Paint Applicator Cleaning Station

Project 17

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1 Abstract

High-speed rotary atomizers attached to robot arms are used to apply the color coat in many of GM's paint shops. These atomizers must be cleaned between the application of each different color. Currently plants that apply water based color coats use a purge solution composed of water and solvent to clean off the over spray from robotic equipment. Significant cost could be saved if a cleaning station was designed that does not use solvent to clean the surface of the paint applicators. Our goal is to design a cleaning station that will clean and dry the rotary atomizers using only water and air.

2 Introduction

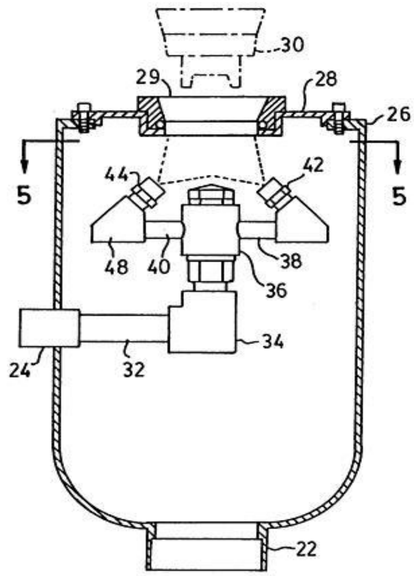
One of the critical stages during the production of a vehicle is the application of the paint. Usually, at General Motors plants that apply water based color coats, each car is painted a different color than the one before it. To avoid performance affecting paint buildup and ensure that the paints are not mixed, it is very important that the paint applicator (a high speed rotary atomizer) is cleaned and dried after each car has been painted. Ideally, it should take about 10 seconds to clean and dry the applicator shroud. The current cleaning process uses a mixture of solvent and water and is very expensive. Our goal is to work closely with General Motors (our sponsor) in order to design, build, and test a working model of a new cleaning station that cleans and dries the paint applicator in 10 seconds without the use of the purge solvent solution. The motivation behind this project is twofold. First of all, General Motors estimates that they would save at least $170,000 per year at each plant if this new cleaning station is put into production, for a total of over $1,000,000 in potential savings per year. Second, with increased awareness of how manufacturing processes effect the environment, a solvent free cleaning process would improve GM's efforts to become more environmentally friendly.

3 Information Search

Any piece of equipment used within a GM facility in a production environment must first undergo rigorous testing to become validated. For this application, GM has imposed several benchmarks in which to measure the success of such a cleaning apparatus. The testing requires that the device be capable of cleaning a water-borne base coat from the shroud and bell cup, prevent liquid splash out during the cleaning process, and minimize residual wetness of the shroud and bell cup after the cleaning cycle. Containment of the solution is extremely important to prevent contamination of any nearby vehicle before, during, and after the topcoat is applied. Cycle time is also an important consideration, as the complete cleaning and drying cycle must occur within 10 seconds.

Currently, the only system that has passed all of the GM validation requirements is the Crystal Cap Cleaner (US Patent 6418944) as shown in Figure 1 (p. 5) [1]. This cleaning system uses a water/solvent mixture that is heated to 120°F. From a reservoir, the solution is pressurized by a low-pressure pump (<75 psi) and fed to the cleaner assembly where it is forced through a solution-driven impeller that spins at 4,000 RPM [2]. The impeller expels the cleaning solution while the angular velocity creates a cleaning action that works to remove the paint over spray from both the shroud and bell cup, as well as flush the inside of the cleaner assembly. As the shroud is extracted from the cleaner assembly by the robot, the solution supply is cut off and a ring of pressurized air removes any residual solution from the shroud and bell cup.

Figure 1: Crystal Cap Cleaner



These systems are very expensive and are typically used for large-scale industrial operations. This makes it difficult for the average consumer to obtain any sort of technical specifications for the devices. What is known is that there currently is no system available for this application that uses only water and air. Since this is the goal of the project (to use only water and air for the cleaning cycle) this makes our system unique to any other products on the present market.

