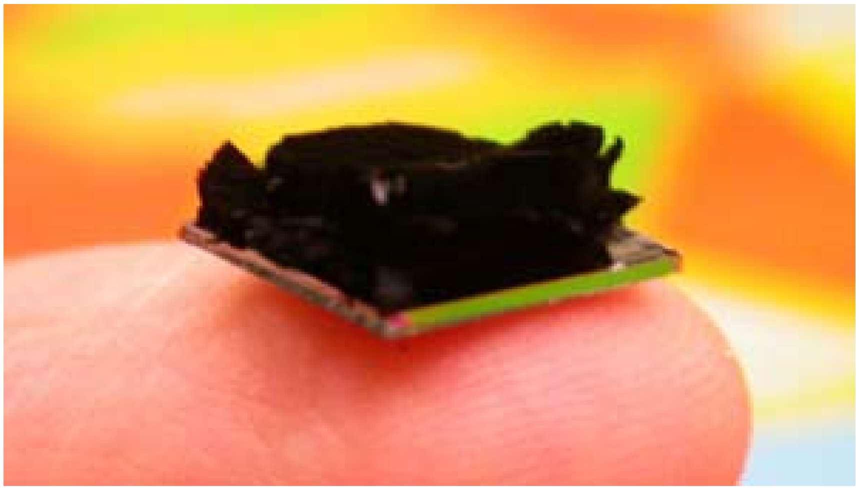
System for Dynamically-Controlled Growth of Hybrid Nanostructure Arrays



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EXECUTIVE SUMMARY

Carbon nanotubes (CNTs) and nanowires (NWs) have been applied in multiple fields due to their high strength, electrical conductivity, and optical properties. New types of nanostructure materials could be suitable for new applications. Our project is therefore to build a machine capable of growing two species of nanostructures on the same substrate. Currently, there exist multiple methods of growing nanostructures such as NWs and CNTs. However, little work has been done to combine methods and grow a hybrid structure. Our sponsor, John Hart, has therefore asked us to build a machine capable of growing such structures.

After a broad literature search, discussions with our sponsor, and multiple design iterations we have finalized our design to that shown in Fig 19(DR3 Presentation Schematic). Our design uses a single pump to move reaction and cleaning solutions into a reaction chamber where nanostructure growth will take place. The system will fully automate the process of switching reaction solutions, heating the reaction chamber, and electrodeposition.

The main subcomponent of our design is the reaction chamber. It consists of a rectangular quartz tube wrapped with a heating wire and sealed on both ends with stainless steel end-caps. Hoses connected to the end-caps are able to move reaction solution in and out of the reaction chamber. A thermocouple and two power wires are also fed in through the end-caps. These wires will provide power to the electrodes. The entire reaction chamber will be wrapped in insulating wool and mounted on firebricks within a metal enclosure.

Many other subcomponents are also incorporated into our design. This includes solenoid valves, a pump, a radiator, computer control electronics, and a power supply. Details of these components can be seen in section 3.1 and 3.2.

Various analyses were performed to help us determine our design parameters. First, a power analysis indicated that about 420W would be needed to heat the reaction chamber within 20s and this was used to size the heating coil. Second, we estimated the stress induced in the nanostructures from the solution flow would be a negligible 0.36 Pa. Thirdly, the steady-state temperature distribution was estimated and used to select reaction chamber materials and dimensions. This was also used to ensure that the reaction chamber seals will remain below their maximum service temperature of 200 °C. Finally, the thermal stress in the quartz tube was estimated to be 5.15 MPa which is safely below its 50MPa yield stress.

A material survey and selection was performed with the help of the CES software. This directed us to use stainless steel, quartz, and a machineable ceramic macor for reaction chamber materials. These materials provide excellent durability at high temperatures and in corrosive solutions.

We will use CNC milling, lathing, drilling to fabricate our prototype. Tests and validations could be executed afterward.

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1 INTRODUCTION

1.1 Introduction and Background

NWs and NTs are structures of nanometer scale. They are applied in multiple fields such as extremely strong materials and solar cells, due to their excellent properties such as high strength and high electrical conductivity. Hybrid nanostructure growth has not been investigated deeply into. Besides, there is no automated fabrication of it with high precision and accuracy. Our team aim at the fabrication of these hybrid materials, as shown in Fig 1. It will bring about more applications of nanostructure materials by increasing the number of their types. We also aim at a fully automated system for its growth with high accuracy, which will be applied for these fabrications conveniently.

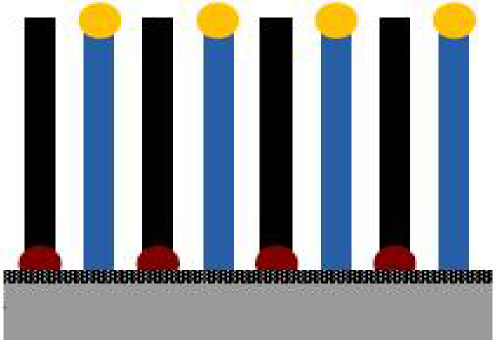


Fig 1: Hybrid Arrays

Our main sponsor is Prof John Hart. He required us to fabricate two types of nanostructures on one substrate and also a complete automated system for controlling the growth with desired transient responses. All these fabrication methods are inside solutions, which offers better environments for hybrid nanostructures growths. We researched the reagents and growth methods for different NWs and NTs. They usually require a temperature from room to 500 °C. The energy sources are always thermal energy and electrodeposition energy. A complete list of our research results could be seen in Appendix 1.

1.2 Customer Requirement and Engineering Specification

Our customer, Prof John Hart, has given us specific requirements. First, and most importantly, the machine must be able to automatically grow two types of nanostructures on the same substrate. This will require that the machine switch reaction conditions. Secondly, the machine must be convenient to use. This means that once the user sets it up and starts it, it should grow the structures automatically. It also means that the machine should grow the nanostructures in a reasonable amount of time. Specifically, our sponsor requested that the machine switch between reaction conditions within 30 seconds. Thirdly, our sponsor requested that the machine supply energy to the reaction site from multiple sources. It is desired that direct heating plus one or two additional energy sources be employed. A more specific list of the sponsor requirements can be seen in the QFD diagram in Appendix 2.

We generated customer requirements into engineering specifications. Before we finalized them, we have considered multiple controls, more specifically, those for pressure, mass, concentration, temperature, flow rate, and voltages for electro-deposition and for ultrasonication. We revised them through analysis and discussions. For the convenience of material selections, we determined to perform the reactions only in one atmosphere pressure. We could directly control reagent masses through pumping. Moreover, the concentrations of solutions will be ensured through reagents preparations and manually mixings, before they enter into our system. Therefore, we eliminated the pressure, mass and concentration controls. We then finalized our engineering specifications after these revises. First and foremost, target range for temperature control is 20 to 500 °C. It means that we will control our solutions to be from room temperature to a certain value less than 500 °C, for multiple reactions. Secondly, the settling time and switching time are respectively 60s and 30s. It requires a significant temperature rise in a period as short as 20s. At the same time, the substrate is set 1cm^2 in area. These requirements determined our preliminary analysis, concept generations and final design, such as the power requirement, pumping rate, and CAD model. A more specific list of the sponsor requirements can be seen in the QFD diagram in Appendix 2.

2 BRAINSTORMING AND CONCEPT GENERATION

In order to aid our brainstorming process, we broke the problem up into functional components as shown in Fig 2. We tried to make this figure as general as possible so that it would not limit our concept generation. The shaded region of the diagram represents our machine and the arrows crossing the borders of the shaded region represent the inputs and outputs of our machine. The white blocks in the diagram represent subcomponents of our machine.

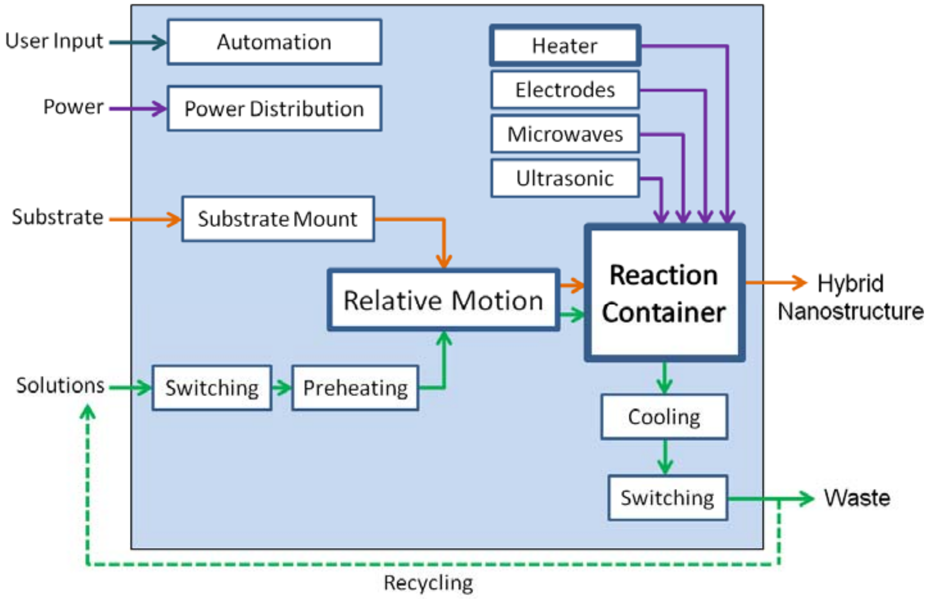


Fig 2: Functional Decomposition

The two main inputs are the Substrate and the Solutions. They will be routed through the system as shown in the diagram. First, some form of mounting, switching, preheating, and relative motion will be employed on them to allow for various reactions to take place. Different forms of energy will also be applied during the reactions. This will come from a heater, electrodes, microwaves, and/or ultrasonic.

When all of the reactions have completed, the only outputs should be waste material and a pristine hybrid nanostructure.

The other two inputs, User Input and Power, are connected to the Automation and Power Distribution subcomponents respectively. These two subcomponents are then connected to nearly every other subcomponent in the diagram. However, for the sake of clarity, we did not show these connections on the figure.

This diagram greatly helped our team understand the design problem. The most significant effect was that it helped our team communicate with each other about the various aspects of the problem.

The four members of our team sat around a table and sketched out possible solutions to the problem, according to our generalized functional diagram in Fig 2. We tried to remain open to all ideas and discouraged any criticism. We mostly focused on system-level ideas, but these naturally contained a number of component-level ideas. We came up with several good sketches for system level concepts and modules.

2.1 Hold Substrate Fixed and Switch Solutions

Our first system-level concept is to hold the substrate fixed in a reaction chamber and to switch solutions within the chamber. Various implementations of this design can be seen in Fig 3 to 5. In all of these sketches, a solution is drawn from a storage container and flown into the reaction chamber. These figures also illustrate some of our component-level concepts. They will be described next.

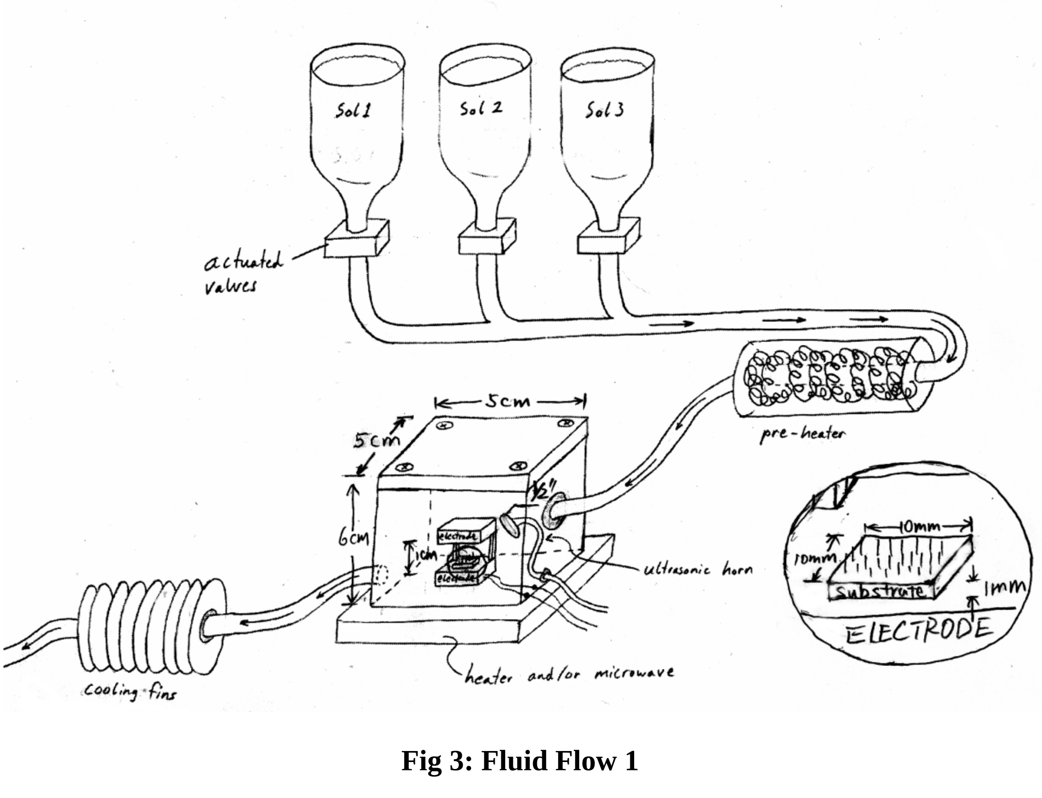


Fig 3: Fluid Flow 1

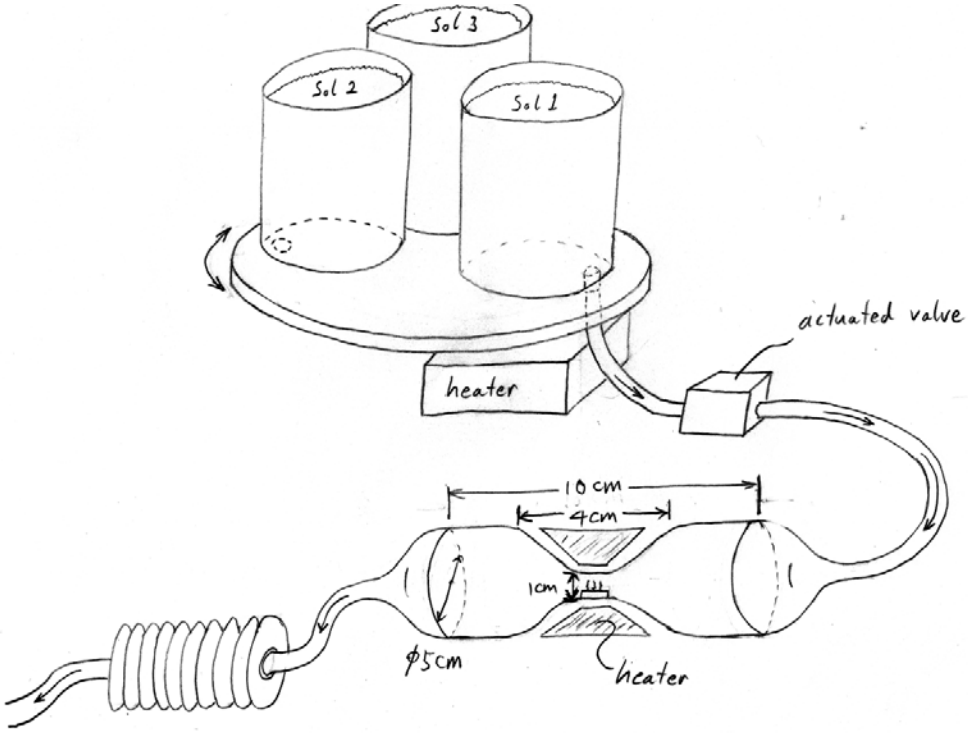


Fig 4: Fluid Flow 2

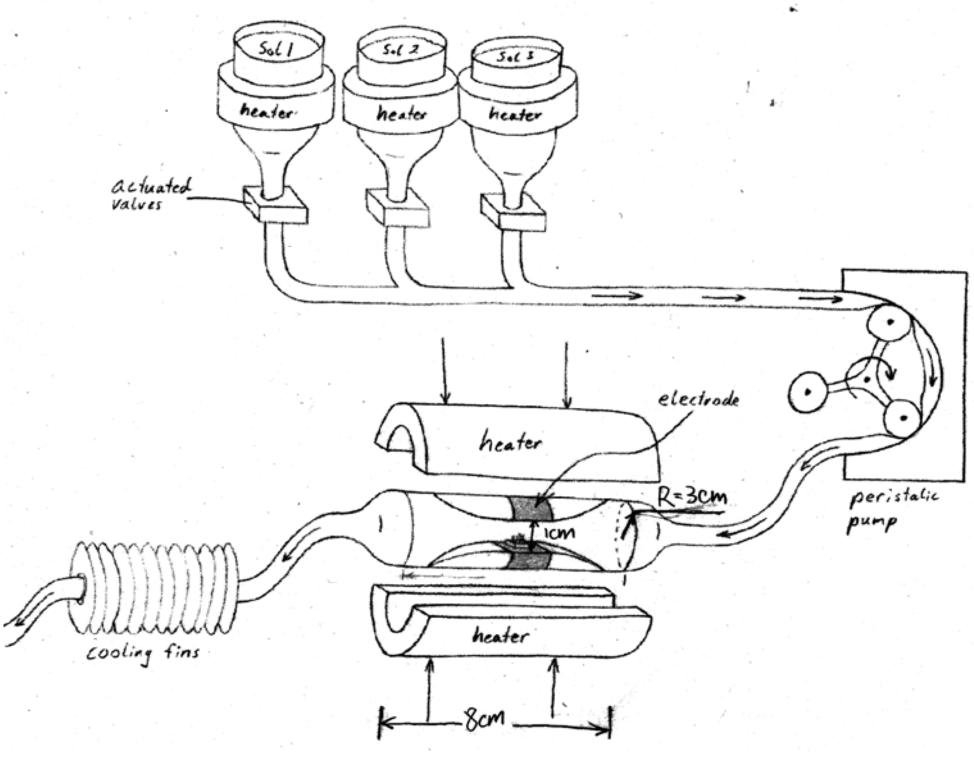


Fig 5: Fluid Flow 3

2.1.1 Solution Switching

We generated two different methods of implementing the solution-switching component. The first uses an actuated valve for each solution as shown in Fig 3 and 5. These valves would be controlled such that the correct fluid would be drawn at the correct time. The second concept would use a revolving table to switch between solutions as shown in Fig 4. In that design, a solution would only flow if the hole in the bottom of its container lined up with a hole in the table. This hole is then connected to a tube which supplies the solution to the rest of the system. In this case, the rotation of the table would be controlled such that the correct solution flows through the system at the correct time.

2.1.2 Solution Transportation

Two different methods for moving the fluid through the system were generated. The first is to use a pump as shown in Fig 5. The second is to rely on gravity as shown in Fig 3 and 4.

2.1.3 Solution Preheating

Two different methods for preheating the solution were generated. One is to preheat the solution as it is being transported to the reaction chamber as shown in Fig 3. The other is to preheat the solution while it is in its storage container as shown in Fig 4 and 5.

2.1.4 Heating

We generated three different methods for heating the reaction chamber. The first of these is to use hotplate as shown in Fig 3. The second is to enclose the chamber with heating coils as shown in Fig 5. A more detailed view of this can be seen in Fig 6. Finally, the third method is to heat the reaction chamber with a solid-state heater as shown in Fig 7.

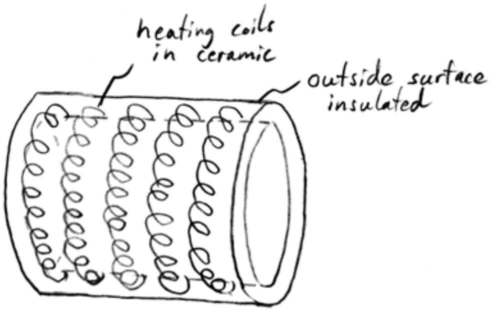


Fig 6: Coil Heating

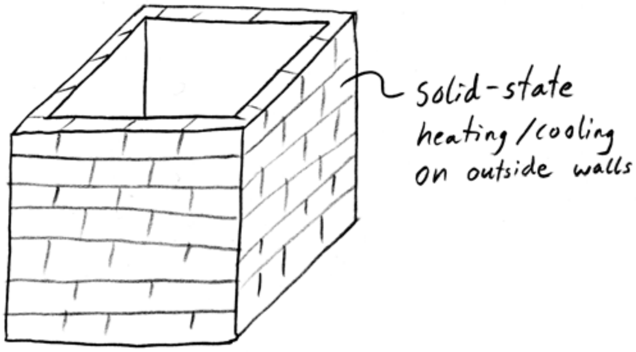


Fig 7: Solid State Heating

2.1.5 Electrolysis

Electrolysis will be employed by either building electrodes into the substrate mount or by building a separate structure which encloses the substrate mount.

2.1.6 Microwave

Microwave irradiation will be applied by generating microwaves outside of the reaction chamber and directing them through the chamber. A focusing horn may be employed to direct the microwaves.

2.1.7 Ultrasonic

Ultrasonic energy will be employed by placing an ultrasonic horn inside of the reaction chamber as shown in Fig 3. The position of this probe will be flexible so that it can be repositioned for each experiment. A bushing will be used where the horn intersects the chamber wall. If selected properly, this bushing will isolate the chamber from the ultrasonic frequencies and will prevent leaking.

2.1.8 Reaction Chamber

Three different reaction chamber designs were generated. The first uses a square shape as shown in Fig 3. In this design, the substrate is accessed by unscrewing the top. The second design uses a tube which has been deformed by pinching the center portion as shown in Fig 4. The substrate would then be placed in the narrow portion of the tube. This idea came from our sponsor, John Hart. The third design uses an undeformed tube with specially shaped inserts as shown in Fig 5. These inserts will contain the substrate mount and electrodes and will be shaped to provide a desirable reaction chamber volume.

2.1.9 Substrate Mount

Three different substrate mounting designs were also generated. The first is to use an intermediate mount as shown in Fig 8. In this design, the substrate is first attached to a mount, and then the mount is attached to the inside of the reaction chamber. This would provide a convenient way to load or unload the substrate. The second design uses a clip to hold the substrate in place as shown in Fig 9. Although only one clip is drawn, multiple clips may be used in this design. The third design is to use a clamping mechanism similar to those used to attach microprocessors on motherboards. An illustration of this is shown in Fig 10. In this design, clamping levers would apply a force on the substrate to hold it into a recessed area. The clamping levers would then be held in place by inserting a pin.

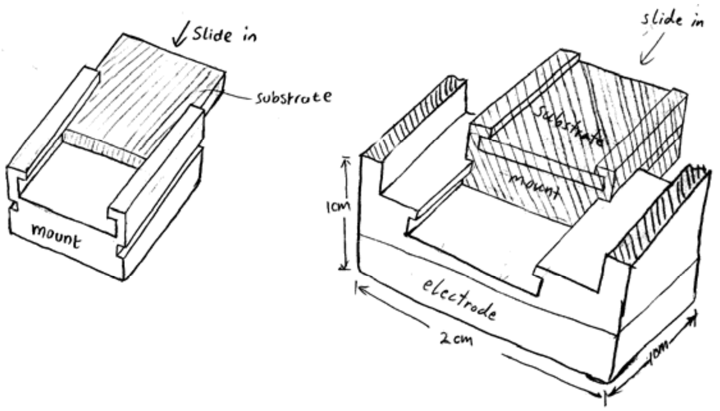


Fig 8: Intermediate Mount

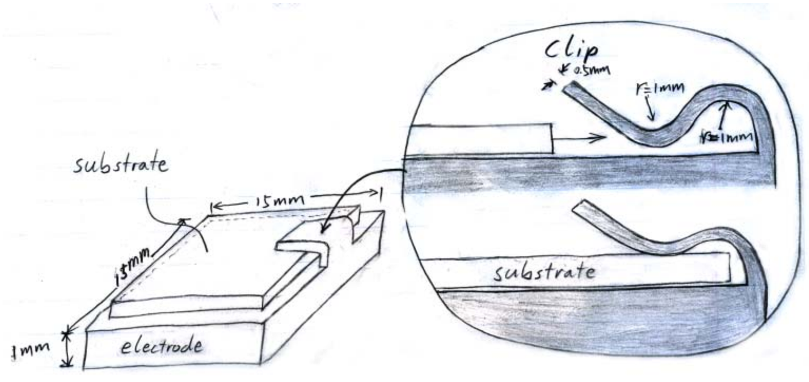


Fig 9: Substrate Clip

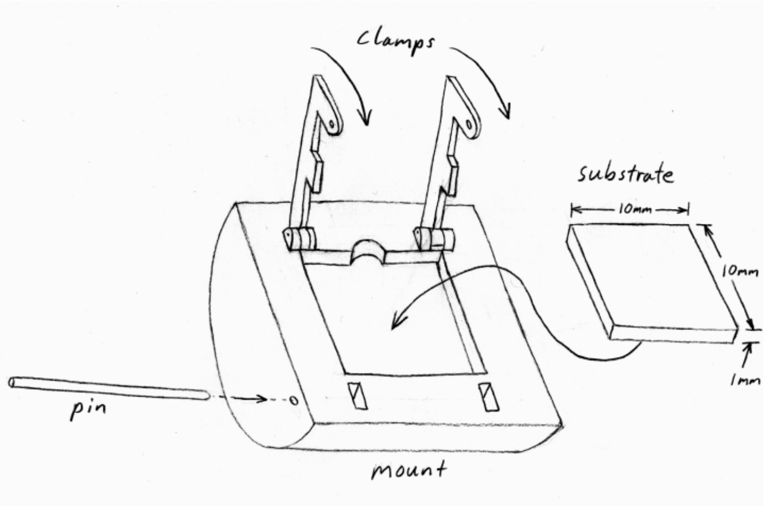


Fig 10: Substrate Clamp

2.1.10 Solution Cooling

As the waste solution exits the reaction chamber, it will be cooled by cooling fins as shown in Fig 3, 4, and 5. An alternative method would be to allow the solution to cool on its own after it exits the machine.

