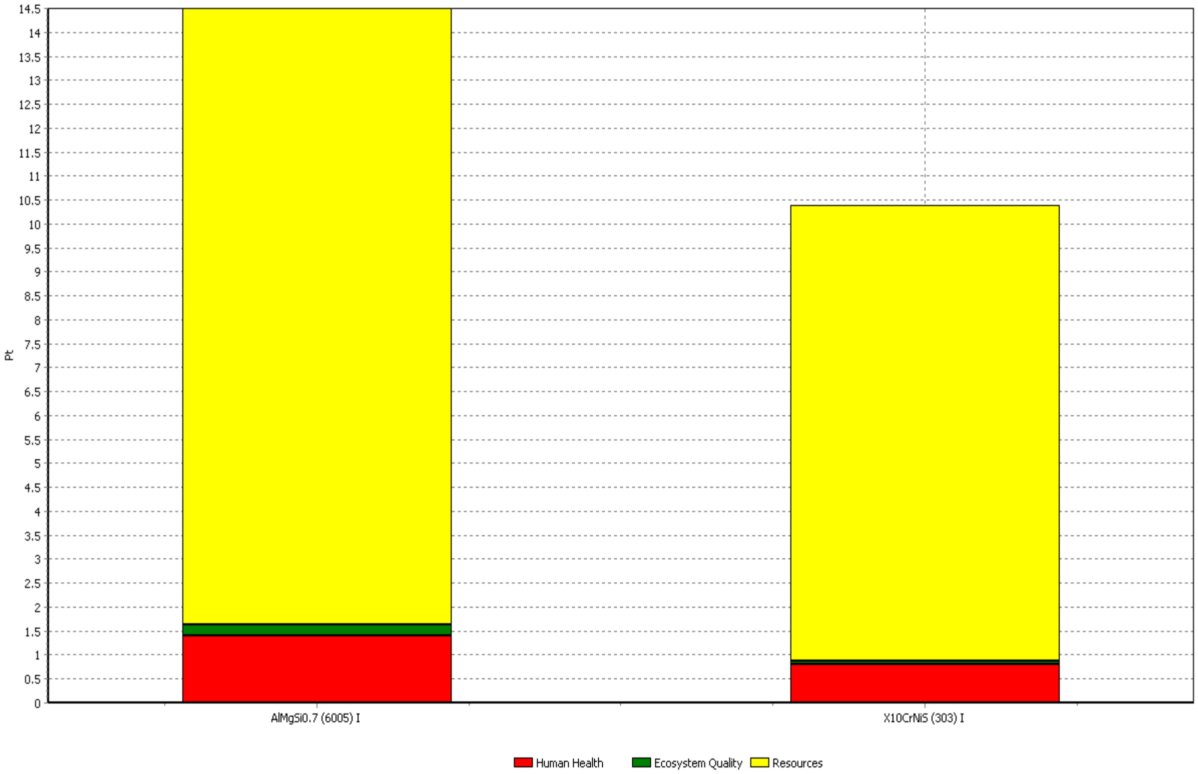


Figure 85. Normalized Score in Human Health, Eco-Toxicity, and Resource Categories