The system is restricted to using only water and air, so possibilities are obviously limited as to what design options may be considered. The obvious method is to direct highly pressurized water towards the shroud in a contained environment to remove contaminants and follow with a drying cycle using pressurized air. General Motors assigned a summer hire to begin initial testing of a high-pressure nozzle arrangement to clean the shroud and bell cup assembly. For the testing, a standard topcoat spray cycle was simulated to create a paint covered shroud and bell cup similar to a worst-case production scenario. To remove the paint, the shroud was then impacted with ambient temperature de-ionized water delivered by a high-pressure pump. Various water nozzles and pressures were studied to find the optimum compromise between cleaning action and water usage. Nozzles tested had spray angles that varied from 0° to 110° and flow rates that varied from 0.21 gpm to 1.50 gpm. Pressures studied varied from 200 psi to 1600 psi. The optimal configuration was found to be a 65° nozzle with a flow rate of 0.50 gpm and a pressure of 600 psi. Additional testing was suggested but for now, our development will make use of the given information. Our system design will include adjustable features so that further testing may take place in order to optimize the final configuration.

4 Customer Requirements and Engineering Specifications

As stated above, our team has been asked to help General Motors reduce the cost involved with painting their vehicles, while at the same time making the process more environmentally friendly. The most effective way to do so is by improving the current cleaning system for the rotary atomizers. General Motors requires (Table 1, p. 6) that our design completely clean and dry the shroud of the rotary atomizer using nothing but water and air, and do so in approximately 10 seconds. Of course, this should be done in the most cost effective way.

4.1 Customer Requirements

During the week of September 10, 2007, our design team met with our sponsors at the GM Tech Center in Warren, MI. We were shown the current rotary atomizer cleaning system and briefed on the project status. Our job was to pick up where the GM intern left off and bring the project to fruition. Through a series of questions and discussion with the paint and polymers group at GM, our design team was able to gather the precise customer requirements (Table 1), which were mainly focused around cleaning and drying the shroud in the specified time and doing so in a cost effective manner. First and foremost, the atomizer shroud had to be completely clean from the bottom edge up approximately 5 inches, including the shaping air ring located on the flat bottom surface of the shroud. It then had to be completely dry and ready for the next spray cycle. More importantly, all of this had to occur within the time it takes to move the next car into position, and no water could spray out onto the vehicles. Our final design also had to be as cost efficient as possible.

Table 1: Comparison of customer requirements and our engineering specifications

Customer Requirements	Engineering Specifications
Clean paint shroud completely	Paint Remaining 0%
Shaping air ring clean	Water Remaining 0%
Dry paint shroud completely	Max water used 0.5 gallons per cycle
Use only water and air	Clean and dry in 10 sec
Clean and dry in specified time	Size limitations (15 x 15) in
Remain within size limitations	Water splash out 0%
Contain Water spray	Minimum water pressure 600psi
Minimize Cost	Production cost ≤ Crystal Cleaner
	Cost per cycle < Crystal Cleaner

4.2 Engineering Specifications

The brainstorming and development of our engineering specifications (Table 1) allowed our design team to quantify what we felt GM was looking for. When it came to the cleaning and drying processes, our team decided that it was important to quantify the task at hand using a percentage system. Completely cleaning and drying the shroud would mean that our design should leave 0% of the paint and 0% of the water on the shroud, as well as keep the water spray-out as close to 0% as possible. Prior testing by GM revealed that a pressure of 600 psi removes the paint from the atomizer surface at an acceptable level. Thus, we set a baseline pressure of 600 psi as the minimum water pressure at which testing for our prototype would begin. To conserve water, we set a goal to design a concept that uses less than 0.5 gallons of water per cycle. The time between cars on the assembly line was found to be approximately 15 seconds; therefore, it was determined that the cleaning and drying process should take no longer than 10 seconds. Size limitations did not turn out to be that big of a constraint; the entire cleaning set-up needed to fit within the current allotted floor space of 15 x 15 inches. Finally, to comply with cost restrictions, our design needed to have a production cost less than or equal to the Crystal Cleaner and a per-cycle cost much less than the Crystal Cleaner.

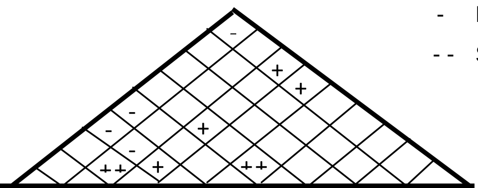
4.3 Quality Functional Development (QFD)

With the help of our QFD diagram (Fig. 2, p. 7), we were able to put numbers to our prior assumptions of which requirements were most important. The weights on the left side represent our initial order of importance, naturally placing priority one on eliminating all but water and air from the cleaning process. The benchmarks on the right highlight the strengths and weaknesses of the current viable alternatives. Research into these systems proved effective in showing what does not work, and, more importantly, what may work with creative innovation. From the QFD, it was apparent that the use of water and air in a cost effective way would be a truly new accomplishment. Finally, correlations were drawn between and among the customer requirements and our engineering specifications. The numbers were totaled and analyzed. These numbers allowed us to narrow our focus, specifically paving the way for further quantitative analysis through lab testing.