2.1.11 Waste Switching

The waste solution exiting the reaction chamber will be directed into different waste containers. This will be achieved by either using actuated valves or by switching the waste containers using a rotating table.

2.2 Moving Substrate through the Air between Solutions

Our second system-level concept is to move the substrate through the air between solutions. This is done by removing the substrate mount from one solution, applying some relative motion, and inserting it into a different solution. Various implementations of this design can be seen in Fig 11 and 12. These figures also illustrate some of the component-level concepts which will be described next.

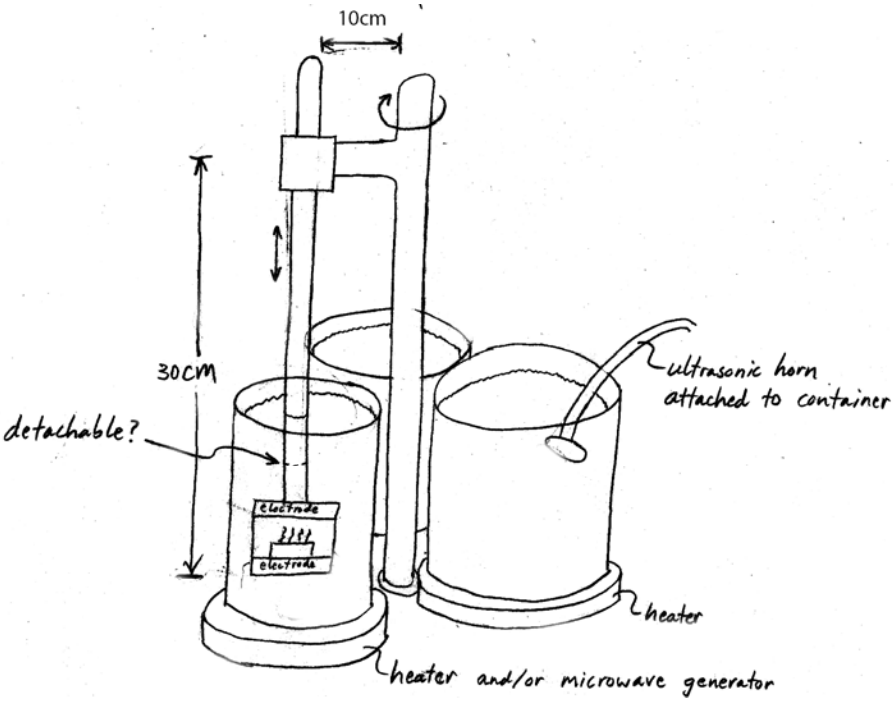


Fig 1: Actuated Arm

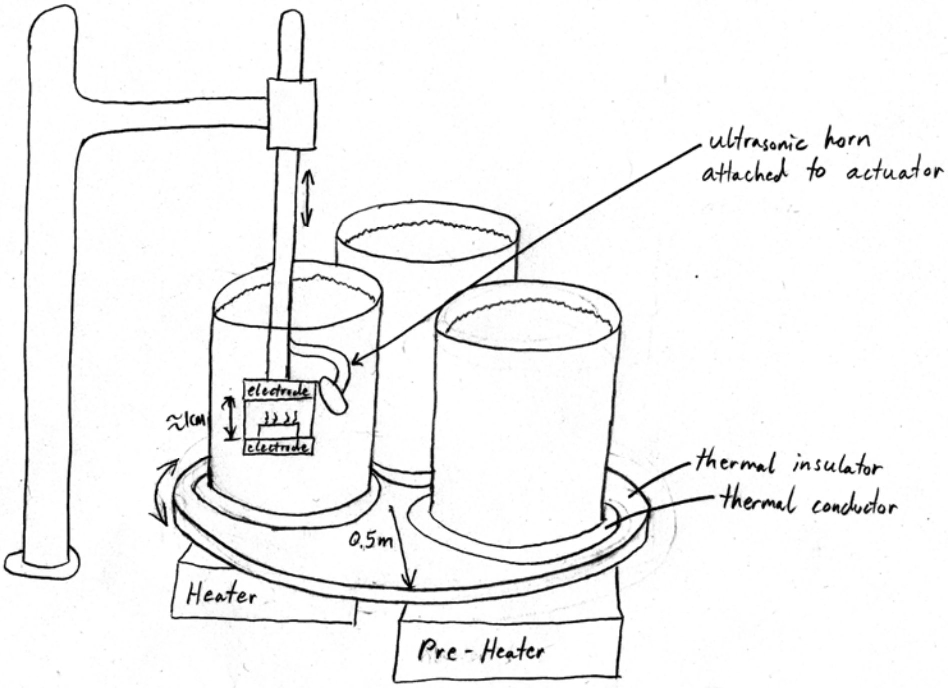


Fig 12: Turn Table

2.2.1 Solution Switching

We generated two different methods of moving the substrate between solutions. The first method is shown in Fig 11. Here an actuated arm moves the substrate vertically and in a circle. The second method, shown in Fig 12, uses an actuator which moves vertically and a rotating table.

2.2.2 Heating and Preheating

Three different methods could be used for heating and preheating. The first method would be to attach a heater to each solution container and heat each solution prior to and during use. This could be done by using hotplates as shown in Fig 13 or by wrapping the containers with heating coils as shown in Fig 14. The second method would be to use only one heater and one preheater underneath the turntable as shown in Fig 12. The turntable would then be designed to conduct heat from the heater only to the targeted solution.

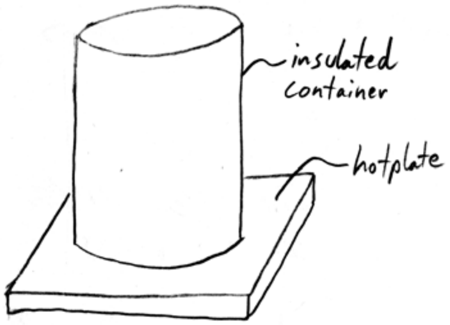


Fig 13: Hotplate

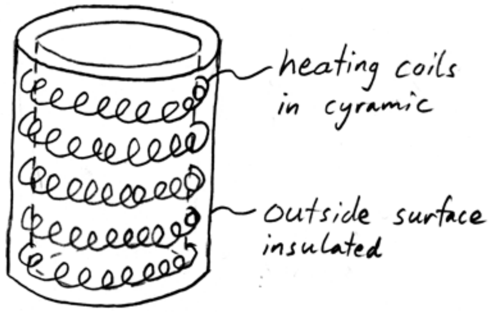


Fig 14: Heating Coils

2.2.3 Electrolysis

Electrolysis can be implemented by building the electrodes directly into the substrate mount and moving them between solutions with the substrate. This is shown in both Fig 11 and 12. An alternative approach would be to leave the electrodes in each of the containers and mechanically slip the substrate between them.

2.2.4 Microwave

Microwave can be implemented by generating the microwaves a container and directing it through the container.

2.2.5 Ultrasonic

We generated two different methods for implementing ultrasonic. The first is to attach the ultrasonic horn to one of the containers as shown in Fig 11. The second is to attach the ultrasonic horn directly to the actuated substrate mount as shown in Fig 12.

2.2.6 Substrate Mount

The same substrate mounting methods shown in Section 2.1.9 could also be used in this system-level design.

2.3 Wild Concept: Move Substrate between Solutions without Air Contact

Our third system-level concept is to move the substrate between solutions without contacting the air. We viewed this as a wild idea because of the stringent requirement that the solutions do not mix with each other and that they remain in layers. Three various implementations of this concept can be seen in Fig 15, 16 and 17.

The first of these is titled "Elevator" because an actuated wall moves the substrate vertically between the solution layers.

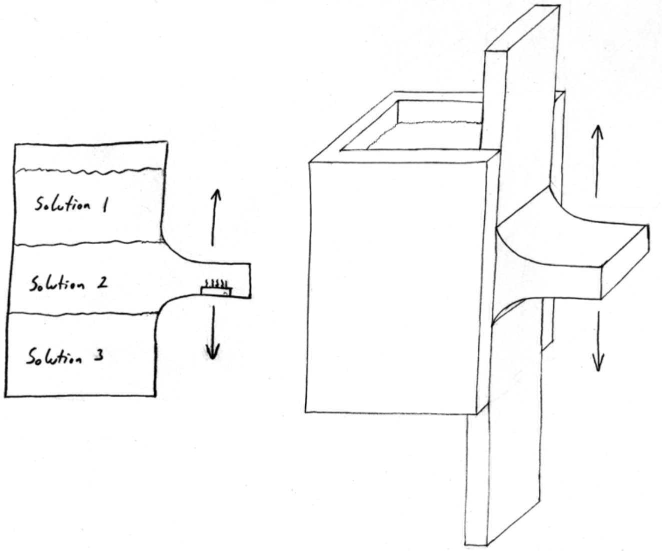


Fig 15: Elevator

The second variation of our wild concept, shown in Fig 16, is titled "Rotation" because the substrate would be mounted in a rotating tube. The rotation of the tube would effectively move the substrate through different fluid levels as shown.

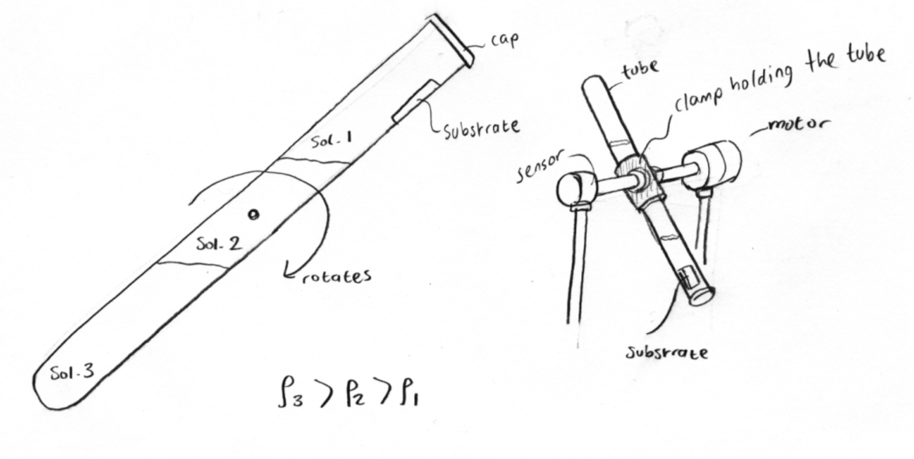


Fig 16: Rotation

Finally, the third variation, shown in Fig 17, employs a lifting mechanism which travels along a track submerged in a cleaning solution. This lifting mechanism then lifts the substrate into reaction solutions which float on top of the cleaning solution.

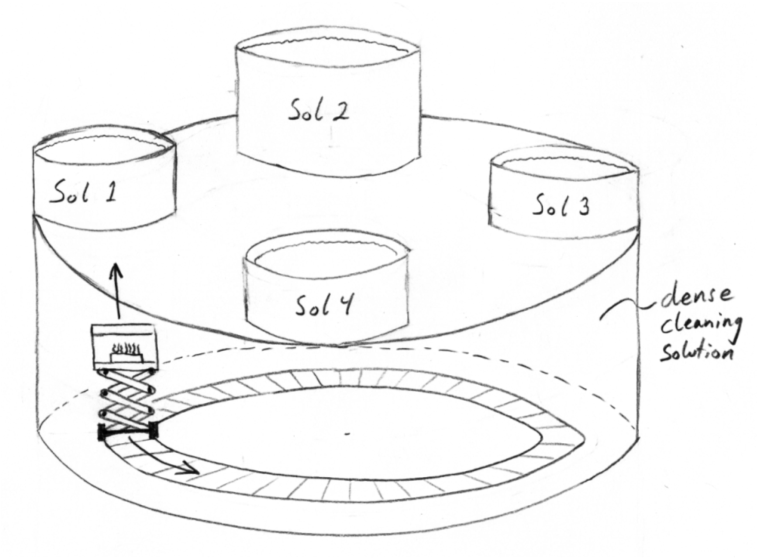
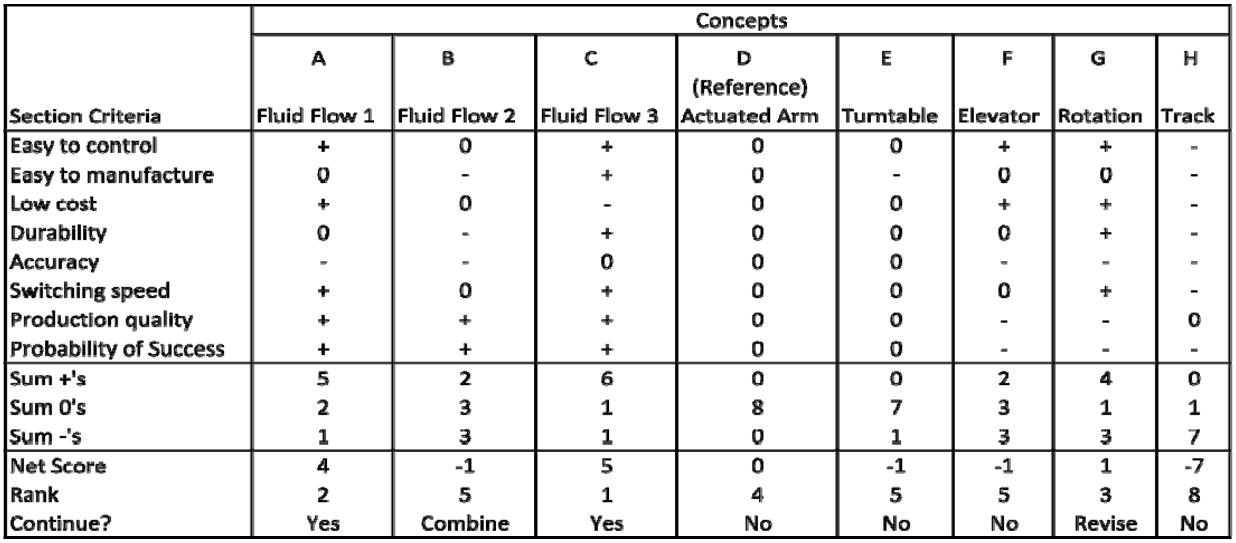


Fig 17: Submerged Track

2.4 Concept Evaluation

We scored our three system-level concepts along with their variations. They were evaluated by section criteria consisting of control and manufacturing convenience, accuracy and flexibility, the probability of making products and their quality, durability and cost. The concept for reference is Actuated Arm, as shown in Fig 11. It leads to very low scores of wild concepts, and relatively higher scores for Fluid Flows, due to their differences of product qualities and cleaning effects.

The best system-level concept is Fluid Flow 3, as shown in Fig 5. It will switch different growth conditions by pumping solutions and controlling valves, preheat different solutions by individual heaters before fluid flow, and drive the reagents into a cylindrical reaction chamber with appropriately shaped middle part for locating both electrodes and substrate mount. We chose it as our system-level concept for our design plan, due to accurate flow rate control by pumping, good preheating and heating condition, well shaped reaction container and located electrodes.



Section Criteria	A Fluid Flow 1	B Fluid Flow 2	C Fluid Flow 3	D (Reference) Actuated Arm	E Turntable	F Elevator	G Rotation	H Track
	Concepts							
Easy to control	+	0	+	0	0	+	+	-
Easy to manufacture	0	-	+	0	-	0	0	-
Low cost	+	0	-	0	0	+	+	-
Durability	0	-	+	0	0	0	+	-
Accuracy	-	-	0	0	0	-	-	-
Switching speed	+	0	+	0	0	0	+	-
Production quality	+	+	+	0	0	-	-	0
Probability of Success	+	+	+	0	0	-	-	-
Sum +'s	5	2	6	0	0	2	4	0
Sum 0's	2	3	1	8	7	3	1	1
Sum -'s	1	3	1	0	1	3	3	7
Net Score	4	-1	5	0	-1	-1	1	-7
Rank	2	5	1	4	5	5	3	8
Continue?	Yes	Combine	Yes	No	No	No	Revise	No

Fig 18: Selection Matrix

It was further enhanced through preliminary analysis. From our power analysis, the temperature near the substrate could be raised up by 500 °C in 20s without any additional preheating. Besides, three way valves perform better for combining tubes. Moreover, rectangular reaction chamber is more fit for locating electrodes and substrate. These will be shown more in detail in the following final design analysis section.

3 FINAL DESIGN AND ANALYSIS

This section presents our final design and the analysis which helped form our design. Fig. 19 shows the system flow of our design and its important components.

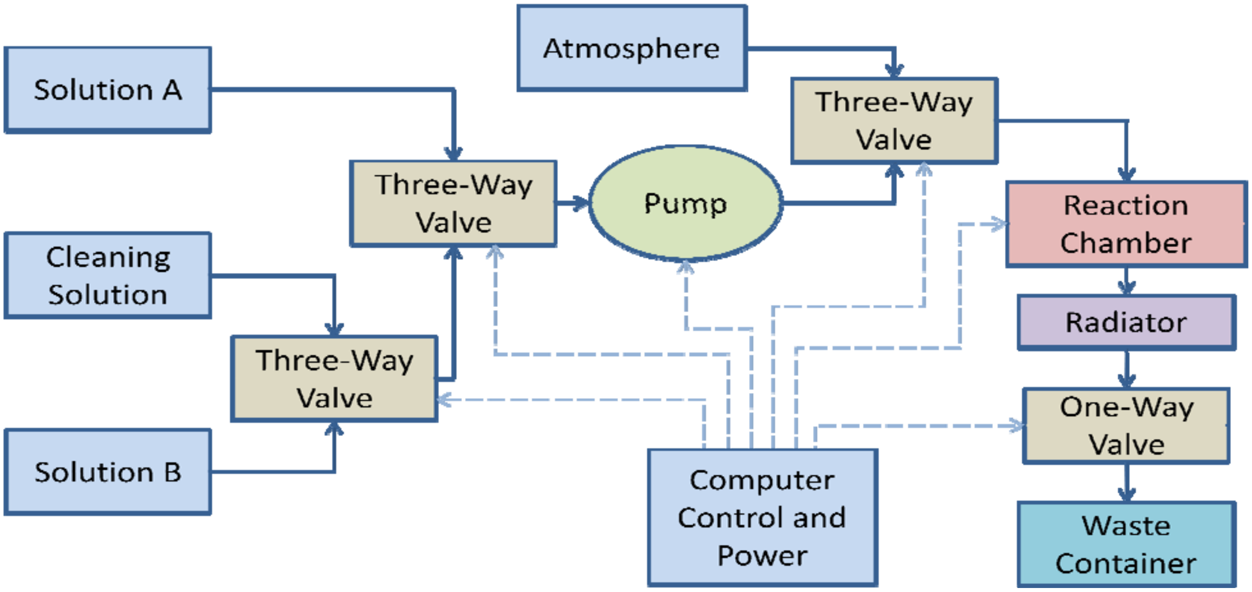


Fig 19: The System Flow Chart for the Final Design

3.1 CAD Model of the Reaction Chamber

The reaction chamber is the most important part of our system because this is the place where the nanostructure is fabricated. The structure of the chamber is designed to hold the electrodes and the substrate firmly while avoiding short circuit between the electrodes and the steel casing. The shape and the dimensions of the chamber is designed to minimize the volume, which means that we can heat the solution faster and switch between solutions faster.

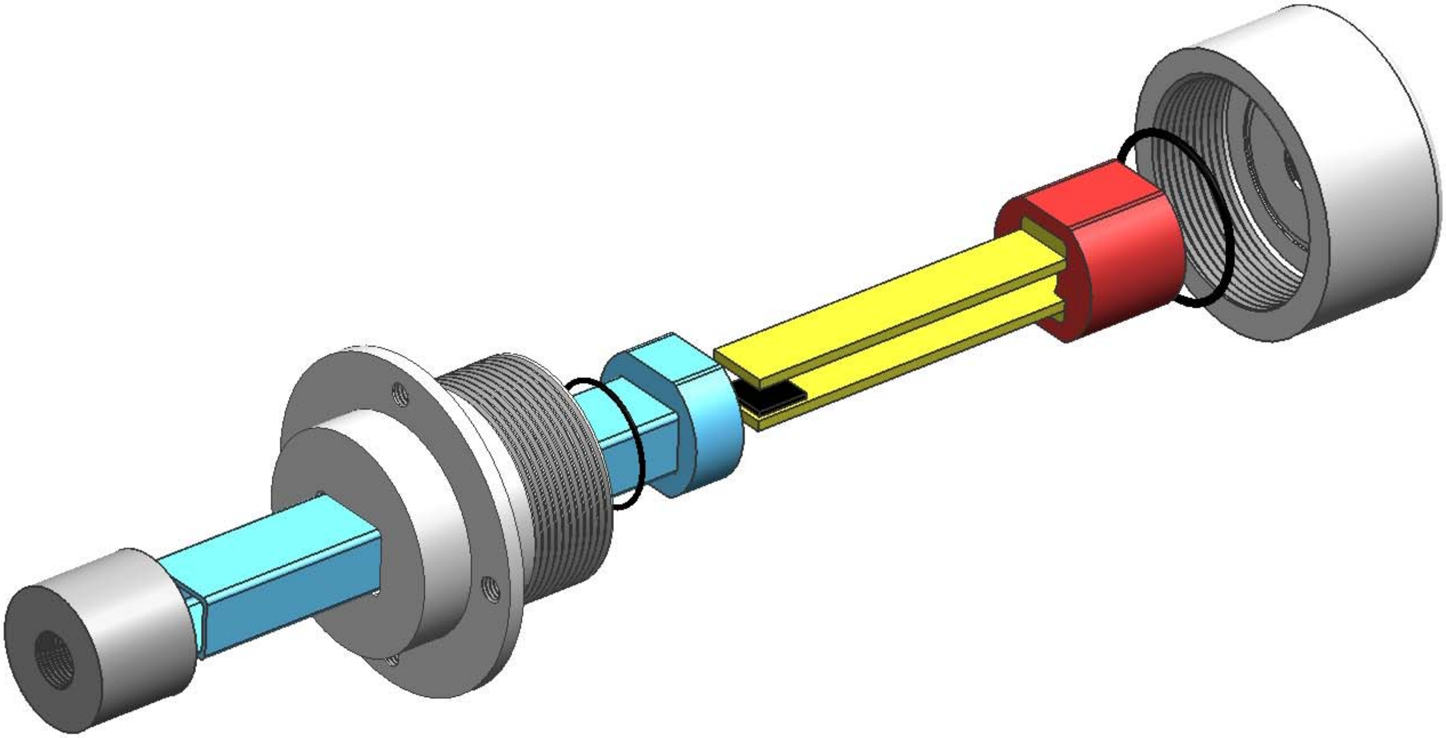


Fig 20: Reaction Chamber Parts and Assembly

All of the parts listed for our design need to be manufactured and then assembled together. The materials used for the reaction chamber are stainless steel type 304, Macor “machinable ceramics”, quartz and polymer o-rings. Following is the list of the parts of the reaction chamber and their detailed specifications. The cross sectional view of the reaction chamber and the clearances can be seen in the Appendix 9.

3.1.1 Electrode Mount

Material: Macor

This part is made of Macor because of the high electrical resistance of the ceramics. This part along with other ceramics is used to separate the electrode from the steel casing. The rectangular holes on one of the surface of the part are where we slide the electrodes in and the circular hole is where the fluid will come in. The circumference of the electrode mount is shaped so that we can only insert the part with the correct alignment.