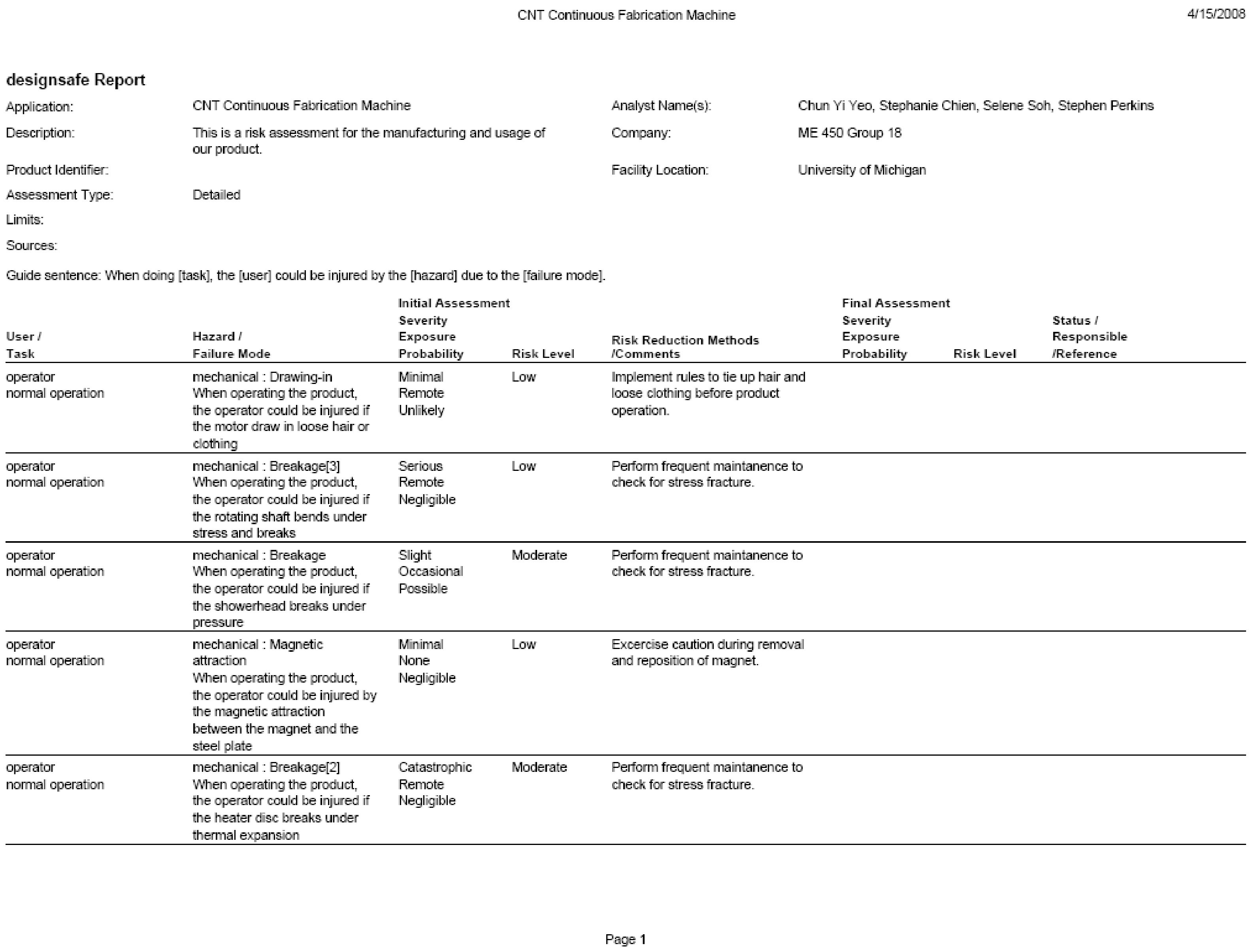


Comparing 5 kg 'AlMgSi0.7 (6005) I' with 3 kg 'X10CrNiS (303) I'; Method: Eco-indicator 99 (I) V2.02 / Europe EI 99 I/A / single score

Figure 86. Single Score Comparison in “Points”

APPENDIX E: DESIGN ANAYLSIS ASSIGNMENT

(4) Design for Safety



CNT Continuous Fabrication Machine 4/15/2008

designsafe Report

Application:	CNT Continuous Fabrication Machine	Analyst Name(s):	Chun Yi Yeo, Stephanie Chien, Selene Soh, Stephen Perkins
Description:	This is a risk assessment for the manufacturing and usage of our product.	Company:	ME 450 Group 18
Product Identifier:		Facility Location:	University of Michigan
Assessment Type:	Detailed		
Limits:			
Sources:			