Figure 2: Quality Functional Development

Relationships

++ Strong Positive
+ Medium Positive
- Medium Negative
- - Strong Negative



Customer Requirements \ Engineering Specifications	Weights	Paint Remaining 0%	Water Remaining 0%	Max water used 3 Liter per cycle	Clean and dry in 10 sec	Minimum water pressure 600psi	Water splash out 0%	Size limitations (15x15) in base	Production cost </= Crystal Cleaner	Cost per cycle < Crystal Cleaner		*Durr EcoBell Cleaner*	*Crystal Shroud Cleaner*	*Sames Rinsing Box*	*Modified Sames (High Pressure)*
Clean paint shroud completely	6	9		3	3	3	1		1	3		4	5	3	3
Dry paint shroud completely	2		9	1	3		1		1	1		4	4	3	2
Use only water and air	7	3		1					1	9		1	1	1	5
Clean and dry in specified time	4	3	3	3	9				1	3		3	4	3	1
Remain within size limitations	1				3		1	9	9			5	5	5	5
Contain water spray	2			3	3	9	9	3		1		4	5	2	1
Minimize cost	1			3				3	9	9		2	2	2	2
Shaping air ring clean	5	9	9	3	3	3	1		1	3		3	5	1	2
Measurement Unit		%	%	L	sec	psi	%	in^2	$	$					
Target Value		0	0	2	10	600	0	225	500	0.80					
Importance Rating		**8**	**6**	**4**	**6**	**2**	**6**	**1**	**1**	**2**					
Total		132	75	63	84	51	32	18	42	121					
Normalized		0.21	0.12	0.10	0.14	0.08	0.05	0.03	0.07	0.20					

Benchmarks: Durr EcoBell Cleaner, Crystal Shroud Cleaner, Sames Rinsing Box, Modified Sames (High Pressure)

Key:
9 => Strong Relationship
3 => Medium Relationship
1 => Small Relationship
(blank) => Not Related

***Weights are figured on a scale of 1 to 10**
(ten being most important)

5 Concept Generation

The FAST, Morphological, and Pugh Chart are used to analyze the functions of the cleaning station, create concept design ideas, determine five main concepts, analyze each, and finally select one design concept.