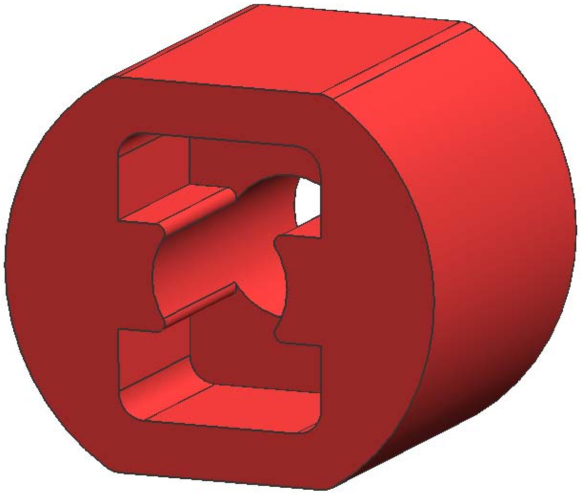


Fig 21: Electrode Mount

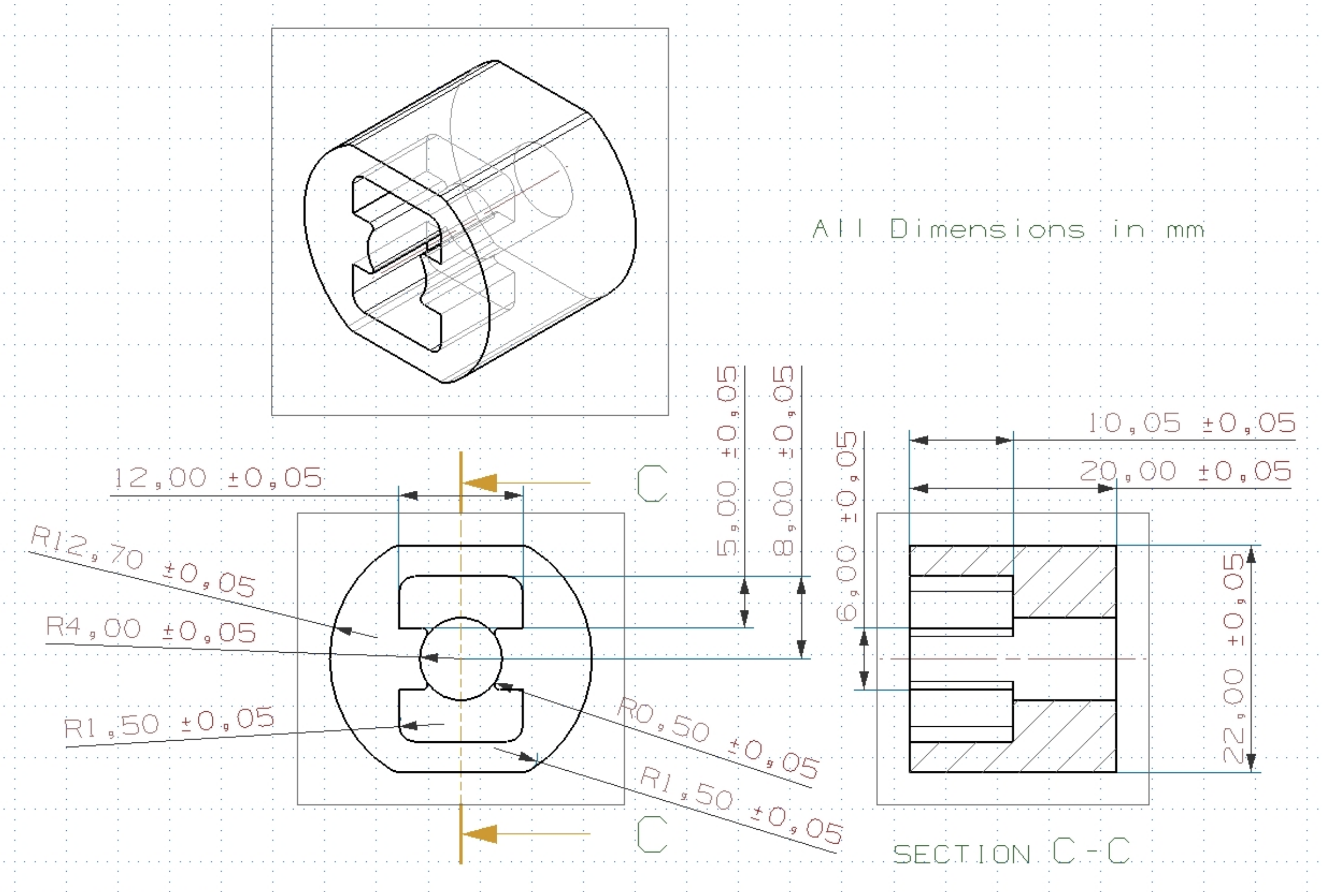


Fig 22: Engineering Drawing of the Electrode Mount

3.1.2 Quartz Tube

Material: Quartz and Macor

The quarts tube is where the reaction takes place; therefore this part is extremely important to the success of this project. In our design, this quartz tube has a flange at one its end to prevent this part from moving. Unfortunately, the quartz tube available in the market is just a rectangular tube, which is why we need to manufacture a flange for this part ourselves. The flange is made of Macor and needs to be cemented to the quartz tube.

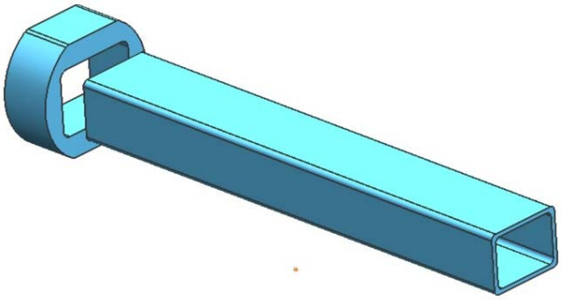


Fig 23: Quartz Tube and the Manufactured Macor

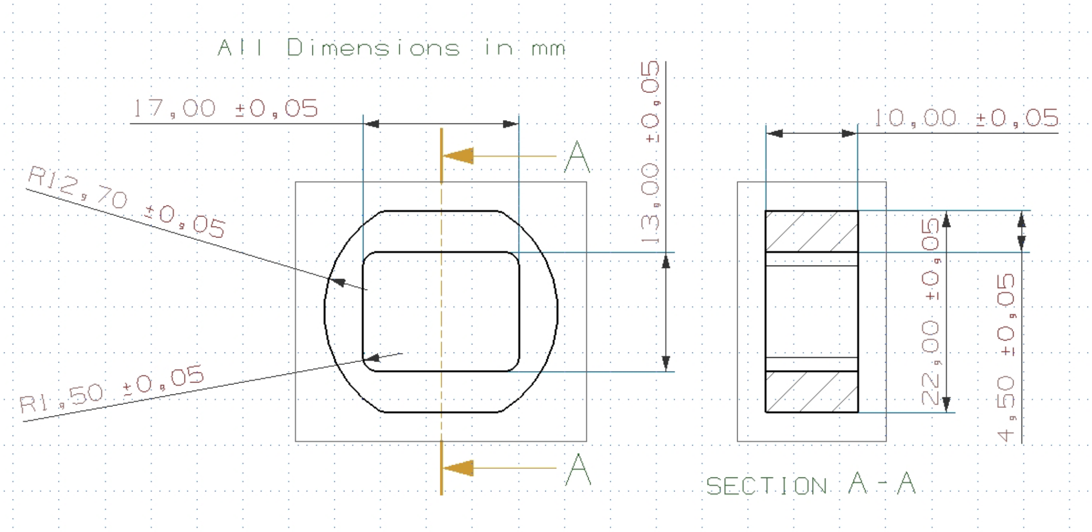


Fig 24: Engineering Drawing of the Macor Piece

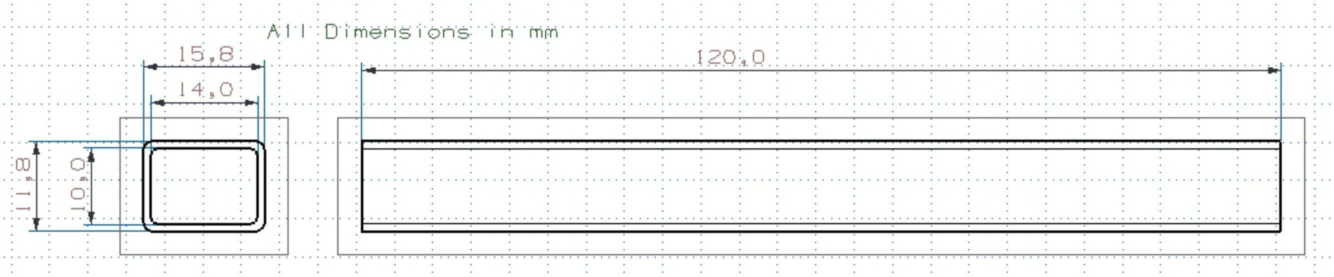


Fig 25: The Quartz Tube

3.1.3 Electrodes

Material: Stainless Steel Type 304

The pair of electrodes in the picture is used for electrodeposition growth and also as the substrate mount. The substrate is mounted on the electrode, possibly on the top piece, by using a clip (not pictured). The substrate used should be at least 1 cm2, but we need to add some space on the substrate for attaching the clip and still have growth area of 1 cm2. The cables connecting the electrodes to the power supply is attached into the M1 threaded hole in the electrode and then screwed by the appropriate M1 screws.

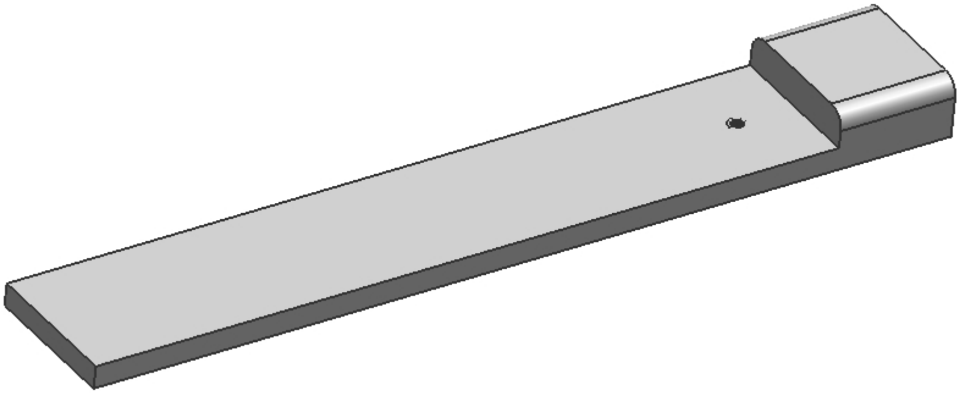


Fig 26: A Single Electrode

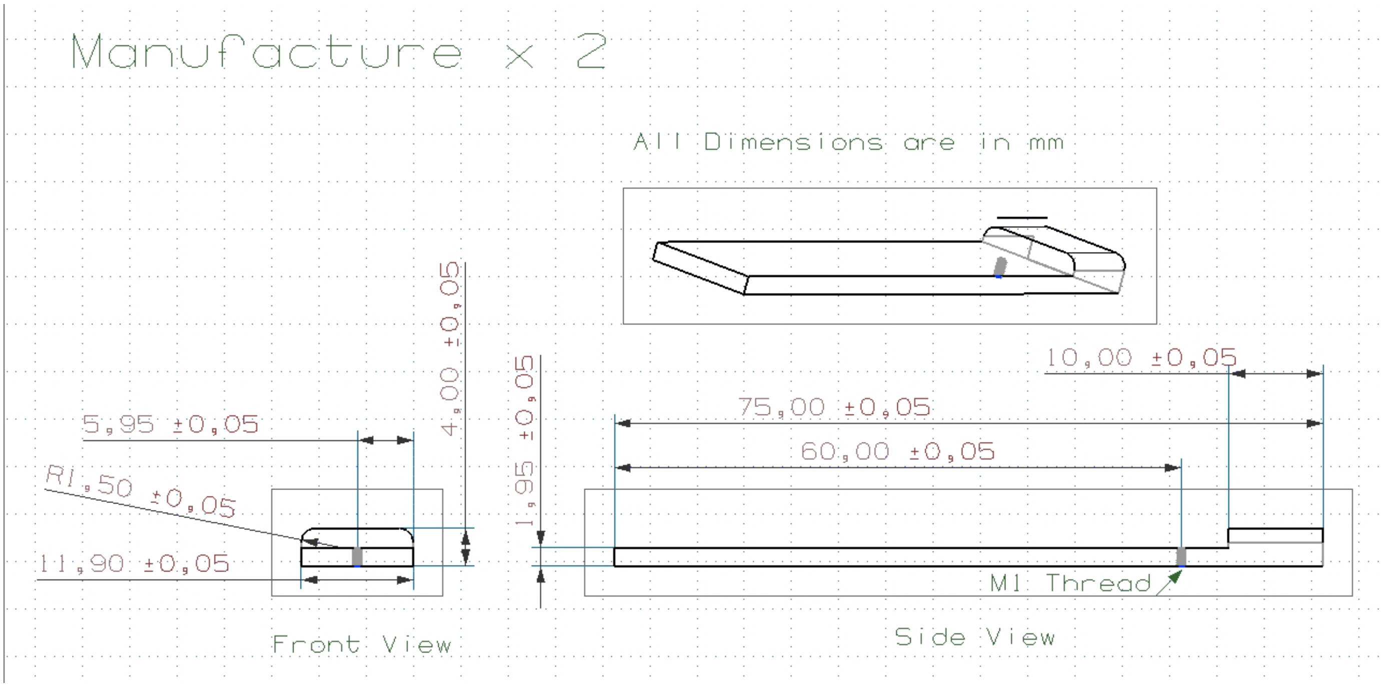


Fig 27: Engineering Drawing of the Electrodes

3.1.4 Steel Casing

Material: Stainless Steel Type 304

This casing envelops the base of the quartz tube and the electrode mount. There are 2 Viton O-Rings used in 2 different locations inside this casing to prevent the solution from leaking out. The “body” and “cap” of this casing is threaded so the chamber can be tightened with enough force to let the o-rings deforms and prevent any leakage.

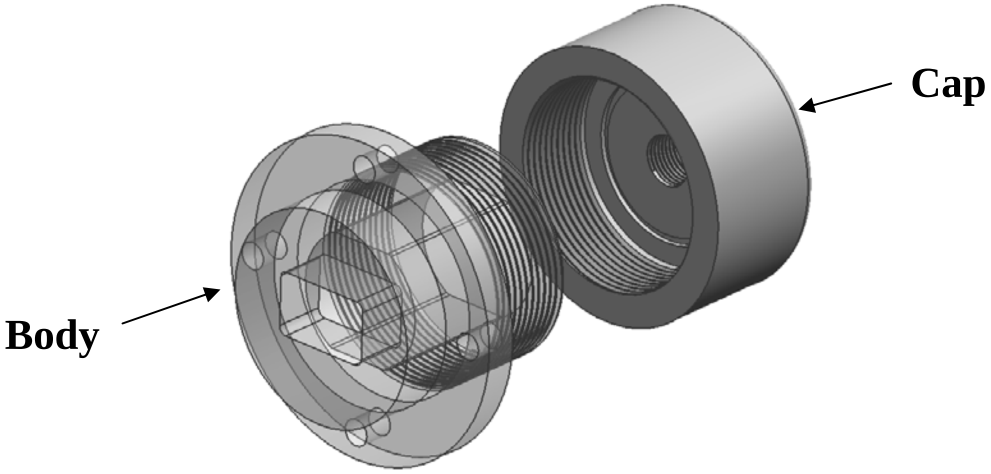


Fig 28: Steel Casing Body and Cap

3.1.4.1 Body

The inner hole of the “body” is shaped in such a way to align the electrode mount correctly and prevent them moving. We provide enough clearance for the electrode mount and quartz tube to slide into the hole in the body.

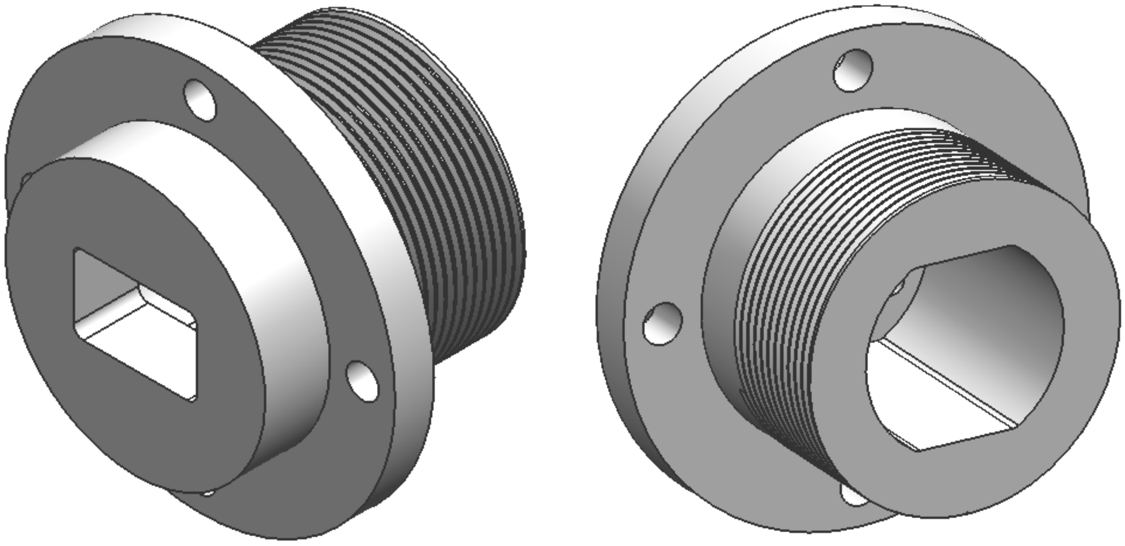


Fig 29: The Body of the Casing

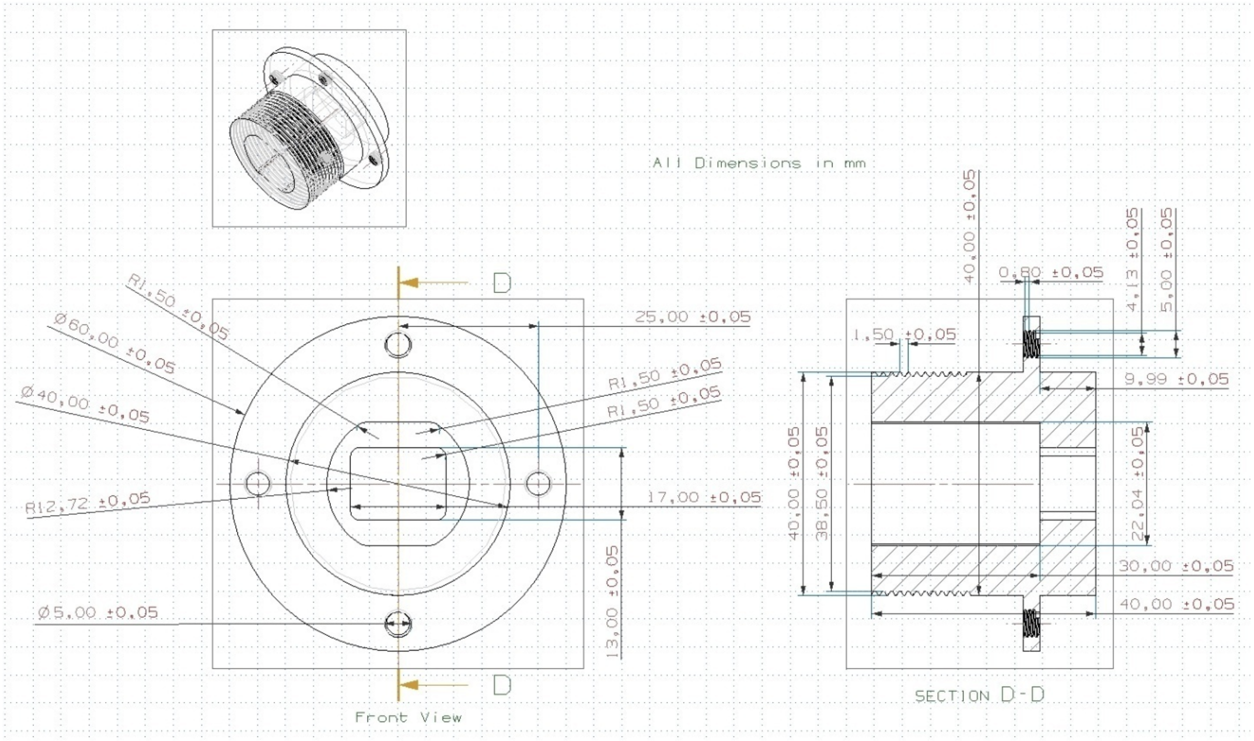


Fig 30: Engineering Drawing of the Body of the Steel Casing

3.1.4.2 Cap

The inner wall of the base of the cap is grooved to provide a space to put in the o-ring. The hole from where the fluid comes in is threaded to put in a Female NPT 1/8, which is connected to a polymer pipe.

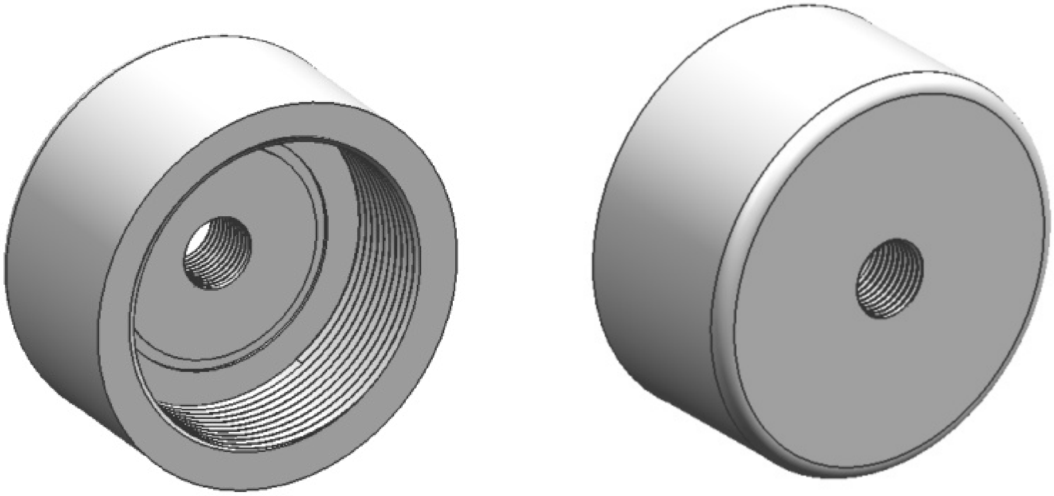


Fig 31: The Cap of the Casing

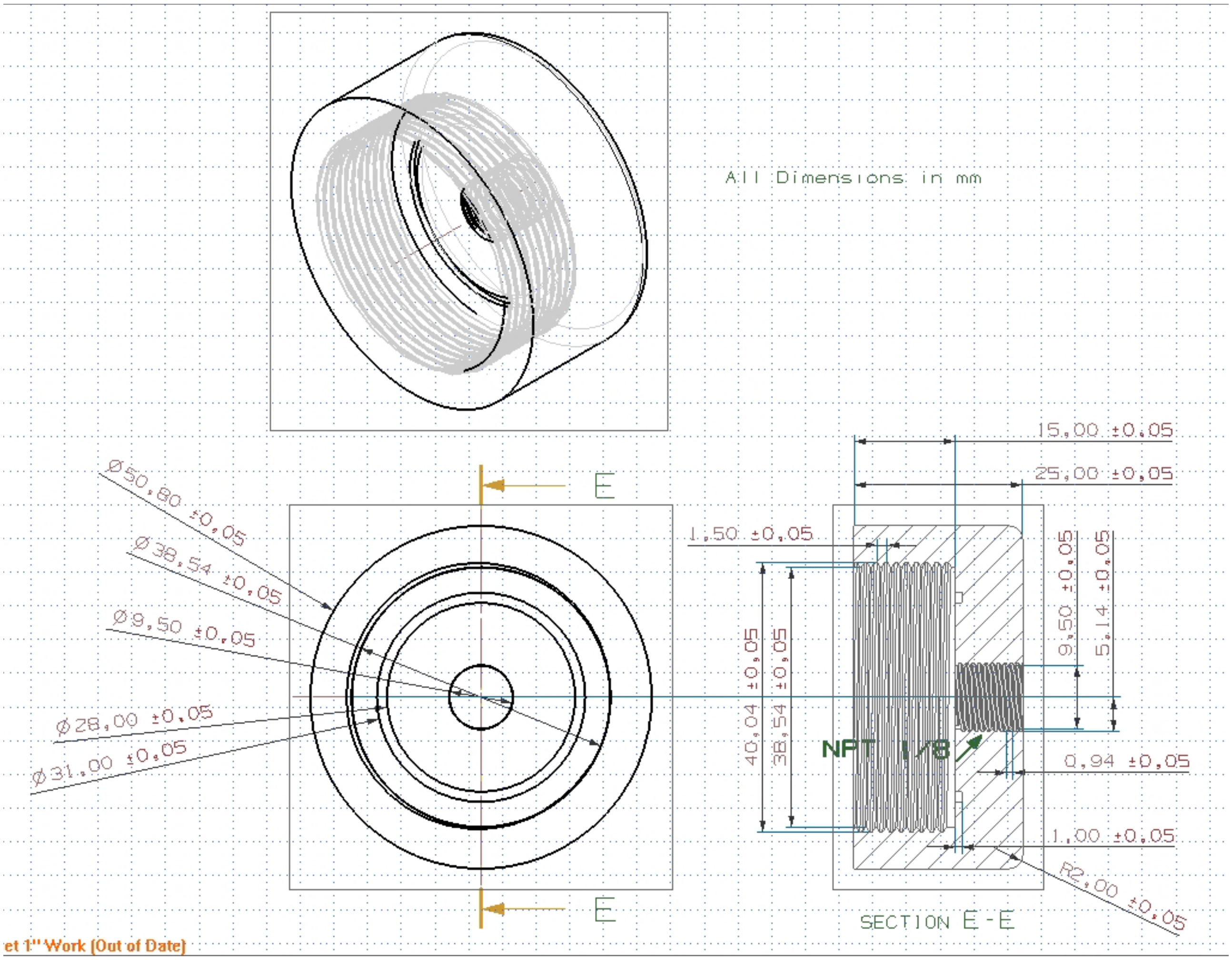


Fig 32: Engineering Drawing of the Cap of the Steel Casing

3.1.5 Output Cap

Material: Stainless Steel Type 304

The output cap is the part connecting the end of the quartz tube into another NPT 1/8 fitting. This fitting connects into a metal tube which connects to a radiator to cool the hot liquid down to a safe temperature for a polymer pipe to be used. The quartz tube will be slid into the rectangular hole and then cemented in place.