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

		Initial Assessment			**Final Assessment**		
User / Task	**Hazard / Failure Mode**	**Severity Exposure Probability**	**Risk Level**	**Risk Reduction Methods /Comments**	**Severity Exposure Probability**	**Risk Level**	**Status / Responsible /Reference**
operator normal operation	mechanical : Drawing-in When operating the product, the operator could be injured if the motor draw in loose hair or clothing	Minimal Remote Unlikely	Low	Implement rules to tie up hair and loose clothing before product operation.			
operator normal operation	mechanical : Breakage[3] When operating the product, the operator could be injured if the rotating shaft bends under stress and breaks	Serious Remote Negligible	Low	Perform frequent maintanence to check for stress fracture.			
operator normal operation	mechanical : Breakage When operating the product, the operator could be injured if the showerhead breaks under pressure	Slight Occasional Possible	Moderate	Perform frequent maintanence to check for stress fracture.			
operator normal operation	mechanical : Magnetic attraction When operating the product, the operator could be injured by the magnetic attraction between the magnet and the steel plate	Minimal None Negligible	Low	Excercise caution during removal and reposition of magnet.			
operator normal operation	mechanical : Breakage[2] When operating the product, the operator could be injured if the heater disc breaks under thermal expansion	Catastrophic Remote Negligible	Moderate	Perform frequent maintanence to check for stress fracture.			

Page 1

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
operator normal operation	electrical / electronic : Machine lack proper grounding When operating the product, the operator could be injured by short circuit due to improper grounding of machine	Serious None Negligible	Low	Perform frequent maintanence to check for exposed wires.			
operator normal operation	electrical / electronic : Insulation failure for heater wires Operator could be injured by insulation failure of heater wires due to thermal cycling and subsequent insulation failure.	Serious None Unlikely	Low	Perform frequent maintanence to check for insulation condition.			
operator normal operation	electrical / electronic : Overloading of motor circuits When operating the product, the operator could be injured by the overlaoding of the motor circuit in an attempt to create bigger torques.	Minimal None Unlikely	Low	Excercise caution during operation of motor.			
operator normal operation	electrical / electronic : Short Circuit When operating the product, the operator could be injured by short circuit from the controllers.	Minimal Remote Unlikely	Low	Perform frequent maintanence to check for exposed wires.			
operator normal operation	ergonomics / human factors : Repetition When operating the product, the operator could be complacent due to repetative nature of work.	Minimal Occasional Possible	Moderate	Take frequent breaks to prevent repetative feeling.			
operator normal operation	ergonomics / human factors : Long duration When operating the product, the operator could suffer from fatigue due to long duration.	Minimal Occasional Possible	Moderate	Take frequent breaks to prevent fatigue.			
operator normal operation	fire and explosions : Hot surfaces When operating the product, the operator could be injured by the hot surface due to faulty isulationt.	Slight Remote Unlikely	Low	Excercise caution during product handling. Install thermocouple to display surface temperature.			

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
operator normal operation	fire and explosions : Flammable gas When operating the product, the operator could be exposed to open flames due to flammable gas.	Slight None Negligible	Low	Install flammable gas detector.			
operator normal operation	heat / temperature : Radiant heat When operating the product, the operator could be injured by radiant heat due to faulty insulation	Minimal Remote Unlikely	Low	Excercise caution during product handling and perform frequent maintanence to check for insulation integrity			
operator normal operation	material handling : Excessive weight When operating the product, the operator could be injured by the excessive weight of the product during handling.	Minimal Remote Possible	Low	Excercise caution during product handling. Use aids such as lifts or cart as neccessay.			
operator normal operation	chemical : Chemical emissions When operating the product, the operator could be exposed to chemical eimssions such as helium and hydrogen.	Minimal Frequent Possible	Moderate	Install gaseous chemical detector.			
operator normal operation	fluid / pressure : High pressure air When operating the product, the operator could be injured by debris due to rupture of high pressure air tube.	Minimal Frequent Negligible	Low	Excercise caution during product handling.			
operator load / unload materials	mechanical : Cutting When loading/unloading the product, the operator could be cut by the sharp edges of the silicon wafer.	Minimal Frequent Unlikely	Moderate	Excercise caution during material loading and unloading and use gloves.			
operator load / unload materials	mechanical : Magnetic attraction When loading/unloading the product, the operator could be injured by the magnetic attraction between magnet and steel plate.	Minimal Frequent Possible	Moderate	Excercise caution during removal and reposition of magnet.			