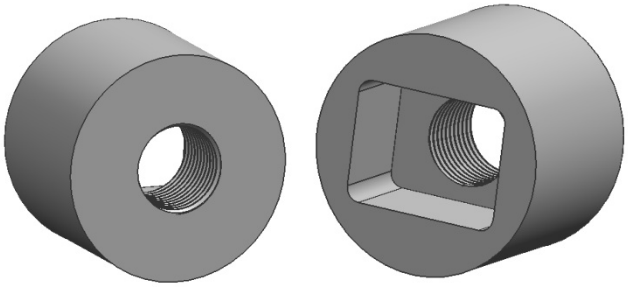


Fig 33: Output Cap

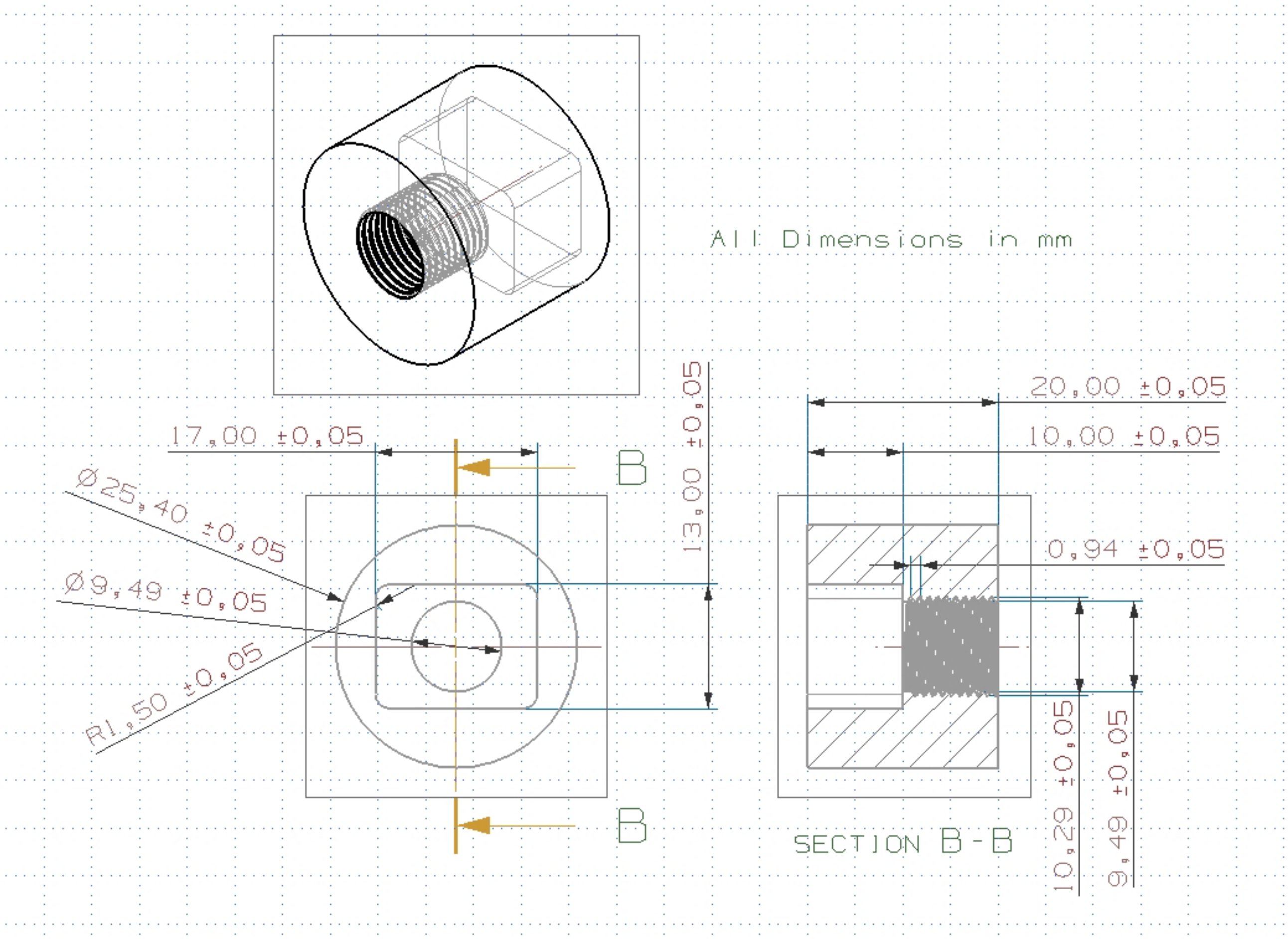


Fig 34: Engineering Drawing of the Output Cap

3.1.6 O-Rings

Material: Viton

We have two polymer o-rings in our system and their only purpose is to seal the steel casing so that the solution does not escape from the system. This part is important because we are dealing with hot solution and we don't want anything to leak out from our system. We also need to make sure that the solution near the o-rings is in the safe operating temperature range of the o-rings. The first o-ring is sealing the gap between the steel casing's body and the cap while the second o-ring is sealing the gap between casing's body and the quartz tube.

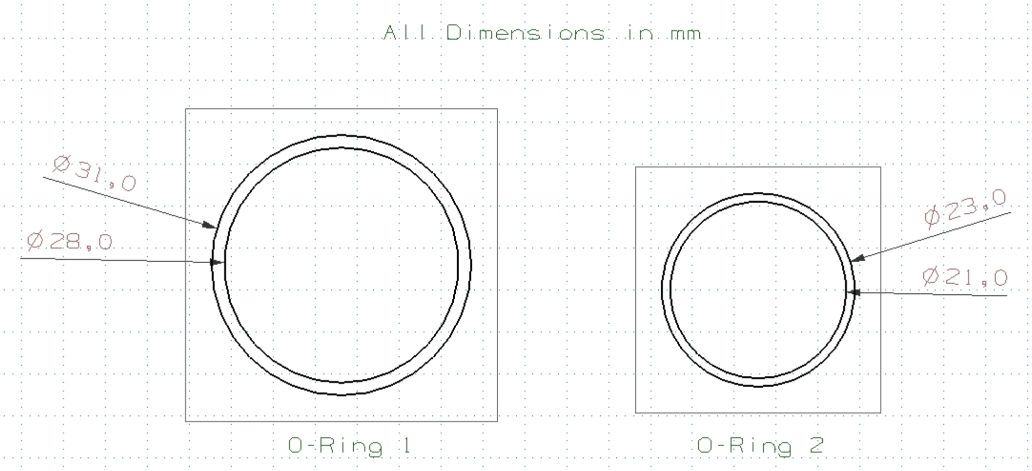


Fig 35: O-Rings

3.2 Other Components

Several other important components include the solenoid valves, pump, radiator, and power supply. These items will be described next.

3.2.1 Solenoid Valves

The solenoid valves used in our system are shown below. They are made by Cole Parmer, require 24V to operate, and draw 8 watts apiece. The ports for each valve are female NPT 1/8. The location of these valves within our overall system can be seen in the Fig 19 (this is the schematic).

The valves will be powered by the power supply listed below. Each one will be controlled by a digital output on our DAQ hardware and a solid state, optically isolated, relay.

Fig 36: Cole Parmer Three-Way Solenoid Valve

Fig 37: Cole Parmer Two-Way Solenoid Valve

3.2.2 Pump

The Watson-Marlow peristaltic pump, shown below, will be used to move solutions throughout the system. It includes a 35Watt 350 RPM motor with a speed controller. We will use 1/4" Bioprene tubing which is rated at 3.6 ml/rev. Therefore, the pumps maximum flow rate will be 1260 ml/min. The motor requires 24V which will be provided by the power supply listed below.

The speed of the pump is controlled by two low power, 1-5V, command signals. The first signal controls the speed of the pump and the second signal controls the direction. These signals will be generated by an analog output and a digital output on our DAQ hardware.

Fig 38: Watson-Marlow 313 VDL/D Peristaltic Pump

3.2.3 Radiator

The figure below shows the radiator that will be used to cool solutions as they exit from the reaction chamber. This radiator will be purchased as part of a PC Cooling System and then removed and placed in its own housing. The fan from the original cooling system will also be used but will be thermally isolated from the radiator. The plastic part shown in Fig 39 will be cut away for avoid likely melting in high temperature.

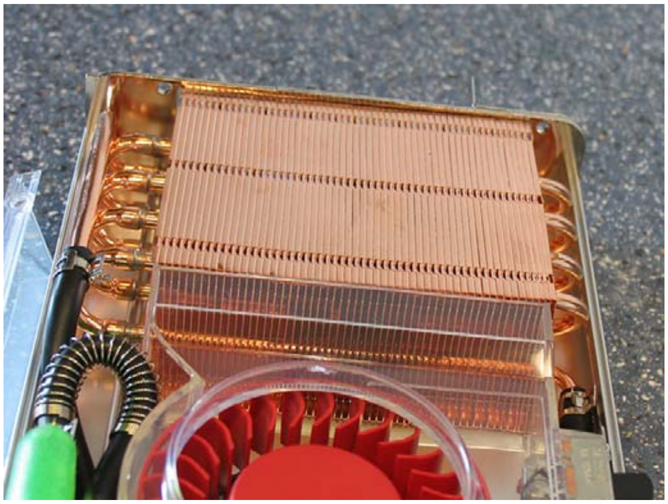


Fig 39: Radiator from Thermaltake CL-W0052 PC Cooling System

3.2.4 Power Supply

Power will be supplied to the solenoid valves and pump with a 24V/5A regulated power supply from Acopain. The four solenoid valves require 8 watts apiece and the pump requires 35 watts. Therefore the total power requirement is 67 watts which is safely within the 120 watt limit of the power supply. An AC/ DC power adapter would not be sufficient since they very rarely provide more than 24 watts.

3.2.5 National Instruments Data Acquitition (DAQ) Hardware

In this project we determined that a National Instruments USB-6211 DAQ was needed due to its 16 analog inputs. These are needed to record the low voltages from the thermocouples. The DAQ also provides four digital outputs to control the four valves and sufficient analog outputs to control the pump speed.

3.3 Bill of Materials

The Bill of Materials in Appendix 3 shows that the total cost of our design is $4150. This list includes all components and raw materials needed to build our final design. However, the bill of materials and the resulting total cost does not include parts that were outsourced to Malaysia.

3.4 Preliminary Analysis

We performed our analysis for several technical data and material selections. First, and most importantly, we performed power supply for the rise of 480 °C in 20 s. It is only for the solution surrounding the region of substrate with heat loss to the solution of nearby regions. Secondly, we analyzed the steady state temperature distribution. It offers the information about steady state power supply and temperature at certain locations. Besides, we figured out the flow rate of solutions and the thermal expansion of the reaction chamber. These ascertain the safety of both the nanostructure on the substrate and the reaction chamber. We also have selected proper materials for different components.

3.4.1 Power Requirement

We decided to heat the solution by using one electrical resistive coil. It will generate electric energy into thermal energy. We used Eq 1 to figure out the power required.

$$P = \frac{E}{\Delta t} = \frac{C_p m \Delta T}{\Delta t} = \frac{\rho C_p V \Delta T}{\Delta t} = \frac{\rho C_p l w h \Delta T}{\Delta t} \qquad \textbf{Eq 1}$$

P is the power need. E is energy for applying P in a period Δt. C_p ,m, ρ and V are the heat capacity, mass, density and volume of the solution to be heated. l, w and h are the inner length, width and height of the reaction chamber. ΔT is the temperature rise. This equation shows the transient power needed for heating a certain solution of certain volume by a certain amount of temperature in a certain amount of time. Under the condition that $\rho = 1 {}^{g}/_{cm^3}$, $C_p = 4.1813\ {}^{J}/_{gK}$, l = 3cm, w = 1.4cm, h =1cm, ΔT = 480 °C, and Δt = 20s, we obtained the value that P = 421.5 W. It shows the power needed for heating water solution around the region of the substrate inside the reaction chamber from room temperature to 500 °C in 20s. The sample heating coil is able to generate 1120 W in maximum. So we assumed that this heating coil could provide sufficient power for such temperature increase in 20s, even if there still exists heat loss. The value of the heat loss was also preliminarily analyzed. It will be shown in section 3.4.3.

3.4.2 Shear Stress on Nanostructure

In order to assure that the nanostructure of the substrate will be safe as solutions are being pumped into the reaction chamber, we analyzed the stress on the substrate under the required flow rate. Since the switching time is required to be 30s and we attempted a heating period of 20s, the cleaning and the pumping of the next reagent solution will both take 5s. First, we figured out the Reynolds Number before we obtained the value of the stress on the substrate, through Eq 2.

$$R_e = \frac{\rho v d}{\mu} \qquad \textbf{Eq 2}$$

R_e is the Reynolds Number, which shows the ratio of the inertial force to the viscous force of a fluid. v is the mean fluid velocity. d is the characteristic dimension. μ is the viscosity of the fluid. For our reaction chamber, d ≈ 2cm. For water solutions, $\rho = 1 {}^{g}/_{cm^3}$, $\mu = 5 \times 10^{-4}$ $P_a s$. The mean fluid velocity could be figured out in Eq 3.

$$\mathrm{v} = \frac{\dot{\mathrm{V}}}{\mathrm{A}} = \frac{\mathrm{V}'}{\mathrm{A}\Delta \mathrm{t}'} \qquad \textbf{Eq 3}$$

$\dot{\mathrm{V}}$ is the volumetric flow rate. A = 1.4 cm^2. It is the side inner surface area of the reaction chamber. V' = 25.2 cm^3. It is taken as twice the volume of the whole reaction chamber, for a better cleaning effect. $\Delta\mathrm{t}'$ = 5s. We therefore obtained the result v = 3.6 cm/s. We plugged it into Eq 2 and obtained $\mathrm{R_e}$ = 1440.

$\mathrm{R_e}$ of greater than 2300 indicates turbulent flow, so the fluids will perform a laminar flow, where the viscous force dominates. Therefore we mainly pay attention to the shear stress from the fluid viscosity. It could be seen in Eq 4.

$$\tau = \frac{\mu \mathrm{d_v}}{\mathrm{d_y}} \approx \frac{\mu \mathrm{v}}{\mathrm{y}} \qquad \textbf{Eq 4}$$

y is the length of our nanostructure. The velocities at its top and bottom are v = 3.6 cm/s and zero. Under the condition that y ≈ 50 µm, we obtained a shear stress of τ = 0.36 $\mathrm{P_a}$. It is of a far smaller order of magnitude than the tensile strength of a common solid material, which is always in $\mathrm{MP_{a.}}$ Therefore, we could assume that these laminar fluid flows applying quite small viscous forces on nanostructure materials will cause no or negligible damages to them.

3.4.3 Temperature Distribution

We desire the solution around the substrate to be 500 °C, and we want to know the power needed for maintaining this temperature. Besides, we also want to know the temperature at certain locations under such condition. Solving these questions manually is a far more complex job than dealing with them through software. At the same time, the graph from software offers a more visible temperature distribution than merely data. We therefore used software COMSOL to solve it. The temperature distribution is under the steady state and with no fluid flows. The graph is shown in Fig 40.

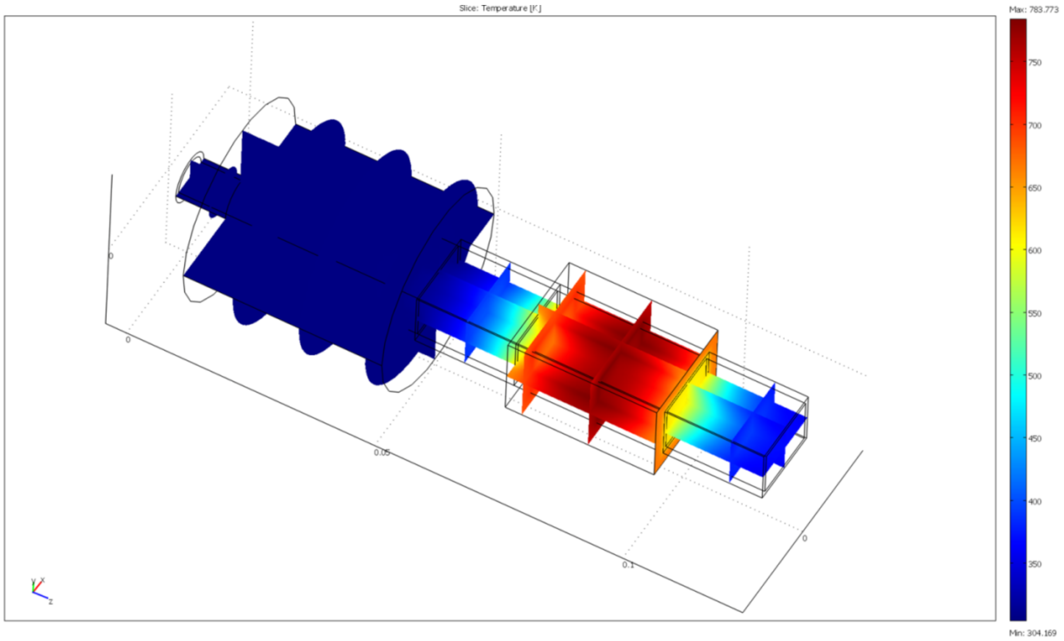


Fig 40: COMSOL Simulation for Temperature Distribution on Steady State Conditions

Instead of using our original CAD model, we analyzed a simplified one with three layers. These are thermal insulation layer, reaction chamber layer and solutions. We assumed conduction to be the only way of heat transfer, since the pumping rate during steady state will be arranged very low. All the constant input data could be seen in Appendix 4. The only variable input data is the power density at the heat region surrounding the reaction chamber. We verified different values to obtain the desired 500 °C near the substrate. We finally obtained the value of the power for the compensation of heat loss at steady state. It is 16.8 W. It also offered an approximate heat loss value during the transient heating step, as we mentioned above.

At the locations where we put the polymer seals (O-rings), the temperatures are desired to fall down lower than 100 °C. The result from COMSOL shows that these temperatures are near room temperature and the O-rings are more than safe. However, this result is only from the preliminary analysis through COMSOL. Therefore, for the sake of safety, we decided not to reduce the chamber size. We will add more insulator if the heat loss is so dominant that the solution near the substrate could not be maintained at 500 °C.

3.4.4 Thermal Expansion of the Reaction Chamber

Quartz is a very brittle material. Meantime, thermal expansion will happen due to the significant temperature difference in this approximate 3cm as shown in Fig 40 and 41. We therefore analyzed its stress to avoid fracture from it. We plotted the temperature distribution and temperature gradient along z-axis in the circled region shown in Fig 41. They could be seen in Fig 42 and 43.

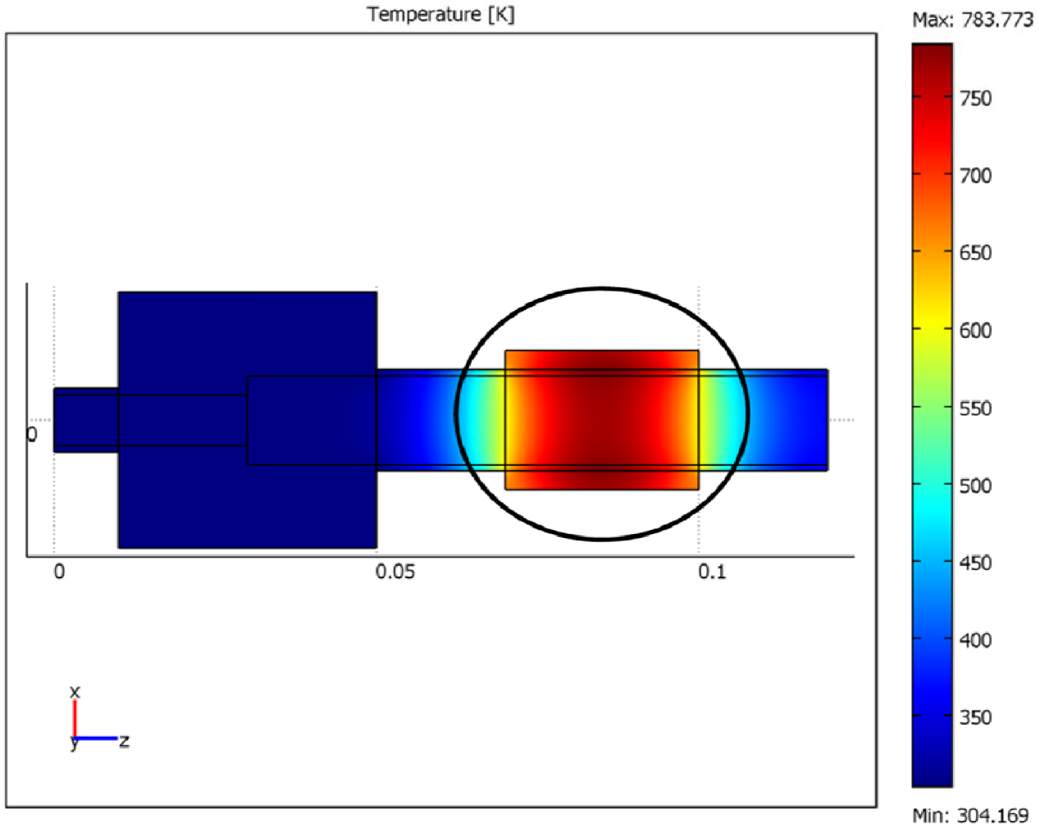


Fig 41: Region for Temperature Distribution and Gradient Analysis from COMSOL Simulation

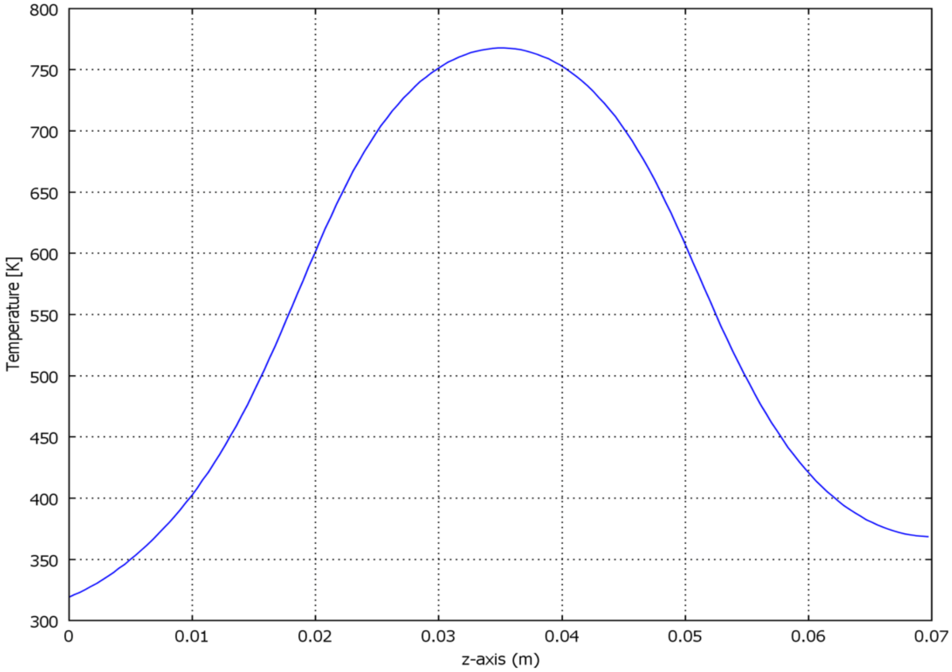


Fig 42: Temperature versus Length along z-axis

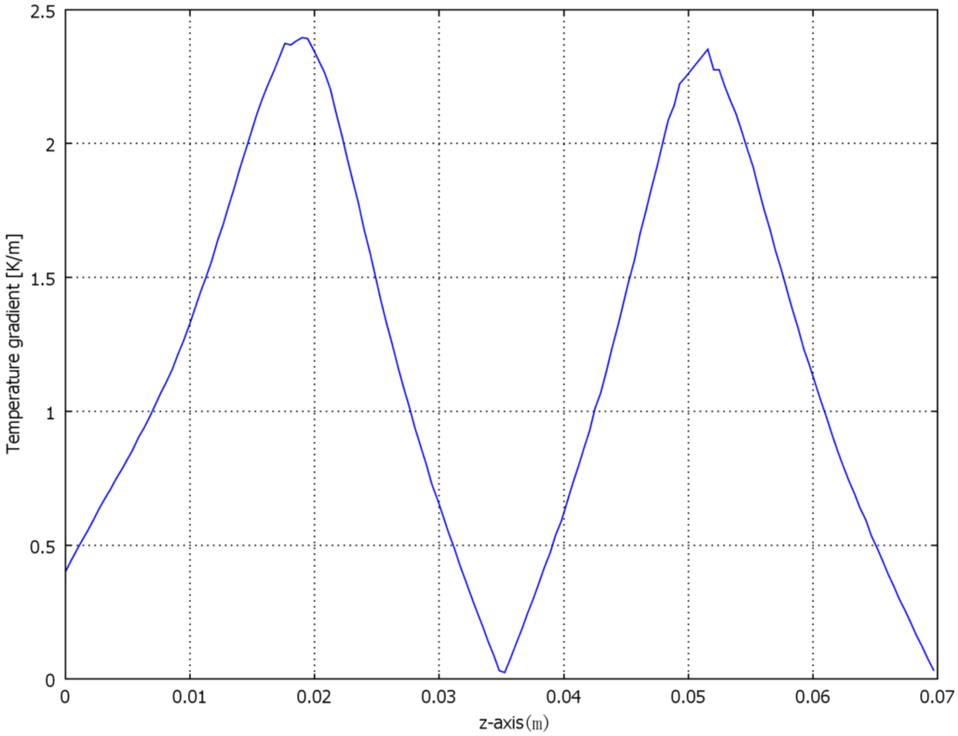


Fig 43: Temperature Gradient versus Length along z-axis

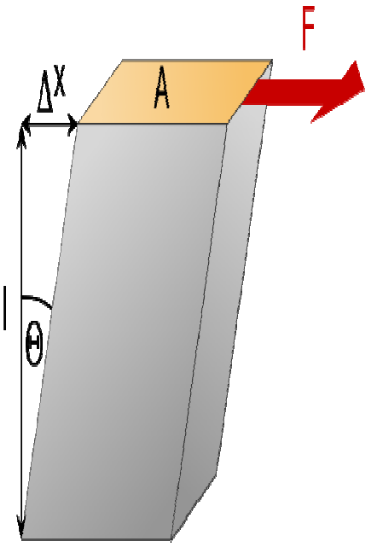


Fig 42: Shear Strain

The maximum temperature difference is about 2.4 × 10^4 K per meter. We figured out the shear strain by using Eq 5.

$$\varepsilon = \tan\theta = \frac{\Delta x}{L} = \frac{\alpha\Delta T x}{2L} \qquad \textbf{Eq 5}$$

ε is the shear strain. It is determined by the angle θ, as shown in Fig 42. The change of width Δx is determined by its original width x and thermal expansion of the material αΔT. α is the thermal expansion coefficient and ΔT is the temperature rise. The ratio of the change in width to the length is the tangent value of θ.

For L = 1 m, x = 1.4 cm, ΔT = 2.4 × 10^4 K and α = 0.5 ustrain/K, we obtain the shear strain to be 8.4×10^{-5}. For x =1, the shear strain is 6×10^{-5}. These are the values of shear strain along y-z plane and x-z plane, as shown in Fig 40 and 41. For conciseness, we assume there is no shear strain along x-y plane and the tensile strain of x-x, y-y and z-z to be the same.

Hooke ‘s Law:

$$\begin{aligned} \epsilon_{xx} &= \frac{1}{E}\left(\sigma_{xx} - \upsilon\left(\sigma_{yy} + \sigma_{zz}\right)\right) & \epsilon_{xy} &= \frac{\sigma_{xy}}{2G} \\ \epsilon_{yy} &= \frac{1}{E}\left(\sigma_{yy} - \upsilon\left(\sigma_{zz} + \sigma_{xx}\right)\right) & \epsilon_{yz} &= \frac{\sigma_{yz}}{2G} \\ \epsilon_{zz} &= \frac{1}{E}\left(\sigma_{zz} - \upsilon\left(\sigma_{xx} + \sigma_{yy}\right)\right) & \epsilon_{xz} &= \frac{\sigma_{xz}}{2G} \end{aligned}$$

As $\epsilon_{xx} = \epsilon_{yy} = \epsilon_{zz}$, from Hooke’s Law, we obtained $\sigma_{xx} = \sigma_{yy} = \sigma_{zz} = \frac{E}{1-2\upsilon}\epsilon_{xx} = \frac{E}{1-2\upsilon}\alpha\Delta T$. These could be neglected as we are figuring out von Mises stress through Eq 6.

$$\overline{\sigma_H} = \sqrt{\frac{(\sigma_{xx}-\sigma_{yy})^2+(\sigma_{yy}-\sigma_{zz})^2+(\sigma_{zz}-\sigma_{xx})^2+6(\sigma_{xy}{}^2+\sigma_{yz}{}^2+\sigma_{zx}{}^2)}{2}}$$

$$\xRightarrow{\sigma_{xx} = \sigma_{yy} = \sigma_{zz} \text{ and } \sigma_{xy}=0} \overline{\sigma_H} = \sqrt{3(\sigma_{yz}{}^2 + \sigma_{zx}{}^2)} \qquad \textbf{Eq 6}$$

For quartz, the shear modulus G = 31.4 $\mathrm{GP_a}$. Under the condition that $\epsilon_{yz} = 8.4 \times 10^{-5}$ and $\epsilon_{xz} = 6 \times 10^{-5}$, we obtained the von Mises stress $\overline{\sigma_H}$ = 11.23 $\mathrm{MP_a}$ through Eq X and Hooke’s Law. The safety factor is assumed to be 2 to 3, which is far less than $\frac{\sigma_Y}{\sigma_H}$ = 50 $\mathrm{MP_a}$/11.23 $\mathrm{MP_a}$ = 4.453 (for quartz, the yield strength σ_Y is 50 $\mathrm{MP_a}$). We achieved a conclusion that the quartz tube is absolutely safe for the shear stress from this heating and thermal expansion. The axial stress is negligible because we applied polymer tubes in several fittings of our system and any axial thermal expansion is assumed to be within the flexibility of its motion.

3.4.5 Material Selection

We have chosen appropriate materials for different components through software CES. These materials are basically for our reaction chamber, which will be manufactured rather than ordered directly. We need them to be able to resist a temperature of 500 °C and a pH-range of 4-13, more specifically for various weak acids, weak alkalis and strong alkalis.

First, we chose quartz as the material for the tube of our reaction chamber. Before we made our decision, we had considered stainless steel. It has high serving temperature and is non-corrosive to most of the chemistries. However, it is an electrical conductive material and will cause a short circuit between our electrodes if we apply it. Therefore, we determined to use quartz as this material, with even higher serving temperature, higher resistance of corrosions, and most essentially far lower electrical conductivity. Besides, quartz also has lower thermal conductivity, so that we could maintain lower temperatures at polymer sealed locations.

At the same time, we need a material with high manufacturability and low electric conductivity to be the electrode mount. Macor is one of the best choices. It has quite high serving temperature, low thermal conductivity, high electrical and corrosion resistances, and most importantly, high machinability. This is the reason for our elimination of quartz, due to its extremely high strength. Besides, we need a durable, machinable , non-corrosive material with high serving temperature for the body of the reaction chamber.

We decided to use stainless steel 304 series. It has high serving temperature, high resistance for corrosions, good durability and machinability. These make stainless steel far more dominant for this choice than others such as copper or aluminum. A more detailed material properties table could be seen in Table 1.

Table 1: Material Properties Table

Materials	Max. Serv. Temperature (C°)	Thermal conductivity (W/m.K)	Electrical Resistance (Ω.m)	Durability	Machinability
Quartz (Fused)	1100-1400	1.4-1.5	$(3.16\text{-}100).10^{16}$	Very Good	Bad
Stainless Steel (304)	750-925	14-16	$(6.5\text{-}7.7).10^{-7}$	Very Good	Good
Macor	1000	1.46	10^{14}	Very Good	Very Good

3.4.6 Safety Analysis

We used software Designsafe to aid us for the analysis of our system safety. We listed all possible safety issues in different categories, such as mechanical, electrical, fire and explosions, and fluid/pressure. We listed their causes and failure modes, and evaluated their severities, exposures and probabilities. We found several hazards to be of high risks. These are software errors, hot surfaces, flammable liquid/vapor, improperly mixed chemicals, burns/scalds, inadequate heating/cooling, reaction to/with materials, and hydraulics rupture. Afterward, we listed the methods for reducing their risk levels and re-evaluate their severities, exposures and probabilities. We had over ten pairs of similar hazards analyzed. For the sake of conciseness, we recombined them and deleted repeated ones. Two samples shown in Table 2 are about how we analyzed them and what the results are. A full list of hazards, their causes, evaluations, and solutions could be seen in Appendix 6.

Table 2: Part of the Deisgnsafe Safety Analysis

Hazard	Cause/Failure Mode	Severity	Exposure	Probability	Risk Level	Reduce Risk	Severity	Exposure	Probability	Risk Level
improperly mixed chemicals	the chamber is not completely cleaned out of the previous solution	Serious	Occasional	Possible	High	make the cleaning period longer, use safe chemical combinations, avoid turbulences	Slight	Remote	Unlikely	Low
hydraulics rupture	too much water pressure, badly attached joints	Serious	Occasional	Possible	High	use safe pumping speed and make sure all the joints are watertight, add safety valves	Slight	Remote	Unlikely	Low

As shown in Table 2, two sample hazards we focused on are improperly mixed chemicals and hydraulics rupture. Improperly mixed chemicals are caused by the leftovers of former reagents and insufficient cleanings, while hydraulics rupture by a huge impulse pressure rise or bad conjunctions of plumbing. Both of them are of high risk levels due to serious severities, occasional exposures and medium probabilities. We planned to solve the first possible hazard through several methods. We will research more on the properties of our reagents and solutions to avoid all dominant dissolutions. We will prevent mixing effects through turbulences, by limiting the maximum flow rate value. We will also lengthen the cleaning period if needed. We did the same thing for the latter hazard. More specifically, we will limit the pressure in the tubes by using safety valves and a pressure sensor, and by limiting the flow rate. We will double check the properties and dimensions of our components before we assemble them, and make sure all joints are watertight. After these planned measures, the severities, exposures and probability of both these two hazards have been reduced to slight, remote and unlikely. Their risk levels therefore fell down to low. Fifty-four hazards have been analyzed in the same way. Almost all of their risks fell down to low after their risk reduction measures. It is as shown in Appendix 6.

3.4.7 Environmental Analysis

Most of our system equipments will be made up of stainless steel, including reaction chamber components, electrodes, tubes, radiator, and parts of valves and pumps. So we performed a comparison between the impacts on environment of stainless steel and another material, mainly for checking their influences on environment. This chosen material is copper, since we have considered it as our base material for reaction chamber and electrodes.

We performed the environmental analysis by Simapro. The mass of the stainless steel parts in our reaction chamber is around 0.66 kg. We assumed that the stainless steel contained in other components will be twice this value. We therefore set the input value of stainless steel mass to be 2kg. Due to similar density, the mass of copper were set 1.9 kg.

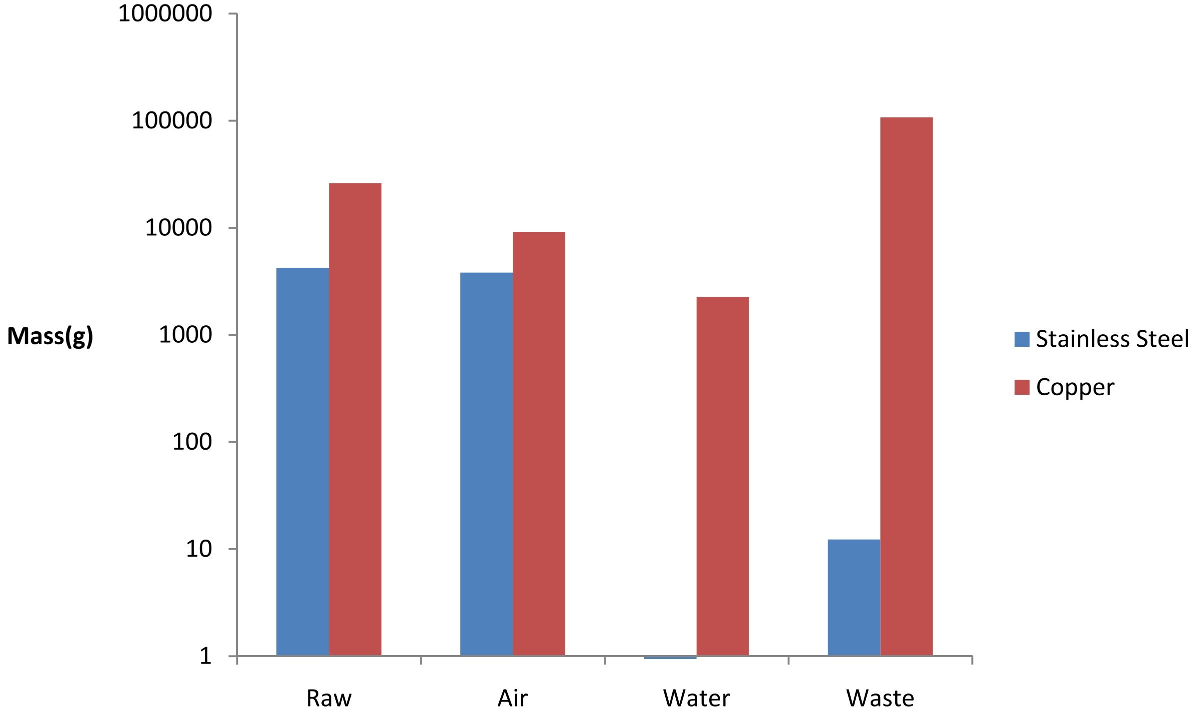


Fig 43: Total Emission of Stainless Steel and Copper

The chart shown in Fig 43 indicates the total emission of these two materials. Based on these results, we concluded that stainless steel has a negligible emission into water compared with copper, while they both have high air and waste emissions, and emission as raw material. In general, stainless steel will perform better due to less impact on environment. It is also shown Appendix 7 their relative impact in disaggregated damage categories, normalized score in human health, eco-toxicity, resource categories, and single score comparison.

3.5 Manufacturing Plan and Part Fabrications

Among all the components that need to be prepared to build our system, we only need to manufacture the components from inside the reaction chamber. All the components that that we need to manufacture with CAM are made of stainless steel and Macor. Here are the lists of the parts that need to be machined, categorized by material:

A. Stainless Steel
    1. Casing Body
    2. Casing Cap
    3. Output Cap
    4. Electrodes

B. Macor
    1. Quartz Tube Flange
    2. Electrode Mount

All of the parts are circular except the electrodes, with the maximum diameter of 2 inches for the stainless steel and 1 inch for the Macor parts. From our search for the source of these materials, the minimum length available for stainless steel rod is 12 inches, which is more than enough to be used for all of our stainless steel parts except the electrodes. For the electrodes, we need to find a steel plate and manufacture the part from there. The Macor cylinder rod is available with 3 inches in length and 1 inch in diameter, which is enough for all the ceramics parts we use in this system.

All the parts can be machined by using combinations of face milling, ball milling, drilling and lathe. The only problem is the material we used for our system is either the extremely strong steel or the brittle ceramics. Another problem is that the parts we are going to manufacture are very small while the minimum diameter of the mill head in our workshop is 3 mm. We need to mill the Macor pieces with extra caution since this material is very brittle. We can try milling these pieces by using mill with carbide tools and at a very slow feed rate, such as 10 mm per minute and 1 mm depth per cut. If we mill it too fast, it can damage the surrounding materials in the piece.

The quartz tube that we are going to use for the reaction chamber is also brittle. The stock piece that we found is 12 inches long and we need to cut it down to our specifications. In order to cut this piece safely, we need to use a glass cutting machine.

3.6 Assembly

With all of the components manufactured and ready, the assembly can be done very quickly since the process is very simple. First, we need to cement down the quartz tube to the ceramic flange as shown in Fig 44. After that, we slide the tube into the steel casing body with the 22 cm diameter o-ring in between, and then cement the free end of the quartz tube into the output cap, as shown in Fig 45.

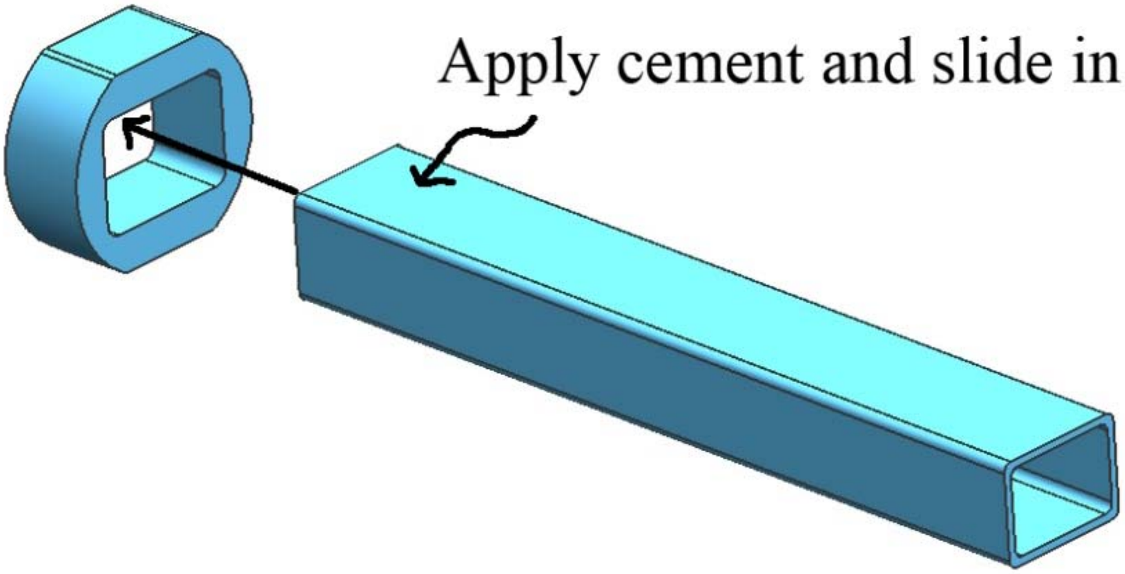


Fig 44: Assembling the Quartz Tube and the Flange

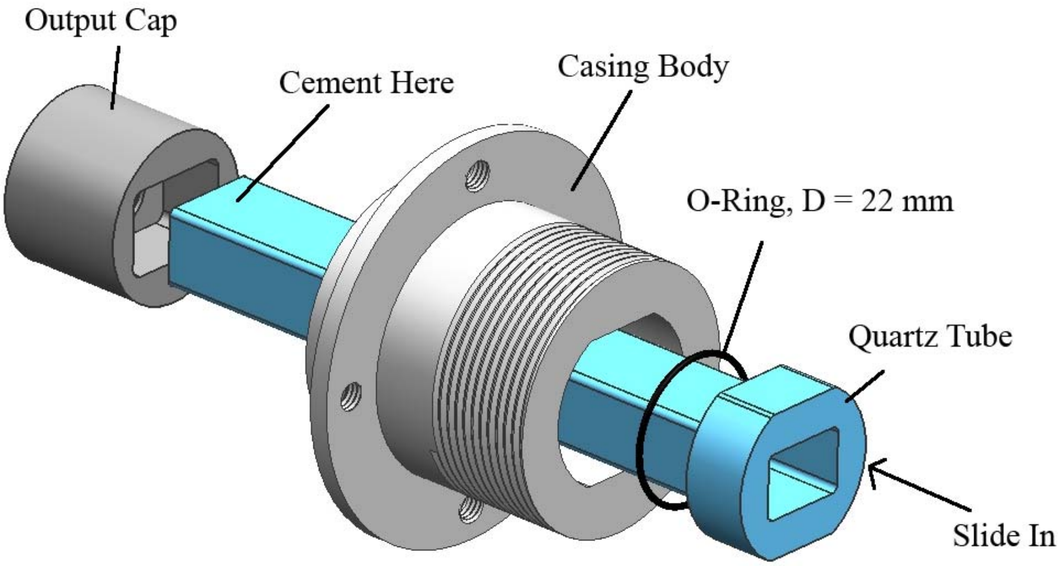


Fig 45: Slide in Quartz Tube into Casing Body and Cement the Free End into Output Cap

Next, we need to attach the substrate onto the electrode and secure its position with a metal clip and then attach the cables into the electrodes with M1 screws into the threads available on the electrodes. After we are done with the electrodes, we can slide them down into the slots inside the electrode mount as you can see in Fig 46.

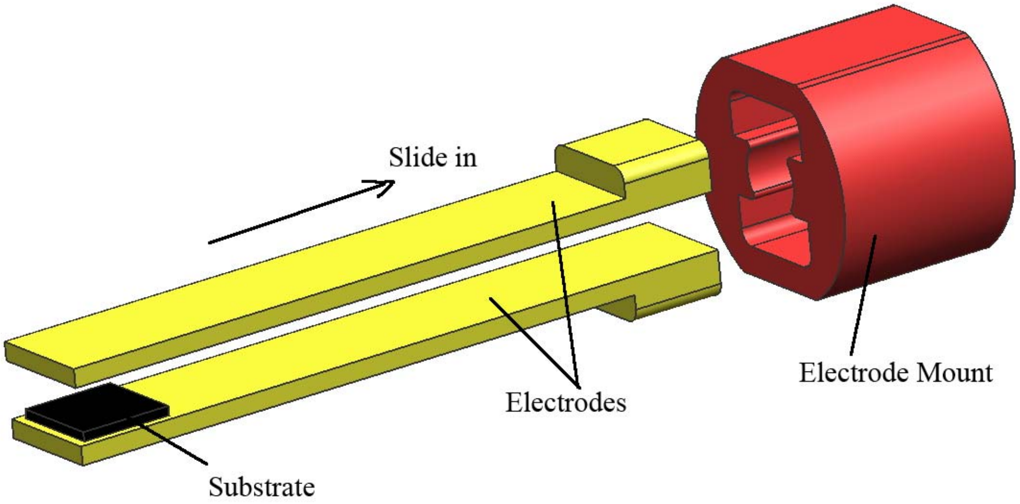


Fig 46: Attach the Substrate and Cables (Clip and Cables are Not Shown) and Slide in the Electrodes into the Mount

We then to slide down the electrodes and the mount into the steel casing body as shown in Fig 47 and 48. We can set and rearrange thermocouples and the cables at this point, attaching a simple cable management rings or something similar to make the cabling less messy and prevent the cables from entangling to each other. After all is done, we can finish the assembly process by sealing the casing with the o-ring followed by the steel cap as shown in Fig 49. After we finished the assembly, the reaction chamber should look like Fig 50.

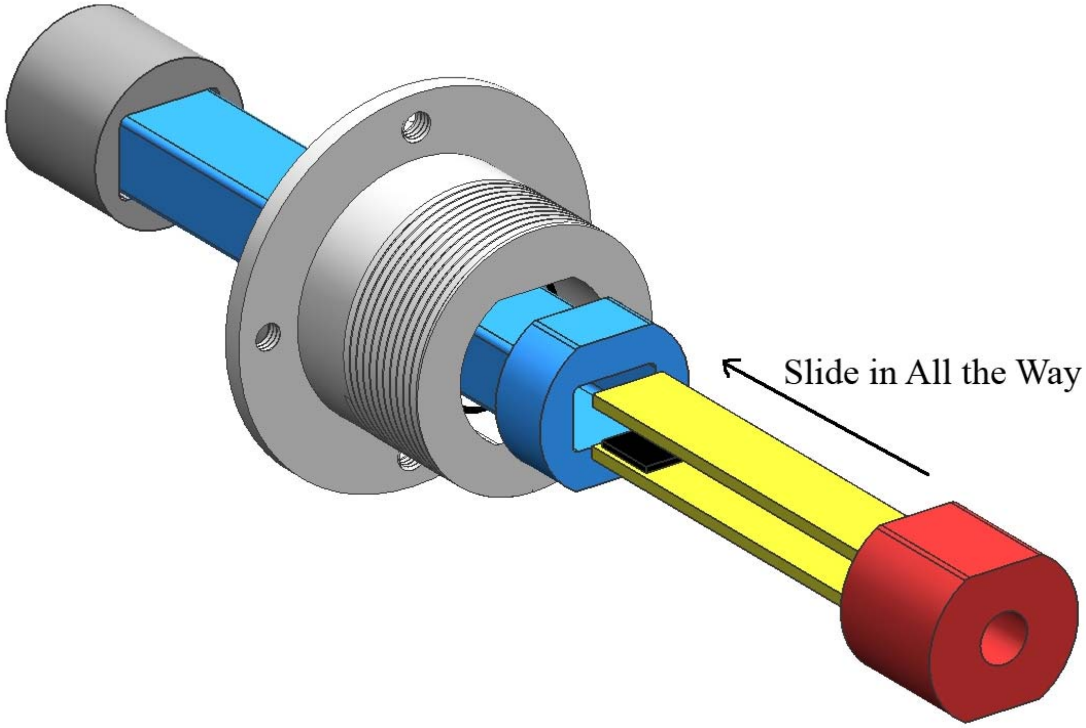


Fig 47: Sliding in the Electrodes and Mount into the Casing

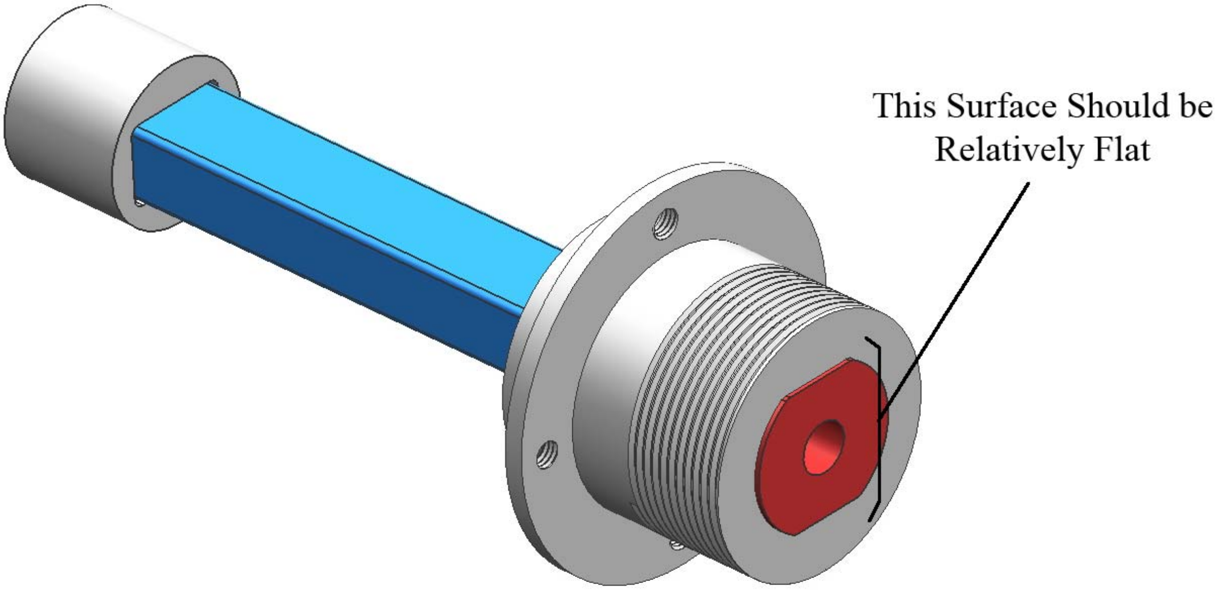


Fig 48: Casing After All the Parts are Inside

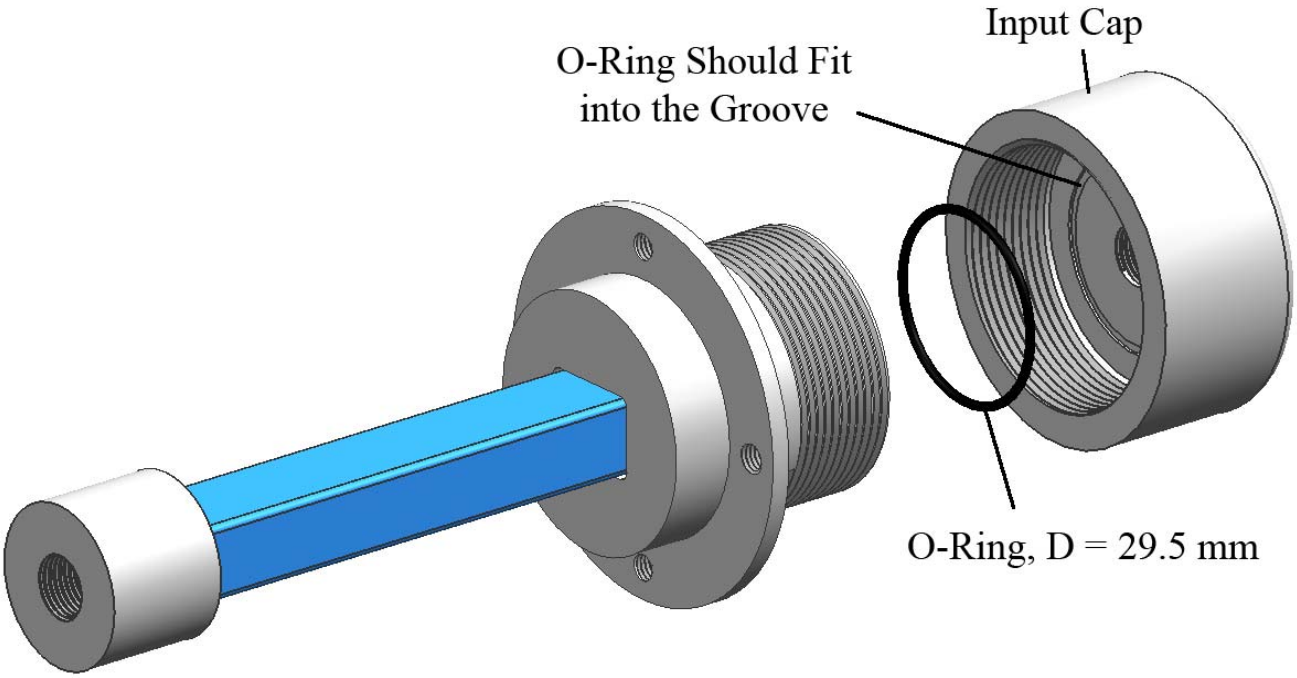


Fig 49: Finishing the Reaction Chamber Assembly by Sealing the Casing with the Cap and O-Ring