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
operator load / unload materials	electrical / electronic : Machine lack proper grounding When loading/unloading the product, the operator could be injured by short circuit due to improper grounding.	Serious Remote Unlikely	Moderate	Perform frequent maintanence to check for exposed wires.			
operator load / unload materials	electrical / electronic : Insulation failure for heater wires When loading/unloading the product, the operator could be injured due to insulation failure of heater wires through thermal cycling and subsequent insulation failure.	Serious Occasional Unlikely	Moderate	Perform frequent maintanence to check for insulation condition.			
operator load / unload materials	fire and explosions : Hot surfaces When loading/unloading the product, the operator could be injured by the hot surface of the chamber.	Slight Occasional Unlikely	Moderate	Excercise caution during product handling. Install thermocouple to display surface temperature.			
operator load / unload materials	heat / temperature : Radiant heat When loading/unloading the product, the operator could be injured by the radiant heat emmited by the chamber due to faulty insulation.	Minimal Occasional Negligible	Low	Excercise caution during product handling and perform frequent maintanence to check for insulation integrity			
operator load / unload materials	material handling : Excessive weight When loading/unloading the product, the operator could be injured by the weight of the project due to product handling.	Minimal Occasional Possible	Moderate	Excercise caution during product handling. Use aids such as lifts or cart as neccessay.			
set-up person set-up or changeover	mechanical : Crushing When setting up the equipment, the set-up person could be injured if the product falls on him.	Minimal Frequent Unlikely	Moderate	Excercise caution during product handling.			

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
set-up person set-up or changeover	mechanical : Cutting When setting up the equipment, the set-up person could be cut by the sharp edges of the silicon wafer.	Minimal Occasional Negligible	Low	Excercise caution during material loading and unloading and use gloves.			
set-up person set-up or changeover	mechanical : Magnetic attraction When setting up the equipment, the set-up person could be injured by the magnetic attraction between magnet and steel plate.	Minimal Frequent Possible	Moderate	Excercise caution during removal and reposition of magnet.			
set-up person set-up or changeover	electrical / electronic : Machine lack proper grounding When setting up the equipment, the set-up person could be injured by short circuit due to improper grounding.	Serious Occasional Negligible	Moderate	Perform frequent maintanence to check for exposed wires.			
set-up person set-up or changeover	electrical / electronic : Insulation failure for heater wires When setting up the equipment, the set-up person could be injured due to insulation failure of heater wires through thermal cycling and subsequent insulation failure.	Serious None Negligible	Low	Perform frequent maintanence to check for insulation condition.			
set-up person set-up or changeover	electrical / electronic : Short Circuit When setting up the equipment, the set-up person could be injured short circuit from the controllers.	Serious Remote Negligible	Low	Perform frequent maintanence to check for exposed wires.			
set-up person set-up or changeover	ergonomics / human factors : Exertion When setting up the equipment, the set-up person could be injured by exertion during the assembly and disaasembly of the product.	Minimal Frequent Negligible	Low	Take frequent breaks to recover from exhaustion.			