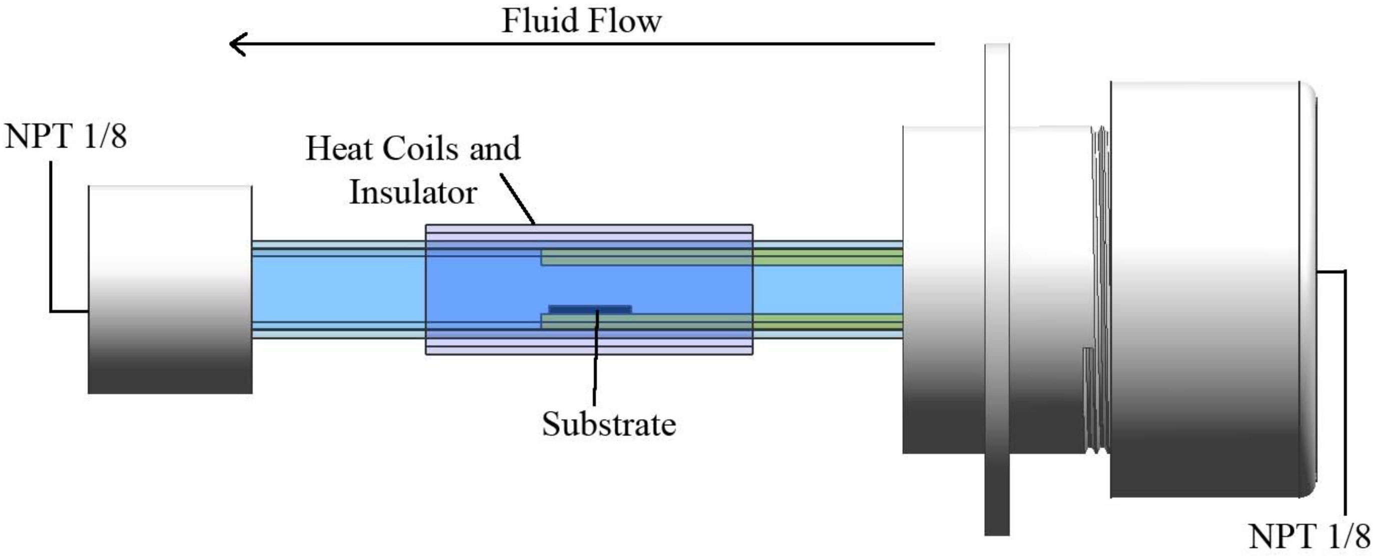


Fig 50: The Reaction Chamber

3.7 Usability Analysis

The basic energy source for our system is thermal energy. For the reactions of growing two different nanostructures on one substrate, we need to control their required power from the heating coil. We also need to control the pump and valves for running cleaning and reagent solutions as we switch these reactions. We figured out the procedures for these steps. A detailed system concept sketch for assisting this analysis is shown in Fig19 (This is the first is the schematic diagram at the beginning of the final design section).

We should get rid of any air inside our plumbing, due to the undesired air bubbles in solution based reactions. Therefore, we will firstly pump all these three solutions to fill the tubes before the reaction chamber. It will be realized one after one, such as Solution A → Solution B → Cleaning Solution. After this step, we will pump the Cleaning Solution to avoid any leftover of Solution A and Solution B until all tubes are filled. The first reaction will start after we stop this cleaning, have pumped Solution A inside the reaction chamber in the next 5s, and begin to heat it in the following 55s. During this reaction, Solution A will be pumped inside in a very low rate, for the sake of changing the reagents near the substrate. Cleaning Solution will be pumped again after the fabrication. We then pump Solution B in the same way. These two subsequential pumpings are done in 5s each. Solution B will be then heated to its steady state temperature in the following 20s. Again we will pump Solution B in a low flow rate for this growth. The hybrid nanostructure (of two types) arrays will be therefore fabricated. After this step, we will turn off the power supply for the heating coil and run Cleaning Solution again. All these switchings for pumping different solution will be turned into realization by two three-way valves.

We will also plug electroplating energy in for some reactions. Without any changes of these steps mentioned above, the voltage for electrodes will be controlled up to its target value as the reaction continues.

3.8 Validation Plan

We will put on several tests after our prototype has been assembled. These are a safety and response test by using colored solution, a test for the fabrication of hybrid nanostructure arrays, and a possible test after required revises.

First, we will test the transient responses of our system by using colored solutions with high boiling temperature, such as octacosane. We will test the temperatures where we locate our thermo-couples, to give out several Temperature vs Time plots. We will see from these plots the values of system rise time, settling time, steady-state error, and precision. Besides, we will check how smooth it is able to run, more specifically, examine any leakage, melting of polymer seals, turbulent flow in tubes, and infirm assemblies. By labeling three solutions with different colors, we could also see the mixing effect as we switch the pumping of two different solutions.

Secondly, we will fabricate a single nanostructure array to test the overall performance of our system and the quality of the resulting nanostructure. We will do the same observation and analysis for the previous test and then scan the result of our fabrication. We will assure that our system will have a smaller mixing effect while switching, be better assembled, sealed and fixed, have higher accuracy and precision of transient responses, have a lower probability of failure, and will be enhanced in other specification after its revision. The scanning of the nanostructure will be done through scanning electron microscope (SEM) and transmission electron microscopy (TEM). We will analyze the result and revise our system again if the product has defects.

Thirdly, we will apply our system for the fabrication of hybrid nanostructure arrays. This will be executed after we have revised our system from the results of the last test through fabrication of a single nanostructure. We will do the same analysis as the previous tests with the fabrication of a single nanostructure.

We need to re-test the safety, responses, and products of our system again. We might perform further revises of our design and manufacturing if the system still does poorly in some expected specifications. A full list of testing, analysis and revises with their corresponding customer requirements or engineering specifications could be seen in Appendix 5.

3.9 Risks and Countermeasures

Although we have made sufficient preliminary analysis, our system will still face several risks.

Our equipments and system control might fail due to various reasons. More specifically, our polymer seals might get degraded at a temperature of more than 200 °C. Our electrodes, thermal couples and sonar probe might be corroded due to the use of strong acids and other reasons such as oxidations and hydrogen corrosions. Moreover, a sudden rise of the pressure inside the reaction chamber might cause its explosion; wrong choices of solutions might cause a fire. The system might also response slower than expected.

We will prevent them through deeper and more detailed preliminary analysis. More specifically, we might slightly change our reaction chamber shape from some more COMSOL analysis. We will leave the question of maintaining high temperature near the substrate but low at the polymer seals to the freedom of changing the size of insulation. We will change once in a while temporary components, such as electrodes and polymer seals, for resisting possible failures. Besides, we will plug a pressure sensor and safety valves into our system, for the sake of avoiding explosions. Moreover, we will eliminate dangerous chemistries for the prevention of fire. We will also try to eliminate control failures by choosing proper sensors and actuators, and designing good control logic.

There also exist several manufacturing and assembly difficulties. Our reaction chamber components have dimensions of only several millimeters, while the minimum milling tool and welding precision are already 3mm and about 1mm. We solved them by adding fillets and appropriately shaping tubes in our CAD model, and will solve any difficulty of assembly by using files and sandpaper. We must also take our time to order, fabricate and assemble components due to time limitation.

APPENDIX

Appendix 1 References

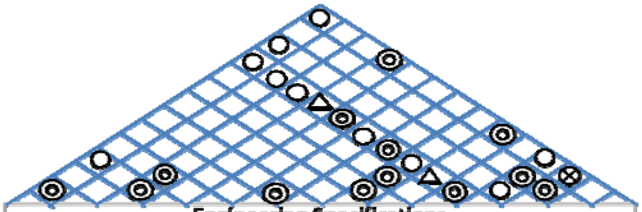
Growth Process	Item Created	Temp (°C)	Pressure (atm)	Substrate Materia	Catalyst/Seed Material	Precursor Source Material or Electrolyte	Precursor Type	pH	Cathode Material	Anode Material	Electrode Separation (mm)	Potential (V)	Creation Time (h)	Typical Diameter (nm)	Typical Length (μm)	Reviewer	Ref
Electrodeposition	CNT	27 (Room T)	1	Si (001) or SiO2/SnO2-coated glass (attached to cathode)	(enhanced by C2 or C3) SCNTs: transitional metal	CH_3CH (acetonitrile, 1% in volume) in Distilled Water	Liquid Organic Aqueous		Copper	Graphite	8	20	4 to 6	100-250 (or 20-30?)		Ben	1, 2
Electrodeposition	NWs(Si)	Room T	1	HOPG with PC Membrane	None	(CF3SO2)2N-, SiCl4(1M)	Liquid Inorganic? Nonaqueous		PC membrane doped with Au layer as working electrode (maybe anode)	Pt wires are counter and reference electrode (maybe cathode)		0~5	annealing: 30min etching: 5min	400, 110, 15 (as the dimensions of membrane pores)	12, 20, 0.8 (respectively)	Chenhao	8
Electrodeposition	NWs (Mg,Cu doped ZnO)	70		PC Membrane		Zn(NO3)2(0.05 moldm−3) Mn(NO3)2(0.01 moldm−3) Cu(NO3)2(0.0005 moldm−3) lactic acid(0.0075 moldm−3) bidistilled water	Liquid Inorganic Aqueous	4.7	PC membrane with Cu or Au layer one side working electrode	Zn rod: counter electrode saturated Hg2Cl2: reference electrode		0.1 to 10^5 Hz, Jmax= +/-5mV -0.7V at cathode				Chenhao	11
Solution Growth	NW (Ge)	300-450	~1?		Alkanethiol-protected gold nanocrystals	C_6H_{12} (cyclohexane) heated and pressurized above its critical point (281 °C, 0.04atm)	Liquid Organic Nonaqueous							10-150	~1 to 6	Ben	3
Wet-Chemical Process	NW (ZnO)	95	?	p-type Si (100) wafer	ZnO particles with quasi-spherical shape and 4 nm diameter	Solution (volume ratio, v/v=1:1, pH 6.8) of 0.1 M $Zn(NO_3)_2$ and 0.1 M $C_6H_{12}N_4$	Liquid Organic Aqueous	6.8					6	100	1.5	Ben	4
Metallocene-Catalyzed MWNT Growth	CNT	600-645	82 / 123 (8.3 Mpa / 12.4 Mpa)	Si wafer	Cobaltocene, nickelocene, ferrocene (Cp2M) , Co/Fe Nanocrystals	C7H8(Toluene) serves as a solvent and a source. Ethanol(30%),hexane(C6H14) and water(0.75%) serve as supplemental sources	Liquid Organic Nonaqueous ?				7 to 12	300		20-40 (outer dia: 10 - 50 wall dia: 5 - 20)	4	Murat Chenhao	7
Hydrothermal growth using PLD (Pulsed Laser Deposition)	CNT	90		ZnO seeded Si(0001) using PLD	ZnO	Zn(NO3)2(pH=5.66) aqueous solution mixed with hexamethylenetetramine(HMT) (pH=4.16) aqueous solution	Liquid Organic Aqueous	5.66	Mercury(Hg)	Chloride(Cl)		1.2	6 to 10	20-40		Murat	6
Decomposition by Heating	NWs(ZnO)	50~200	1	Independent (Si, Glass, SrO2, etc)	Substrate with ZnO seeds, done by dip-coat catalyst: HTMA (necessary), PEI	Zn(NO3)2·6H2O	Liquid Inorganic Aqueous	5~12 (>9 better)					>1.5h	without PEI: 40 - 80 avg asp ratio = 30 with PEI: 20 - 300 avg asp ratio = 5 ~ 150 (depend on PEI quantity)	without PEI: 1.5 - 2 with PEI: 0.05 ~ 25	Chenhao	9
Decomposition by Heating	NWs(ZnO)	~300	1	Independent (Si, Glass, SrO2, etc)	catalyst (for multi purposes) Trioctylamine for nanorods, 1-hexadecanol for nanotriangles, 1-octadecene for spherical nanoparticles dope with Co(OAc)2	ZnAc2, C24H51N	Liquid Organic Nonaqueous							30 ± 5	0.5 to 5	Chenhao	9
Combined Thermal and Sonic	DWNTs	85–95	1		Azobis-type radical initiators (30 mmol) PtRu nanoparticles	Washed thoroughly with hexane, acetone, and deionized water	Liquid Organic? Aqueous						30min Ar purging, 6h			Chenhao	12
Solution-Liquid-Solid (SLS) Growth	NW (Si)	264-363	1	None	Gold (Au) or Bismuth (Bi) powders	Trisilane (Si3H8) in Octacosane (C28H58) or Squalane (C30H62)	Liquid Organic Aqueous?						?	20-30	> 1	Eric	13
Seedless Solution Growth	NW (ZnO)	70	1?	Si(100) wafer, with very thin layers of Ti and then Au on top	None	1:1 Zinc Nitrate and Hexamethylenetetramine (HMTA)	Liquid Organic Aqueous						6 - 48	~200-400 (from picture)	(from picture)	Eric	14
Arc discharge growth	CNT		0.05-0.07	Carbon Rod	N/A	Nitrogen	Gas Inorganic		Graphite	Graphite	1	20		10		Murat	5

Microwave (400W) Plasma Enhanced Chemical Vapor	CNT	700	0.013	Si substrate coated with thin Nickel film		CH4 (20%) and H2 (80%)	Gas Organic						10 min	20-35	7	Eric	16
Plasma Enhanced Chemical Vapor Deposition	CNT	120-350		Si, SiO2	Fe, Ni, Co	C2H2, CH4, C2H6, CO	Gas Organic							15		Murat	5
Thermal Chemical vapor deposition	CNT	750-1050		Si, SiO2	Fe, Ni, Co	CH4, CO in HF solution	Gas Organic							100-200		Murat	5
Alcohol catalytic chemical vapor	CNT	550		Si, SiO2	Fe, Co	Evaporated Alcohols, Methanol, Ethano	Gas Organic							1		Murat	5
Chemical Vapor Deposition (CVD)	NW (Si)				Au	SiCl4	Gas									Ben	15
Chemical Vapor Deposition (CVD)	NW (Si)				Au, Ag, Cu, Pt	SiCl4	Gas									Ben	15
Chemical Vapor Deposition (CVD)	NW (Si, Ge)				Au	SiH4, GeH4	Gas									Ben	15
Chemical Vapor Deposition (CVD)	NW (Si)				Au	SiH4	Gas									Ben	15
Pulsed Laser Deposition (PLD)	NW (Si, Ge)				Fe, Si/Fe, Ge/Fe		Gas									Ben	15
Chemical Beam Epitaxy (CBE)	NW (Si)				Au	Si2H6	Gas									Ben	15
Pulsed Laser Deposition (PLD)	NW (GaAs)				Au	GaAs/Au	Gas									Ben	15
Pulsed Laser Deposition (PLD)	NW (InP)				Au	InP/Au	Gas									Ben	15
Pulsed Laser Deposition (PLD)	NW (CdSe)				Au	CdSe/Au	Gas									Ben	15
Microwave Plasma	NW (Si)				Ga	Si	Gas									Ben	15
Chemical Beam Epitaxy (CBE)	NW (GaAs)				Au	Et3Ga, Bu3As	Gas									Ben	15
Evaporation	NW (ZnO)				Au	ZnO, C	Gas									Ben	15
MBE	NW (Si)				Au	Si	Gas									Ben	15
Evaporation	NW (Si)				Au	SiO	Gas									Ben	15
Microwave Plasma Etching	NW (Si)				Ga	silyl radicals	Gas									Ben	15
Chemical Vapor Deposition (CVD)	NW (Si)				Ti	SiH4 or SiH2Cl2	Gas									Ben	15
Pulsed Laser Deposition (PLD)	NW (GaAs/GaP)				Au	GaAs/GaP	Gas									Ben	15
Chemical Beam Epitaxy (CBE)	NW (GaAs/InAs				Au	Me3Ga, Bu3As, Me3In	Gas									Ben	15
Pulsed Laser Deposition (PLD)	NW (Si/SiGe)				Au	SiCl4	Gas									Ben	15

Ref #	Title	Authors	Citation
1	Growth mechanism of carbon nanotubes deposited by electrochemical technique	S K Mandal, S Hussain, and A K Pal*	
2	Electrodeposited carbon nanotube thin films	A.K. Pal*, R.K. Roy, S.K. Mandal, S. Gupta, B. Deb	
3	Nucleation and growth of germanium nanowires seeded by organic monolayer-coated gold nanocrystals	Hanrath, T; Korgel, BA	T. Hanrath, B. A. Korgel, J.Am. Chem. Soc. 2002, 124, 1424.
4	Soft Solution Route to Directionally Grown ZnO Nanorod Arrays on Si Wafer; Room-Temperature Ultraviolet Laser	Jin-Ho Choy, Eue-Soon Jang, Jung-Hee Won, Jae-Hun Chung, Du-Jeon Jang, and Young-Woon Kim	J.-H. Choy, E.-S. Jang, J.-H. Won, J.-H. Chung, D.-J. Jang, Y.-W. Kim, Adv.Mater . 2003, 15, 1911.
5	http://students.chem.tue.nl/ifp03/synthesis.html		
6	The kinetics of the hydrothermal growth of ZnO nanostructures	Michael N.R. Ashfold, Rachel P. Doherty, N. George Ndifor-Angwafor, D. Jason Riley, Ye Sun	
7	High Yield Multiwall Carbon Nanotube Synthesis in Supercritical Fluids	Danielle K. Smith, Doh C. Lee, and Brian A. Korgel	
8	Growth of Silicon Nanowires of Controlled Diameters by Electrodeposition in Ionic Liquid at Room Temperature	J. Mallet, M. Molinari, F. Martineau, F. Delavoie, P. Fricoteaux, and M. Troyon	
9	Solution-Grown Zinc Oxide Nanowires	Lori E. Greene, Benjamin D. Yuhas, Matt Law, David Zitoun, and Peidong Yang*	
		Smith, DK; Lee, DC; Korgel, BA	
11	EIS studies of electrodeposition process of manganese and copper doped ZnO wires	Marian Sima, Enculescu, Mariana Sima, Eugen Vasileb, and Teodor Visanc	
12	Ultrasonication-assisted surface functionalization of double-walled carbon nanotubes with azobis-type radical initiators	Jia-Yaw Chang, Hsin-Yi Wu, Gan Lin Hwang and Ting-Yao Su	
13	Solution - Liquid - Solid (SLS) Growth of Silicon Nanowires. Does not use substrate, nanowires not aligned (growing to random direction)	Andrew T. Heitsch, Dayne D. Fanfair, Hsing-Yu Tuan, Brian A. Korgel	
14	Density - Controlled Growth of Aligned ZnO Nanowire Arrays by Seedless Chemical Approach on Smooth Surfaces. No special requirement for the substrate as long as its surface is locally flat. Low cost and time efficient method.	Sheng Xu, Changshi Lao, Benjamin Weintraub, Zhong Lin Wang	
15	Semiconductor Nanowires: From Self-Organization to Patterned Growth	Hong Jin Fan, Peter Werner, and Margit Zacharias*	
16	Effects of surface morphology of Ni thin film on the growth of aligned carbon nanotubes by microwave plasma-enhanced chemical vapor deposition	Young Chul Choi, Young Min Shin, Seong Chu Lim, Dong Jae Bae, Young Hee Lee, Byung Soo Lee, and Dong-Chul Chung	

Appendix 2 Quality Function Diagram

◎ Strongly Positive
○ Somewhat Positive
△ Somewhat Negative
⊗ Strongly Negative

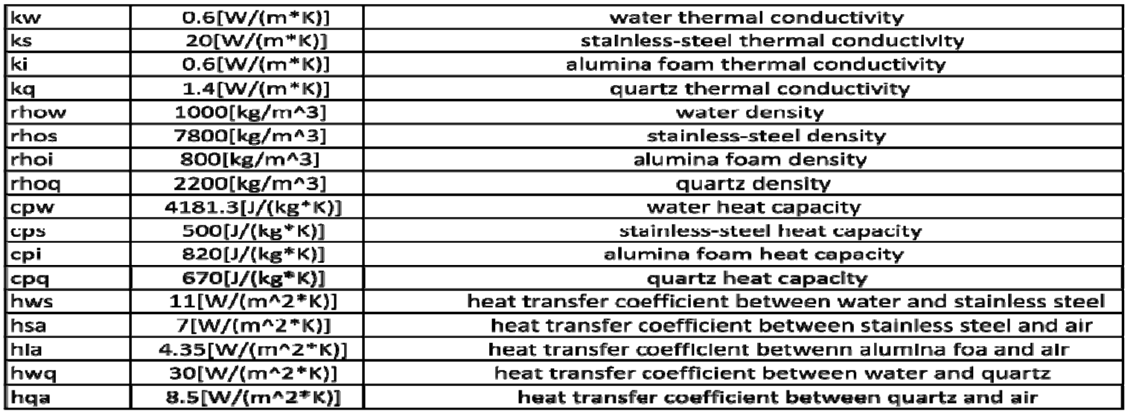


			Engineering Specifications												
		Necessity	Reaction chamber volume (cm^3)	Substrate dimensions (cm^2)	Temperature target range (°C)	Temperature settling time (s)	Temperature steady state accuracy (% F.S.)	Voltage targeting range(v)	Voltage steady state accuracy (% F.S.)	Ultrasonic target range (kHz)	Ultrasonic settling time(s)	Ultrasonic steady state accuracy (%F.S.)	Cost($)	Flow rate of fluids (cm^3/s)	Flow rate steady state accuracy (% F.S.)	Switching time between reactants(s)
Customer Requirements	**Two types of NTs or NWs on one substrate**	**9**			**9**	**1**	1	9	3	3	3	1	1	3		3
	Precise control of growth conditions	**8**		**1**	**9**	**9**	9	9	9	9	9	9	3	9	9	3
	Muilt-energy sourses	**7**	**3**	**1**		**1**		3	3	9	1	3	3	1		1
	Short Settling time	**7**	**3**	**1**	**3**	**9**	1		1	3	9	1	1	3	1	9
	Easy to operate	7	1	3	3	3		3		3	1		3	1		3
	Automated control of reaction conditions	7	1		3	3	1	3	1	3	3	1	9	3	3	3
	Flexible and fast at switching between two growth	**6**	**3**	**1**	**3**	**9**				3	9		3	9		9
	Appropriate substrate dimension	**5**	**9**	**9**				3	3	1			3			
	Affordable	5	**1**	**1**	**1**	**3**	3	1	3	1	3	3	9	1	3	3
	Small equipment volume	3	**9**	**3**			1	3					1			
	Low energy costs	2	**3**	**1**	**9**	**9**	1	3	1	3	3	1	9	1	1	1
	Importance weighings		**157**	**110**	**257**	**280**	**115**	**251**	**166**	**259**	**272**	**133**	**244**	**216**	**117**	**234**
	Target Values		**10 to 20**	**1**	**20 to 500**	**60**	**<1**	**~20**	**<1**	**20**	**<60**	**<1**	**3.5k**	**10 to 20**	**<1**	**30**

Appendix 3 Bill of Materials

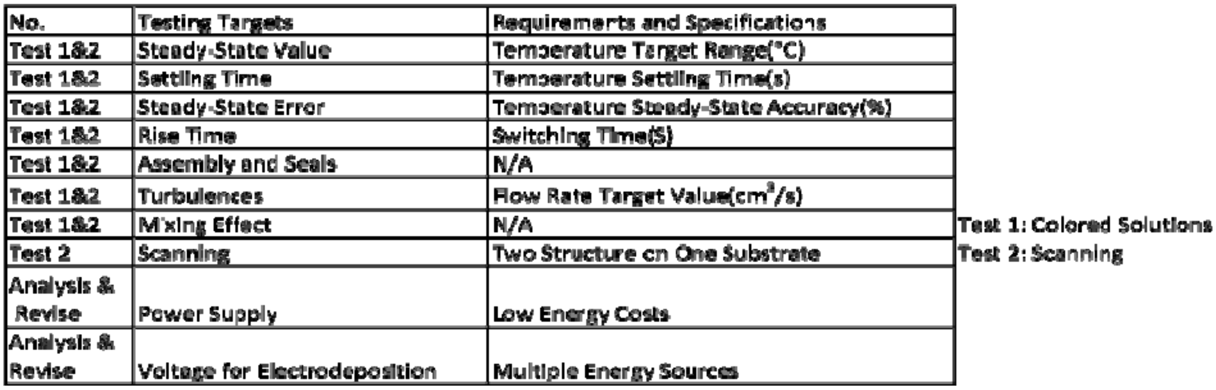
Function or module	Item name	Vendor	Part#	Qty	Unit price	TOTAL
Cooling	Thermaltake CL-W0052 Cooling System	XPC Gear	CL-W0052	1	79.99	79.99
Electronics	24V/5A Regulated Power Supply	Acopain	B24G500	1	225	225.00
Electronics	Quad Op-Amp	Digikey	LM124J-ND	2	6.93	13.86
Electronics	Solderless Breadboard	Digikey	438-1045-ND	1	8.73	8.73
Fittings	Brass Hose Connector, 1/8 in. Male NPT, 1/4 in. Hose ID	Swagelok	B-4-HC-1-2	8	3.30	26.40
Fittings	Brass Pipe Fitting, Street Tee, 1/8 in. Female NPT x 1/8 in. M NPT x 1/8 in. F NPT	Swagelok	B-2-ST	3	12.00	36.00
Fittings	Brass Swagelok Tube Fitting, Male Connector, 1/4 in. Tube OD x 1/8 in. Male NPT	Swagelok	B-400-1-2	2	2.60	5.20
Fittings	Brass Swagelok Tube Fitting, Male Connector, 1/4 in. Tube OD x 1/4 in. Male NPT	Swagelok	B-400-1-4	1	2.60	2.60
Fittings	SS Full Flow Quick-Connect Body, 2.2 Cv, 1/4 in. Swagelok Tube Fitting	Swagelok	SS-QF4-B-400	1	36.3	36.30
Fittings	SS Full Flow Quick-Connect Stem without Valve, 1/8 in. Male NPT (QF4 Series)	Swagelok	SS-QF4-S-2PM	1	23.00	23.00
Fittings	Brass Pipe Fitting, Tee, 1/4 in. Female NPT	Swagelok	B-4-T	1	12.40	12.40
Fittings	Brass Swagelok Tube Fitting, Male Connector, 1/8 in. Tube OD x 1/8 in. Male NPT	Swagelok	B-200-1-2	1	2.70	2.70
Fittings	Brass Swagelok Tube Fitting, Male Connector, 3/16 in. Tube OD x 1/8 in. Male NPT	Swagelok	B-300-1-2	1	2.70	2.70
Fittings	Brass Swagelok Tube Fitting, Male Connector, 1/4 in. Tube OD x 1/8 in. Male NPT	Swagelok	B-400-1-2	1	2.60	2.60
Fittings	Brass Swagelok Tube Fitting, Male Connector, 3 mm Tube OD x 1/8 in. Male NPT	Swagelok	B-3M0-1-2	1	2.70	2.70
Fittings	Brass Swagelok Tube Fitting, Male Connector, 4 mm Tube OD x 1/8 in. Male NPT	Swagelok	B-4M0-1-2	1	2.70	2.70
Fittings	Brass Swagelok Tube Fitting, Male Connector, 6 mm Tube OD x 1/8 in. Male NPT	Swagelok	B-6M0-1-2	1	2.60	2.60
Fittings	Brass Swagelok Tube Fitting, Male Connector, 1/8 in. Tube OD x 1/4 in. Male NPT	Swagelok	B-200-1-4	1	3.00	3.00
Fittings	Brass Swagelok Tube Fitting, Male Connector, 3/16 in. Tube OD x 1/4 in. Male NPT	Swagelok	B-300-1-4	1	3.00	3.00
Fittings	Brass Swagelok Tube Fitting, Male Connector, 1/4 in. Tube OD x 1/4 in. Male NPT	Swagelok	B-400-1-4	1	2.60	2.60
Fittings	Brass Swagelok Tube Fitting, Male Connector, 3 mm Tube OD x 1/4 in. Male NPT	Swagelok	B-3M0-1-4	1	3.80	3.80
Fittings	Brass Swagelok Tube Fitting, Male Connector, 4 mm Tube OD x 1/4 in. Male NPT	Swagelok	B-4M0-1-4	1	3.00	3.00
Fittings	Brass Swagelok Tube Fitting, Male Connector, 6 mm Tube OD x 1/4 in. Male NPT	Swagelok	B-6M0-1-4	1	2.60	2.60
Fittings	Brass Swagelok Tube Fitting, Male Connector, 1/16 in. Tube OD x 1/8 in. Male NPT	Swagelok	B-100-1-2BT	1	5	5.00
Fittings	Brass Pipe Fitting, Pipe Plug, 1/8 in. Male NPT	Swagelok	B-2-P	2	2.1	4.20
Fittings	Compression Seal Fitting for Electrode Wires, 230 C Max Temp, Male 1/8 NPT	Conax Technologies	TG-24T(CU)-A2-T-60/12	1	67	67.00
Heating	Power Controller for Heating Coil	Omega	SCR19Z-12-040	1	300	300.00
Heating	Resistance Heating Ribbon Wire	Omega	NCRR-18-100	1	85	85.00
Pressure Control	10V Regulator for Pressure Transducer	Digikey	296-8007-1-ND	1	0.68	0.68
Pressure Control	5V to 15V DC/DC Converter for Pressure Transducer	Digikey	DCP010515BP-ND	1	8.91	8.91
Pressure Control	Pressure Transducer, 1/8 NPT Male	Omega	PX180B-006GV	1	165	165.00
Pressure Control	SS Low-Pressure Proportional Relief Valve, 1/4 in. MNPT x 1/4 in. Tube Fitting	Swagelok	SS-RL3M4-S4	1	162.3	162.30
Pump	Pump tube, Marprene, 1/4" bore, 0.063" wall, 15 meters in length	Watson-Marlow	902.0064.016	1	154.5	154.50
Pump	Peristaltic Pump, Watson-Marlow 313 VDL/D, With 15% Educational Discount	Watson-Marlow	030.0561.000	1	804.95	804.95
Reactino Chamber	Macor Easy-to-Machine Glass-Mica Ceramic, 1" Diameter, 3" Length	McMaster-Carr	8489K31	1	109.99	109.99
Reaction Chamber	Small stainless steel screw for electrode power connection	McMaster-Carr	91800A050	1	7.45	7.45
Reaction Chamber	Refractory Firebrick High Temperature, 9" X 4-1/2" X 2-1/2"	McMaster-Carr	9355K2	1	8.12	8.12
Reaction Chamber	Viton O-Ring, 28mm ID, 31mm OD, 205 C Max Temp	McMaster-Carr	9263K595	1	6.62	6.62
Reaction Chamber	Viton O-Ring, 21mm ID, 23mm OD, 205 C Max Temp	McMaster-Carr	9263K557	1	11.47	11.47
Reaction Chamber	Electrode Holder (Stainless Steel)	Micro Carbide Engr.		1	180	180.00
Reaction Chamber	Electrode (Stainless Steel)	Micro Carbide Engr.		2	120.00	240.00
Reaction Chamber	Input Cap (Stainless Steel)	Micro Carbide Engr.		1	140.00	140.00
Reaction Chamber	Output Cap (Stainless Steel)	Micro Carbide Engr.		1	100.00	100.00
Reaction Chamber	Quartz Rectangular Tube, 8x16mm inside, 0.9mm thick, Length: 12"	Friedrich & Dimmock	QRT-8-16-90, 12"	1	61.39	61.39
Stand	Aluminum (Alloy 3003) sheet, 24"x6", 0.025" thick	McMaster-Carr	9536K19	1	7.43	7.43
Stand	Aluminum, L = 12”, Thread: 5/8” – 11	McMaster-Carr	94435A370	4	55.16	220.64
Stand	Aluminum, 8” x 36” x 0.25”	McMaster-Carr	8975K444	1	46.51	46.51
Stand	Hex nut, Steel Zinc Plated Finish, 5/8” – 11	McMaster-Carr	94895A035	1	6.10	6.10
Stand	Flat Washer, Steel Zinc Finish, D = 5/8” – 1.25”, t = 0.075”	McMaster-Carr	97669A305	1	6.32	6.32
Temperature Control	Thermocouple for Reaction Chamber	Omega	KTXL-116U-12	1	28	28.00
Valves	Solid State Relays 40V/0.5A	Digikey	255-1352-5-ND	6	5.19	31.14
Valves	3-Way Solenoid Valve, 24V, 8Watt, Ports: NPT(F) 1/8	Cole-Parmer	K-01540-18	3	180	540.00
Valves	2-Way Solenoid Valve, 24V, 8Watt, Ports: NPT(F) 1/8, Normally Closed	Cole-Parmer	K-01540-08	1	156	156.00

Appendix 4 Constant Inputs for COMSOL



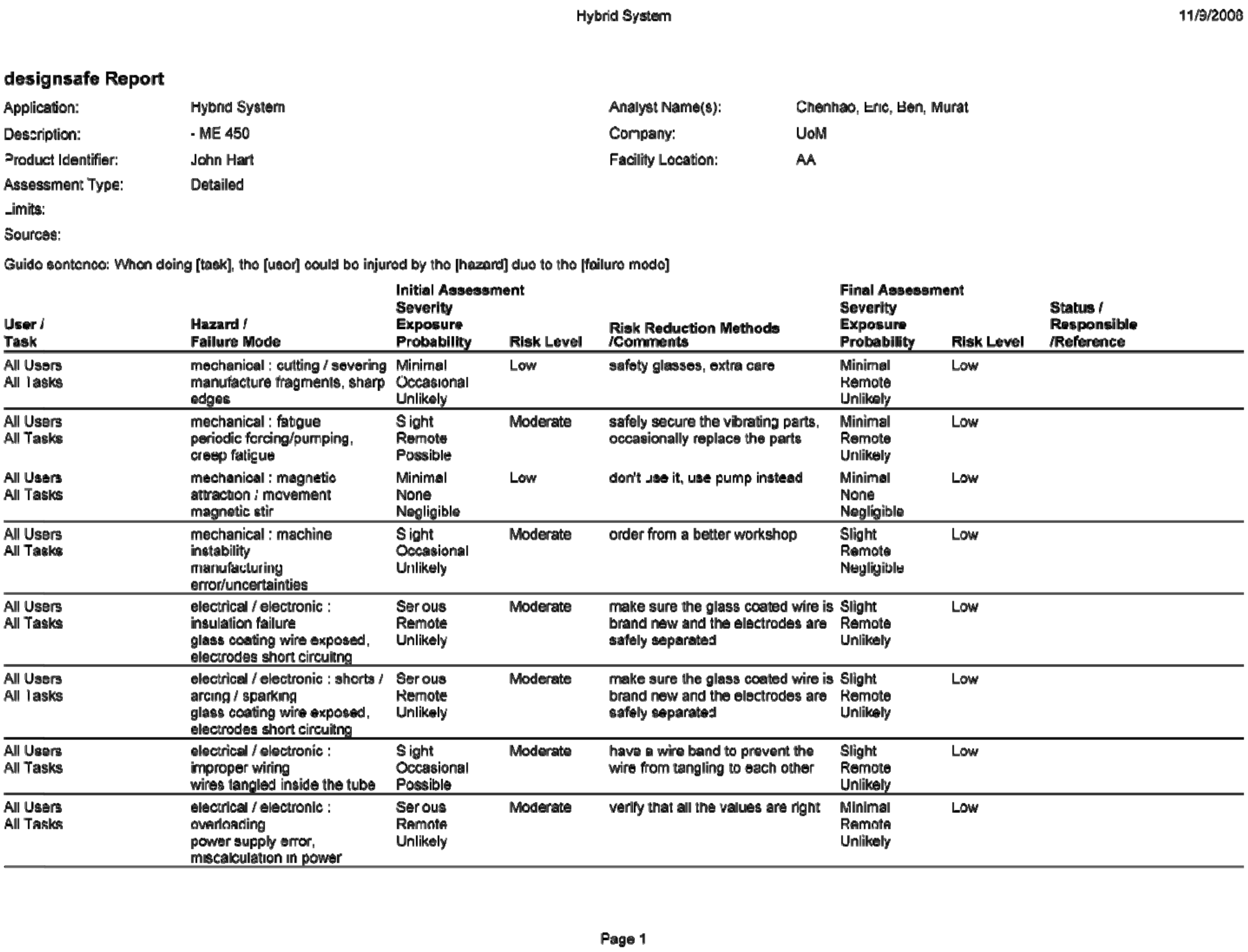
kw	0.6[W/(m*K)]	water thermal conductivity
ks	20[W/(m*K)]	stainless-steel thermal conductivity
ki	0.6[W/(m*K)]	alumina foam thermal conductivity
kq	1.4[W/(m*K)]	quartz thermal conductivity
rhow	1000[kg/m^3]	water density
rhos	7800[kg/m^3]	stainless-steel density
rhoi	800[kg/m^3]	alumina foam density
rhoq	2200[kg/m^3]	quartz density
cpw	4181.3[J/(kg*K)]	water heat capacity
cps	500[J/(kg*K)]	stainless-steel heat capacity
cpi	820[J/(kg*K)]	alumina foam heat capacity
cpq	670[J/(kg*K)]	quartz heat capacity
hws	11[W/(m^2*K)]	heat transfer coefficient between water and stainless steel
hsa	7[W/(m^2*K)]	heat transfer coefficient between stainless steel and air
hia	4.35[W/(m^2*K)]	heat transfer coefficient betwenn alumina foa and air
hwq	30[W/(m^2*K)]	heat transfer coefficient between water and quartz
hqa	8.5[W/(m^2*K)]	heat transfer coefficient between quartz and air

Appendix 5 Validations for Specifications



No.	Testing Targets	Requirements and Specifications	
Test 1&2	Steady-State Value	Temperature Target Range(°C)	
Test 1&2	Settling Time	Temperature Settling Time(s)	
Test 1&2	Steady-State Error	Temperature Steady-State Accuracy(%)	
Test 1&2	Rise Time	Switching Time(S)	
Test 1&2	Assembly and Seals	N/A	
Test 1&2	Turbulences	Flow Rate Target Value(cm^3/s)	
Test 1&2	Mixing Effect	N/A	Test 1: Colored Solutions
Test 2	Scanning	Two Structure on One Substrate	Test 2: Scanning
Analysis & Revise	Power Supply	Low Energy Costs	
Analysis & Revise	Voltage for Electrodeposition	Multiple Energy Sources	

Appendix 6 DesignSafe FMEA Analysis



Hybrid System 11/9/2008

designsafe Report

Application:	Hybrid System	Analyst Name(s):	Chenhao, Eric, Ben, Murat
Description:	- ME 450	Company:	UoM
Product Identifier:	John Hart	Facility Location:	AA
Assessment Type:	Detailed		
Limits:			
Sources:			

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

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
All Users All Tasks	mechanical : cutting / severing manufacture fragments, sharp edges	Minimal Occasional Unlikely	Low	safety glasses, extra care	Minimal Remote Unlikely	Low	
All Users All Tasks	mechanical : fatigue periodic forcing/pumping, creep fatigue	Slight Remote Possible	Moderate	safely secure the vibrating parts, occasionally replace the parts	Minimal Remote Unlikely	Low	
All Users All Tasks	mechanical : magnetic attraction / movement magnetic stir	Minimal None Negligible	Low	don't use it, use pump instead	Minimal None Negligible	Low	
All Users All Tasks	mechanical : machine instability manufacturing error/uncertainties	Slight Occasional Unlikely	Moderate	order from a better workshop	Slight Remote Negligible	Low	
All Users All Tasks	electrical / electronic : insulation failure glass coating wire exposed, electrodes short circuiting	Serious Remote Unlikely	Moderate	make sure the glass coated wire is brand new and the electrodes are safely separated	Slight Remote Unlikely	Low	
All Users All Tasks	electrical / electronic : shorts / arcing / sparking glass coating wire exposed, electrodes short circuiting	Serious Remote Unlikely	Moderate	make sure the glass coated wire is brand new and the electrodes are safely separated	Slight Remote Unlikely	Low	
All Users All Tasks	electrical / electronic : improper wiring wires tangled inside the tube	Slight Occasional Possible	Moderate	have a wire band to prevent the wire from tangling to each other	Slight Remote Unlikely	Low	
All Users All Tasks	electrical / electronic : overloading power supply error, miscalculation in power	Serious Remote Unlikely	Moderate	verify that all the values are right	Minimal Remote Unlikely	Low	

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
All Users All Tasks	electrical / electronic : water / wet locations electrically conductive solutions short circuiting the electrodes	Serious Remote Unlikely	Moderate	using ionized water or other non-conducting solutions	Minimal None Unlikely	Low	
All Users All Tasks	electrical / electronic : electrical noise power supply or input voltage instability	Slight Remote Negligible	Low	use better power supply	Minimal None Negligible	Low	
All Users All Tasks	electrical / electronic : unexpected start up / motion flawed control logic	Slight Remote Unlikely	Low	verify that the system logic is correct	Minimal None Negligible	Low	
All Users All Tasks	electrical / electronic : software errors hardware malfunction, input error	Serious Occasional Possible	High	test runs to verify that the system works, emergency mechanism to manually abort the system	Serious Remote Unlikely	Moderate	
All Users All Tasks	electrical / electronic : power supply interruption power supply error	Slight Remote Unlikely	Low	use better power supply	Minimal None Negligible	Low	
All Users All Tasks	electrical / electronic : electromagnetic susceptibility electrodeposition	Minimal None Negligible	Low	use safe current range	Minimal None Negligible	Low	
All Users All Tasks	electrical / electronic : electrostatic discharge electrodeposition	Minimal None Negligible	Low	use safe current range	Minimal None Negligible	Low	
All Users All Tasks	slips / trips / falls : instability unstable surface, locks, housing, etc	Slight Remote Unlikely	Low	place it in a very stable position	Slight None Negligible	Low	
All Users All Tasks	ergonomics / human factors : human errors / behaviors miscalculations in system control, wrong selection of solutions, careless motions	Serious Remote Possible	Moderate	be extra careful and double check the system before executing	Slight Remote Unlikely	Low	
All Users All Tasks	ergonomics / human factors : deviations from safe work practices using dangerous chemicals, getting close to the reaction chamber while it's still hot	Serious Remote Unlikely	Moderate	practice safe work	Minimal None Negligible	Low	

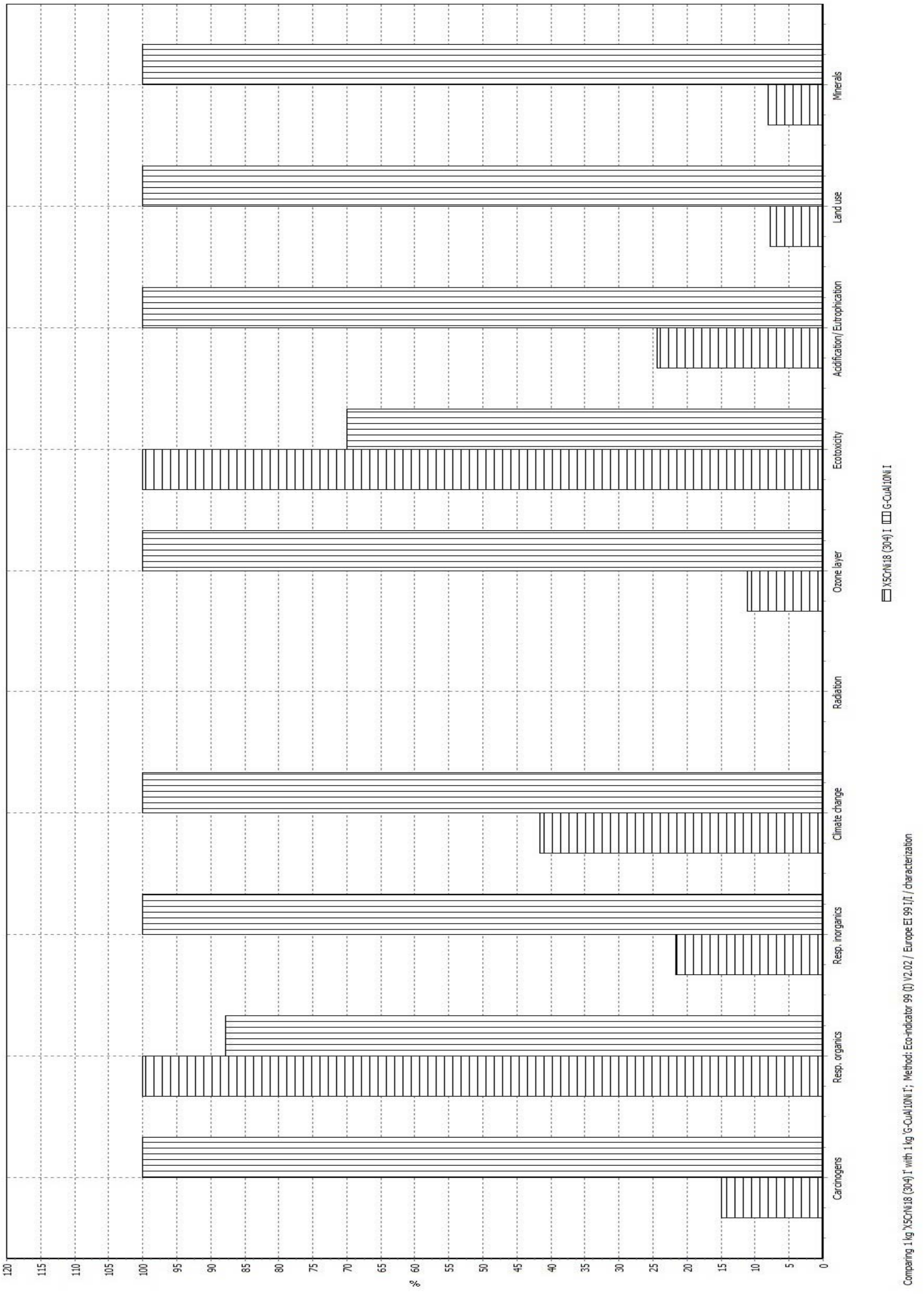
User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
All Users All Tasks	ergonomics / human factors : interactions between persons miscommunications	Minimal Remote Unlikely	Low	divide the works evenly and clearly, make sure everyone knows what they are doing	Minimal None Negligible	Low	
All Users All Tasks	fire and explosions : hot surfaces heating coils	Serious Frequent Probable	High	thermal insulator	Slight Remote Unlikely	Low	
All Users All Tasks	fire and explosions : flammable liquid / vapor dangerous chemicals	Catastrophic Occasional Possible	High	use safe chemicals	Slight Remote Possible	Moderate	
All Users All Tasks	fire and explosions : improperly mixed chemicals the chamber is not completely cleaned out of the previous solution	Serious Occasional Possible	High	make the cleaning period longer, use safe chemicals.	Slight Remote Unlikely	Low	
All Users All Tasks	fire and explosions : dust some dust caught in the system from the solution chamber or other sources	Minimal Remote Negligible	Low	add filters, clean the chamber before working	Minimal None Negligible	Low	
All Users All Tasks	heat / temperature : burns / scalds high temperature surfaces/fluids	Serious Occasional Possible	High	wait for the system to cool down, safe distance from the hot parts. thermal insulators	Minimal Remote Unlikely	Low	
All Users All Tasks	heat / temperature : severe heat high temperature reactions	Serious Remote Possible	Moderate	thermal isulators	Slight Remote Unlikely	Low	
All Users All Tasks	heat / temperature : inadequate heating / cooling heating coil not strong enough, bad placement of the heating coils, bad thermal insulation. bad radiator, bad assembly	Serious Occasional Possible	High	use better parts, precise and good assembly	Serious Remote Unlikely	Moderate	
All Users All Tasks	noise / vibration : equipment damage high temperature. corrosion. fatigue	Serious Remote Unlikely	Moderate	check for integrity of the material once in a while and exchange the parts when they are not in good condition	Slight Remote Unlikely	Low	
All Users All Tasks	material handling : stacking unstable stacking	Slight Remote Negligible	Low	shaped mounting	Slight None Negligible	Low	