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
set-up person set-up or changeover	ergonomics / human factors : Posture When setting up the equipment, the set-up person could be injured by bad posture during the assembly and disassembly of the product.	Minimal Frequent Unlikely	Moderate	Customize workplace to allow for better positioning of posture.			
set-up person set-up or changeover	ergonomics / human factors : Repetition When setting up the equipment, the set-up person could be complacent due to repetative nature of work.	Minimal Frequent Unlikely	Moderate	Take frequent breaks to prevent repetative feeling.			
set-up person set-up or changeover	ergonomics / human factors : Long duration When setting up the equipment, the set-up person could suffer from fatigue due to long duration.	Minimal Frequent Unlikely	Moderate	Take frequent breaks to prevent fatigue.			
set-up person set-up or changeover	material handling : Excessive weight When setting up the equipment, the set-up person could be injured by the weight of the project due to product handling.	Minimal Frequent Negligible	Low	Excercise caution during product handling. Use aids such as lifts or cart as neccessay.			
set-up person trouble-shooting / problem solving	mechanical : Crushing When troubleshooting the equipment, the set-up person could be injured if the product falls on him.	Minimal Frequent Negligible	Low	Excercise caution during product handling.			
set-up person trouble-shooting / problem solving	mechanical : Cutting When troubleshooting the equipment, the set-up person could be cut by the sharp edges of the silicon wafer.	Minimal Frequent Negligible	Low	Excercise caution during material loading and unloading and use gloves.			
set-up person trouble-shooting / problem solving	mechanical : Drawing-in When troubleshooting the equipment, the set-up person could be injured if the motor draw in loose hair or clothing	Minimal Remote Negligible	Low	Implement rules to tie up hair and loose clothing before product operation.			

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
set-up person trouble-shooting / problem solving	mechanical : Magnetic attraction When troubleshooting the equipment, the set-up person could be injured by the magnetic attraction between magnet and steel plate.	Minimal Frequent Unlikely	Moderate	Excercise caution during removal and reposition of magnet.			
set-up person trouble-shooting / problem solving	electrical / electronic : Machine lack proper grounding When troubleshooting the equipment, the set-up person could be injured by short circuit due to improper grounding.	Serious None Negligible	Low	Perform frequent maintanence to check for exposed wires.			
set-up person trouble-shooting / problem solving	electrical / electronic : Insulation failure for heater wires When troubleshooting the equipment, the set-up person could be injured due to insulation failure of heater wires through thermal cycling and subsequent insulation failure.	Serious None Negligible	Low	Perform frequent maintanence to check for insulation condition.			
set-up person trouble-shooting / problem solving	electrical / electronic : Short Circuit When troubleshooting the equipment, the set-up person could be injured short circuit from the controllers.	Serious Remote Negligible	Low	Perform frequent maintanence to check for exposed wires.			
set-up person trouble-shooting / problem solving	ergonomics / human factors : Exertion When troubleshooting the equipment, the set-up person could be injured by exertion during the assembly and disaasembly of the product.	Minimal Remote Unlikely	Low	Take frequent breaks to recover from exhaustion.			
set-up person trouble-shooting / problem solving	ergonomics / human factors : Posture When troubleshooting the equipment, the set-up person could be injured by bad posture during the assembly and disassembly of the product.	Minimal Remote Unlikely	Low	Customize workplace to allow for better positioning of posture.			

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
set-up person trouble-shooting / problem solving	ergonomics / human factors : Repetition When troubleshooting the equipment, the set-up person could be complacent due to repetative nature of work.	Minimal Occasional Possible	Moderate	Take frequent breaks to prevent repetative feeling.			
set-up person trouble-shooting / problem solving	ergonomics / human factors : Long duration When troubleshooting the equipment, the set-up person could suffer from fatigue due to long duration.	Minimal Occasional Possible	Moderate	Take frequent breaks to prevent fatigue.			
set-up person trouble-shooting / problem solving	fire and explosions : Hot surfaces When troubleshooting the equipment, the set-up person could be injured by the hot surface of the chamber	Serious None Negligible	Low	Excercise caution during product handling. Install thermocouple to display surface temperature.			
set-up person trouble-shooting / problem solving	heat / temperature : Radiant heat When troubleshooting the equipment, the set-up person could be injured by the radiant heat emmited by the chamber due to faulty insulation.	Slight Remote Unlikely	Low	Excercise caution during product handling and perform frequent maintanence to check for insulation integrity			
set-up person trouble-shooting / problem solving	material handling : Excessive weight When troubleshooting the equipment, the set-up person could be injured by the weight of the project due to product handling.	Minimal Occasional Unlikely	Low	Excercise caution during product handling. Use aids such as lifts or cart as neccessay.			