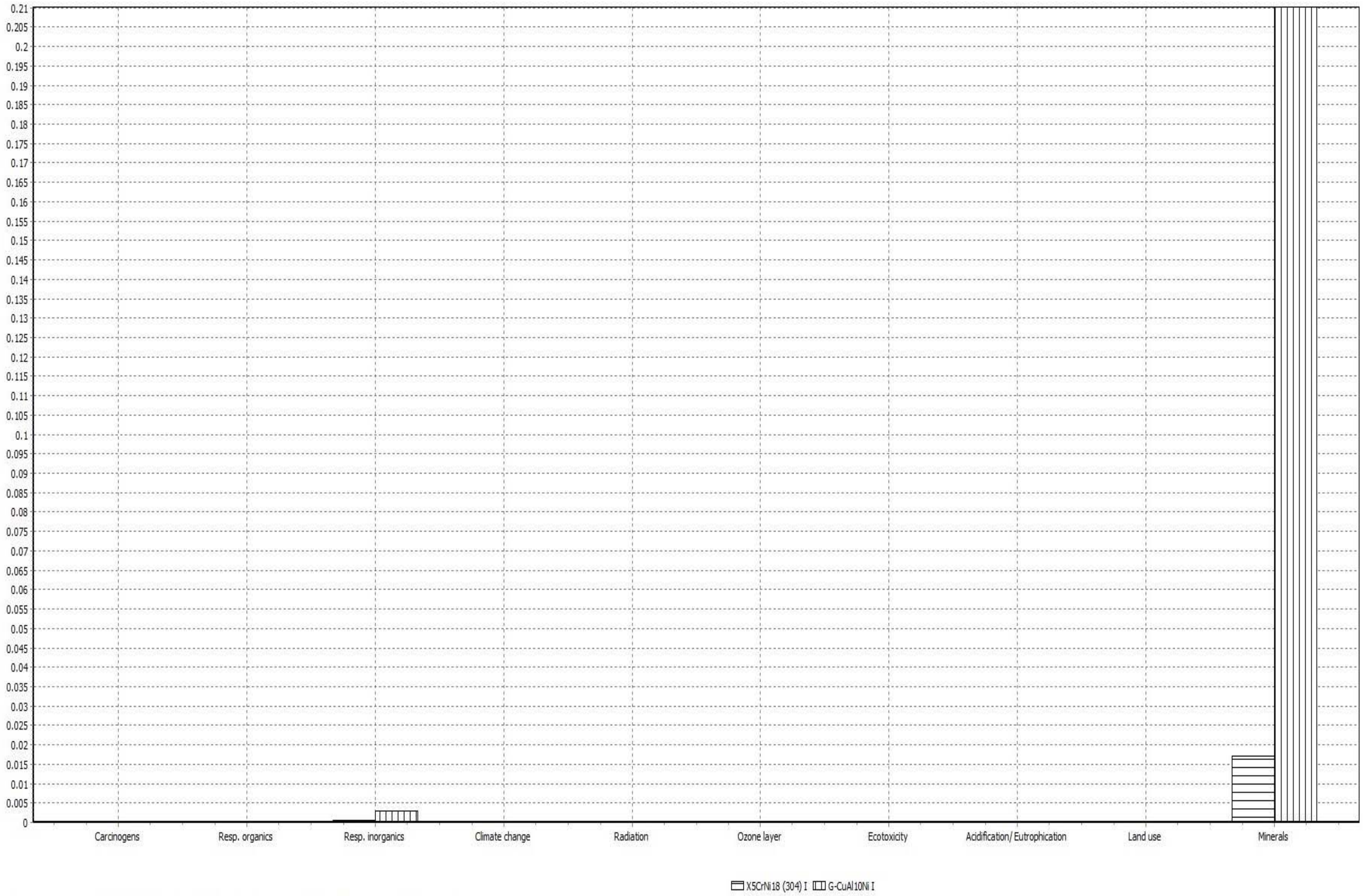
User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
All Users All Tasks	confined spaces : confined spaces the substrate and fluid is inaccessible without dissambling the parts	Slight Remote Possible	Moderate	scanning aided assembly, good operation	Minimal Remote Unlikely	Low	
All Users All Tasks	environmental / industrial hygiene : irritants vaporized gases from reactions	Serious Remote Unlikely	Moderate	dissolve in solutions	Minimal None Unlikely	Low	
All Users All Tasks	environmental / industrial hygiene : poisons toxic reagents	Serious Remote Unlikely	Moderate	dissolve in solutions	Serious None Negligible	Low	
All Users All Tasks	environmental / industrial hygiene : solvents high toxicity, high volatile	Serious Remote Unlikely	Moderate	mixing with another solution or catalyst	Slight Remote Negligible	Low	
All Users All Tasks	environmental / industrial hygiene : effluent / effluent handling spilled solutions, leakage in the pipes	Serious Remote Unlikely	Moderate	use safe chemicals	Slight Remote Unlikely	Low	
All Users All Tasks	environmental / industrial hygiene : corrosion acidic or base solutions	Serious Remote Possible	Moderate	use corrosion resistant materials, periodically change the part if it corrodes	Slight Remote Unlikely	Low	
All Users All Tasks	environmental / industrial hygiene : contamination undesired fabrication of solids in solutions	Serious Remote Unlikely	Moderate	add other solvents, clean the tubes and electrodes once in a while	Slight Remote Negligible	Low	
All Users All Tasks	ventilation : concentration cleaning solution or the other solution mixing with the current solution	Slight Remote Probable	Moderate	increase the duration of the cleaning process, reduce turbulence	Minimal Remote Unlikely	Low	
All Users All Tasks	chemical : reaction to / with chemicals corrosion, reaction with other chemicals	Serious Occasional Possible	High	use safe chemicals combinations	Slight Remote Unlikely	Low	

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
All Users All Tasks	chemical : chemical / toxicity effects felt at distant time / place chemicals that can cause cancer	Serious Remote Unlikely	Moderate	be extra careful, wear protections, or avoid using those chemicals	Slight Remote Unlikely	Low	
All Users All Tasks	chemical : mixing incompatible chemicals wrong selection of chemicals	Serious Occasional Possible	High	research the compability of the solutions beforehand	Slight Remote Unlikely	Low	
All Users All Tasks	chemicals and gases : carbon dioxide reaction products	Slight Remote Unlikely	Low	addtional reagent or solution	Minimal None Negligible	Low	
All Users All Tasks	chemicals and gases : hydrogen electrodeposition	Slight Remote Possible	Moderate	addtional reagent or solution	Minimal None Negligible	Low	
All Users All Tasks	chemicals and gases : methanol solvent	Slight Remote Unlikely	Low	addtional reagent or solution	Minimal None Negligible	Low	
All Users All Tasks	chemicals and gases : methyl ethyl ketone solvent	Slight Remote Unlikely	Low	addtional reagent or solution	Minimal None Negligible	Low	
All Users All Tasks	chemicals and gases : nitric acid solvent	Slight Remote Unlikely	Low	addtional reagent or solution	Minimal None Negligible	Low	
All Users All Tasks	chemicals and gases : oxygen surrounding environment	Serious Remote Possible	Moderate	addtional reagent or solution	Minimal None Negligible	Low	
All Users All Tasks	chemicals and gases : peroxide solvent	Slight Remote Unlikely	Low	addtional reagent or solution	Minimal None Negligible	Low	
All Users All Tasks	chemicals and gases : sodium hydroxide solvent	Slight Remote Unlikely	Low	addtional reagent or solution	Minimal None Negligible	Low	
All Users All Tasks	chemicals and gases : trichloroethane solvent	Slight Remote Unlikely	Low	addtional reagent or solution	Minimal None Negligible	Low	
All Users All Tasks	biological / health : lack of first aid burns, acidic solutions, heat	Slight Remote Unlikely	Low	prepare the first aid kit nearby	Slight None Negligible	Low	

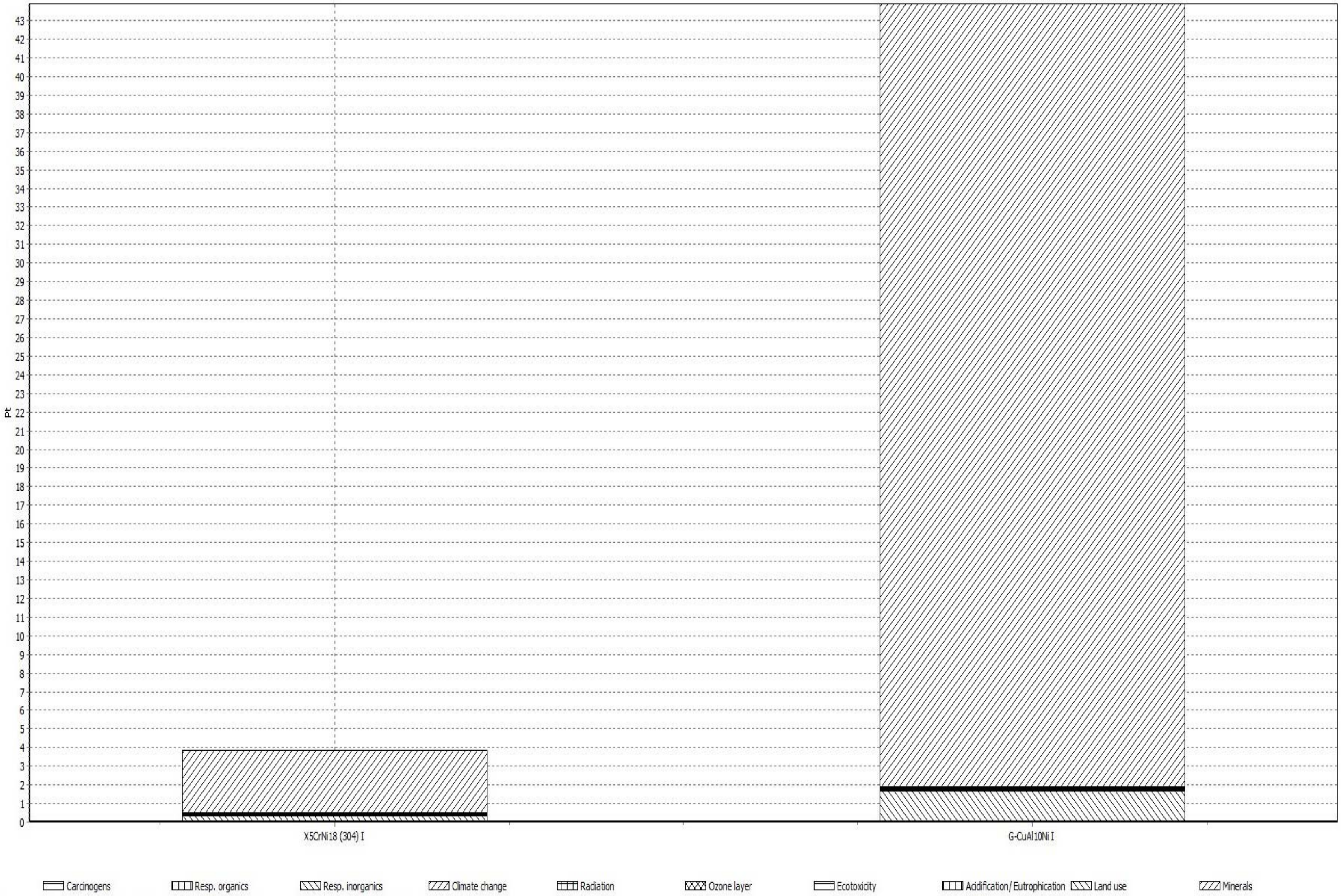
User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
All Users All Tasks	fluid / pressure : hydraulics rupture too much water pressure, badly attached joints	Serious Occasional Possible	High	use safe pumping speed and make sure all the joints are watertight	Slight Remote Unlikely	Low	
All Users All Tasks	fluid / pressure : explosion / implosion the solution inside is boiling, combusting or reacting badly with other chemicals	Catastrophic Remote Unlikely	Moderate	use safety valves to prevent sudden increase in pressure, use safe chemical combinations	Slight Remote Unlikely	Low	
All Users All Tasks	fluid / pressure : surges / sloshing leakage	Serious Remote Unlikely	Moderate	make sure the system is watertight	Slight Remote Unlikely	Low	
All Users All Tasks	fluid / pressure : fluid leakage / ejection leakage, sudden increase in pressure	Serious Remote Unlikely	Moderate	make sure the system is watertight, use safety valves, operate in the safe range	Slight Remote Unlikely	Low	
All Users All Tasks	fluid / pressure : liquid / vapor hazards the solution boils	Serious Remote Unlikely	Moderate	use safety valves and operate at the safe range	Slight Remote Unlikely	Low	

Appendix 7 Simapro Charts





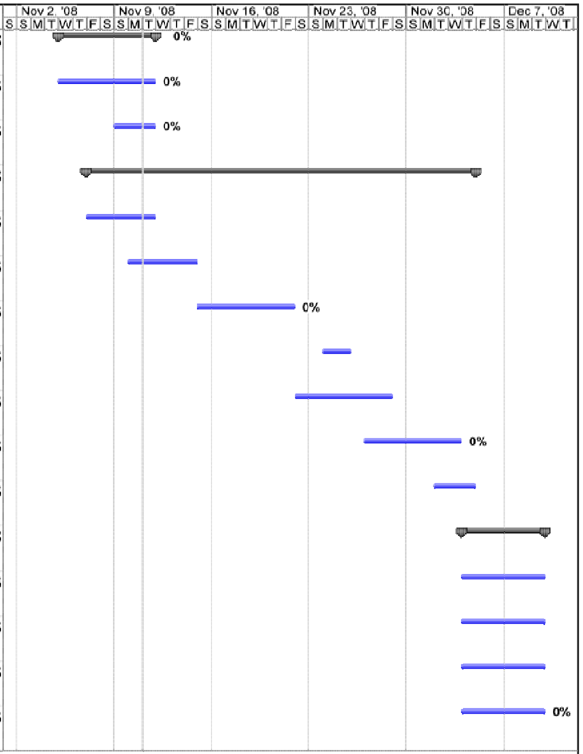
Comparing 1 kg 'X5CrNi18 (304) I' with 1 kg 'G-CuAl10Ni I'; Method: Eco-indicator 99 (I) V2.02 / Europe EI 99 I/I / normalization



Comparing 1 kg 'X5CrNi18 (304) I' with 1 kg 'G-CuAl10Ni I'; Method: Eco-indicator 99 (I) V2.02 / Europe EI 99 I/I / single score

Appendix.8 Schedule

ID	Task Name	Duration	Start	Finish
1	**Design Review#3**	**7 days**	**Wed 11/5/08**	**Tue 11/11/08**
2	Design Review#3 Report	7 days	Wed 11/5/08	Tue 11/11/08
3	Design Expo Abstract	3 days	Sun 11/9/08	Tue 11/11/08
4	**Validation Plan for Prototype**	**28 days**	**Fri 11/7/08**	**Thu 12/4/08**
5	Order All Parts Needed For Prototype	5 days	Fri 11/7/08	Tue 11/11/08
6	Custom Fabrication and Assembly	5 days	Mon 11/10/08	Fri 11/14/08
7	Build Prototype	7 days	Sat 11/15/08	Fri 11/21/08
8	Design Review #4(No report or power point needed)	2 days	Mon 11/24/08	Tue 11/25/08
9	Testing, Revising and Validation for Prototype	7 days	Sat 11/22/08	Fri 11/28/08
10	Design Expo Preperation	7 days	Thu 11/27/08	Wed 12/3/08
11	Make Poster for Design Expo	3 days	Tue 12/2/08	Thu 12/4/08
12	**Write Design Critique**	**6 days**	**Thu 12/4/08**	**Tue 12/9/08**
13	Final Report Presentation	6 days	Thu 12/4/08	Tue 12/9/08
14	Perform Failure/Safety Analysis	6 days	Thu 12/4/08	Tue 12/9/08
15	Document what has changed since DR#3	6 days	Thu 12/4/08	Tue 12/9/08
16	Write Recommendations For Future Work	6 days	Thu 12/4/08	Tue 12/9/08

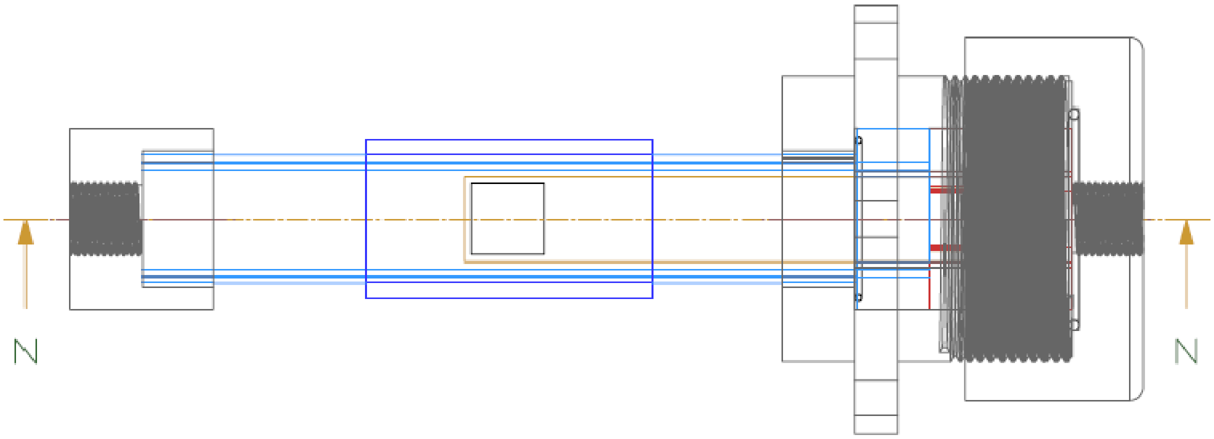


Project: Project1 Schedule
Date: Tue 11/11/08

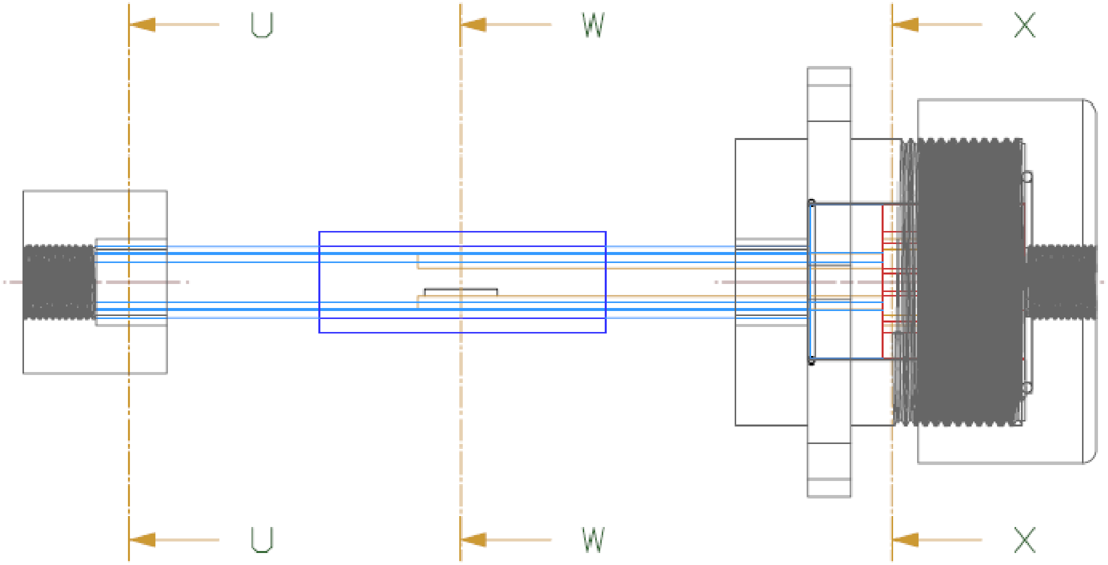
Critical		Split		Baseline Milestone	◇	Project Summary	
Critical Split		Task Progress		Milestone	◆	External Tasks	
Critical Progress		Baseline		Summary Progress		External Milestone	◆
Task		Baseline Split		Summary		Deadline	⇩

Appendix.9 Reaction Chamber Clearances

All Dimensions in mm

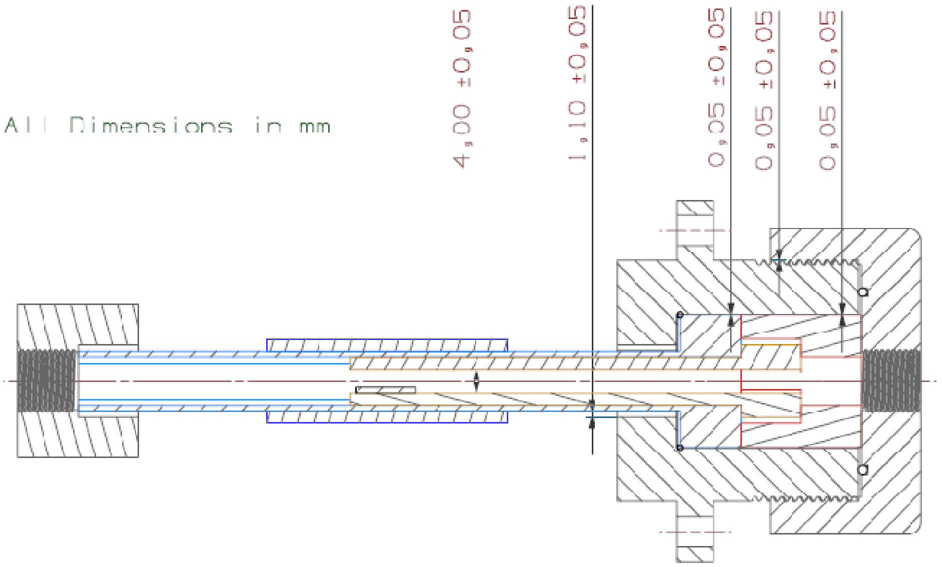


Top View

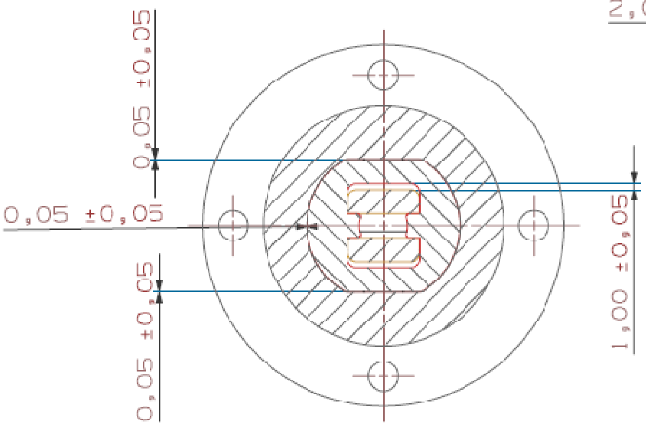


Side View

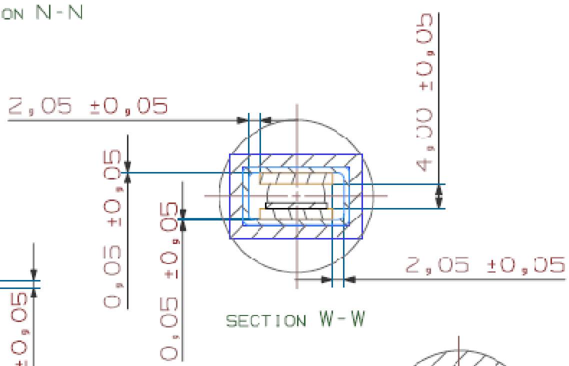
All Dimensions in mm



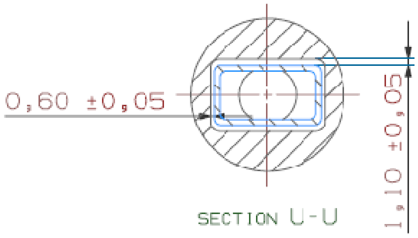
SECTION N-N



SECTION X-X

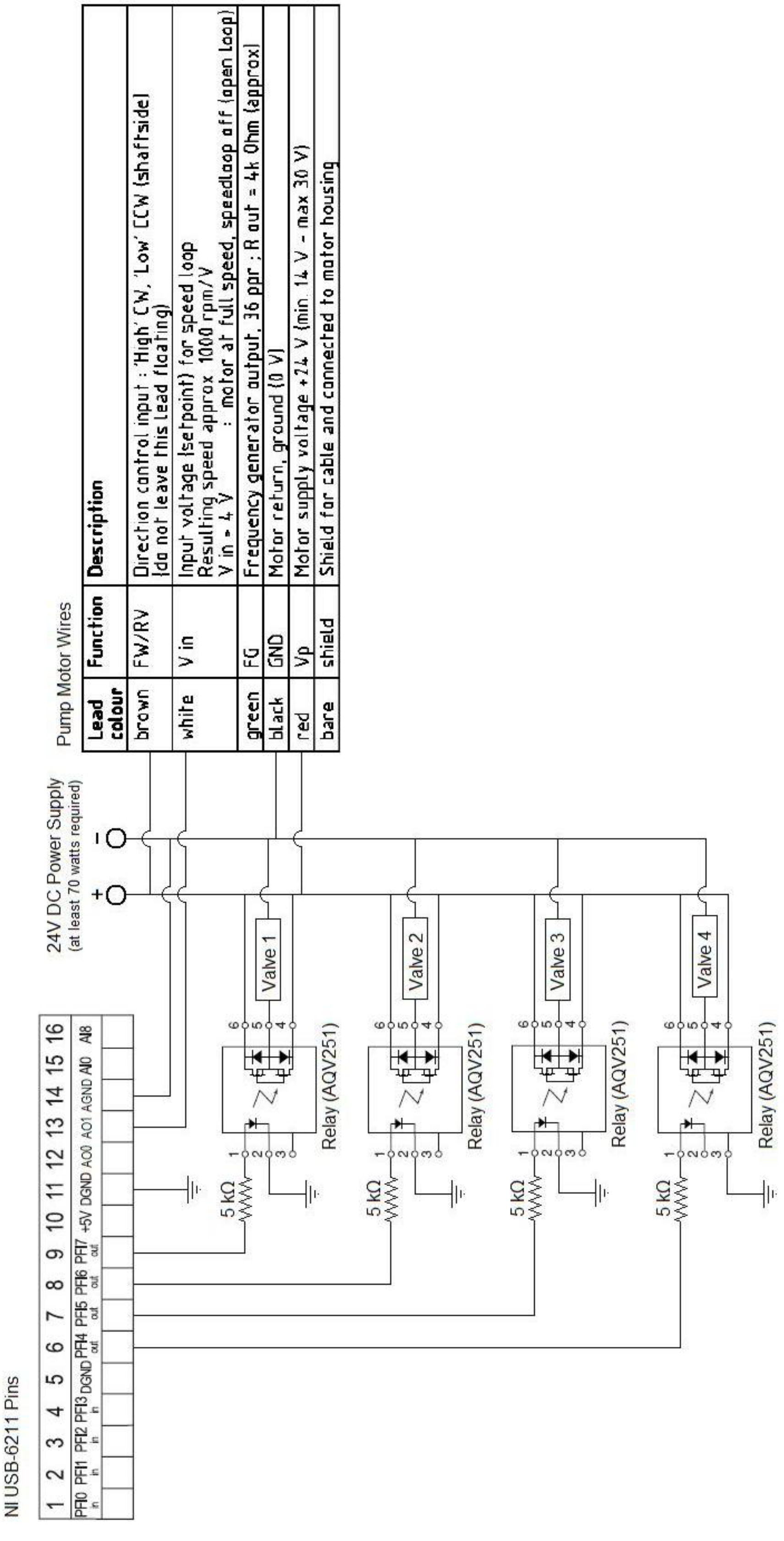


SECTION W-W



SECTION U-U

Appendex.10 Electrical Schematic



Pump Motor Wires

Lead colour	Function	Description
brown	FW/RV	Direction control input : 'High' CW, 'Low' CCW (shaftside) (do not leave this lead floating)
white	V in	Input voltage (setpoint) for speed loop Resulting speed approx 1000 rpm/V V in > 4 V : motor at full speed, speedloop off (open loop)
green	FG	Frequency generator output, 36 ppr ; R out = 4k Ohm (approx)
black	GND	Motor return, ground (0 V)
red	Vp	Motor supply voltage +24 V (min. 14 V - max 30 V)
bare	shield	Shield for cable and connected to motor housing