As you can observe from the DesignSafe report above, the major risks involved in the operation of the product includes short circuits by exposed wires and crushing effect of the magnet. Although these hazards do not result in catastrophic accidents compared to scalding from hot surfaces, because the operator has to interact with these components on an everyday basis the risk is higher. The person most at risk of these hazards includes the operator and the set-up person. In the case of our lab, the operator is also usually the set-up person therefore he faces most of the risks. The DesignSafe report has given us a complete analysis of our project which prompted the group to incorporate extra safety features into our design. This includes the positioning of thermocouples on the outer walls of the chamber to monitor and display its temperature to the user. Another measure is the installation of gaseous detector near the operating area to detect for harmful emission of hydrogen and helium. However, DesignSafe has pointed out unexpected risks such as user fatigue due to long operating hours and repetitive tasks.

A Failure mode and effects analysis (FMEA**)** is a procedure for analysis of potential failure modes within a system for the classification by severity or determination of the failure's effect upon the system. It is widely used in the manufacturing industries in various phases of the product life cycle. Failure causes are any errors or defects in process, design, or item especially ones that affect the customer, and can be potential or actual. Effects analysis refers to studying the consequences of those failures[17]. Risk assessment is the identification of potential hazards during user interaction and the possible consequences. After which the major risks and victims will be identified in a report such as DesignSafe which may be used to incorporate extra safety features.

Zero risk refers to a situation where no hazards or accidents are guaranteed to happen. However this is an impossible scenario as hazards may stem from the simplest reason such as bad human posture. Therefore it is only realistic to pursue an acceptable risk level during operation where hazards exist but is reduced to a comfortable amount. This can be seen in my project where extra safety features are incorporated to reduce risks level associated with hazards that may have a catastrophic result. This has succeeded in reducing their risks level to moderate or low which is acceptable.

[17] Wikipedia, www.wikipedia.com

APPENDIX E: DESIGN ANAYLSIS ASSIGNMENT

(5) Manufacturing Process Selection

The product of our project is a machine that allows continuous fabrication of carbon nanotubes (CNTs). Therefore we assume that our target consumers are researchers in colleges who are interested in studying and manufacturing CNTs. A recent study has shown that there are approximately 4000 colleges in the United States[18]. Further assuming that only forty percent of those colleges have an engineering department, therefore only 1600 colleges may purchase our product. Lastly we assume that only ten percent of these colleges are interested involved in CNT study, thus we will most likely sell 160 machines in a year.

The first material we chose is alloy 6013 aluminum which is used to make the main chamber. The CES selector has suggested that ceramic molding casting is the best manufacturing process that we should use in the real world. According to the CES selector, this process is capable of producing complex shapes with a low tolerance of 0.002 inches. Furthermore it supports a wide range of ferrous and non-ferrous castings materials such as alloy 6013 aluminum. Lastly an economic batch size range from 50 to 1000 which is of the right size for our application. However the tooling and capital cost for this process is relatively high ranging from 200 dollars to 2000 dollars. This can be balanced by a higher retail price. As our product is highly specialized and our target groups are well funded research labs, we do not foresee price as a limiting factor.

The second material we chose is type 303 stainless steel which is used to make the stainless steel insert in our chamber. The CES selector suggested that electro-discharge machining is the best manufacturing process that we should use in the real world. According to the CES selector, this process is capable of machining hard materials such as stainless steel in small quantities to a high degree of accuracy. Its tolerance level is within 0.002 inches which is desirable because any misalignment in our chamber parts may adversely affect its performance. Furthermore an economic batch size range between 50 and 5000 units which is of the right size for our application. However it has a very slow machining speed, but we do not foresee this as a problem because our target volume is very small.

Overall I agree that these two process suggested by the CES selector would be the best manufacturing process to adopt in the real world.

[18] Google, http://answers.google.com, 2008