5.1 Fast Chart

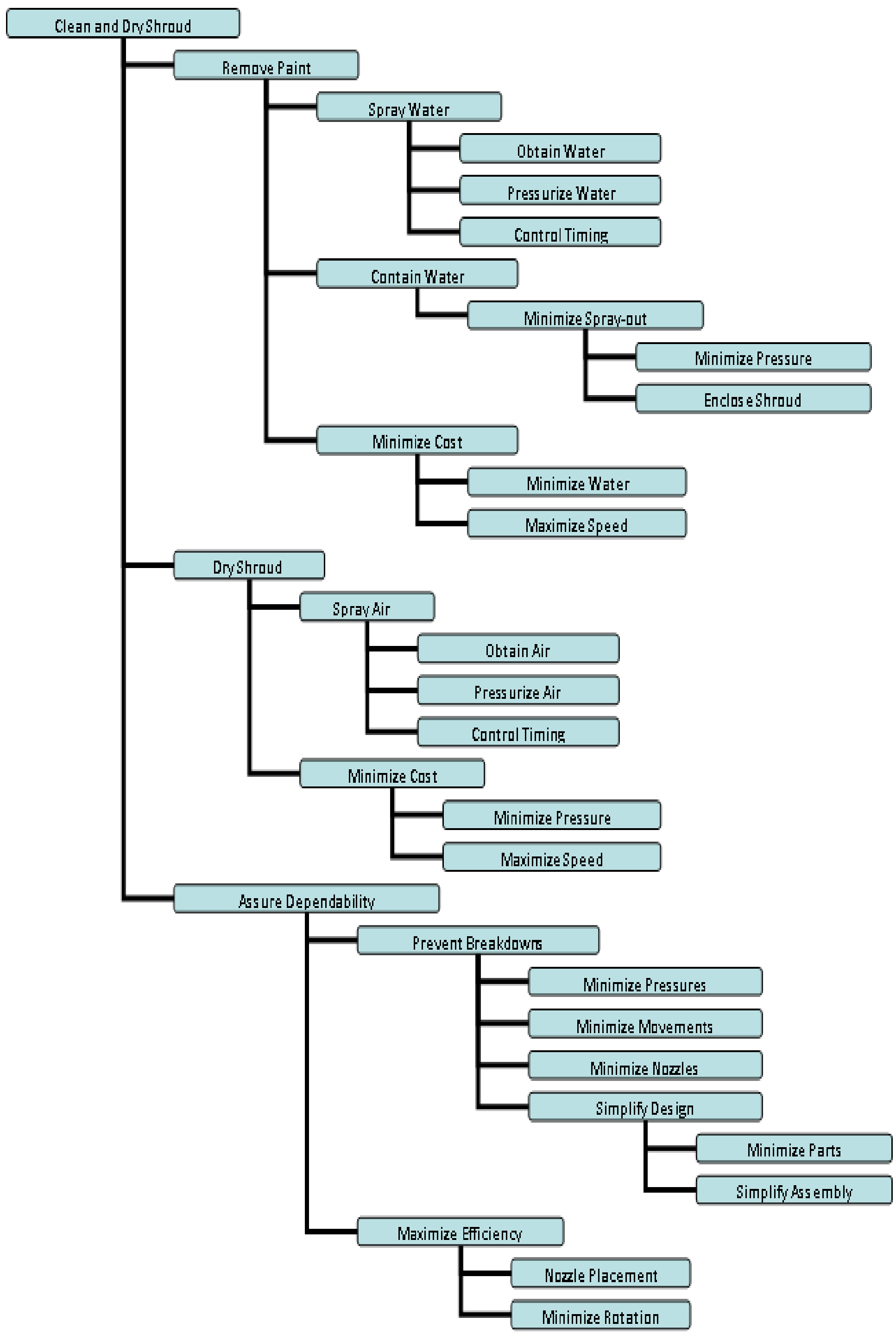
We used the FAST Chart to breakdown the functions of the cleaning station so it became easier to see what tasks our design needed to perform. The summary of this chart is shown in Figure 3 (p.9). The overall function of the paint applicator cleaning station is to clean and dry the paint shroud. From there, removing the paint from the shroud and drying the shroud are two of the major sub-functions. In addition to these, assuring dependability of the cleaning station was found to be important in our design and is included as another major sub-function that must be taken into consideration for our design concept.

Water must be sprayed onto the shroud to remove the paint, and, subsequently, the water must be contained inside the cleaning station. These functions must also be done in such a way that minimizes the cost of running the machine. Important details in spraying the water include obtaining the water, pressurizing it, and then controlling the time to start and stop the spray. The two important parts of spraying the water is how hard and for how long it needs to be sprayed at the shroud in order to clean off the paint. Controlling these functions will directly affect the quality of the machine's cleaning performance. The major concern with containing the water is minimizing the spray-out that could potentially contaminate the car's coat of paint. In order to do this, the pressure of the water should be minimized and the shroud itself should be enclosed. As little water as possible should be used during the process to limit the expenses spent on resources and minimize the amount of time the station runs water.

Completely drying the shroud in this cleaning process involves spraying air. Minimizing the cost is again important and needs to be taken into consideration to define the limitations of this function. The functions involved in spraying air are similar to spraying the water in the previous function: obtaining the air, pressurizing it, and then controlling the timing of switching it on and off. Pressurizing the air is necessary so that the shroud can be dried off in the specified amount of time listed in the customer requirements (Table 1, p.6). In order to minimize the costs in drying the shroud, the pressure should be minimized. Also, drying the shroud quickly will decrease the amount of time the machine is running, lessening the energy used and minimizing the cost.

Assuring dependability of the machine is another function to consider since it must be able to run hundreds of times a day on a production line. To assure dependability, the cleaning station should be designed to prevent breakdowns and maximize its efficiency. Using minimal water and air pressures would lighten the wear on all the components of the cleaning station. Fewer nozzles will decrease the number of parts that need to be checked for cleaning and replacement due to wear. This also limits the places where the cleaning station may fail. Minimizing moving parts will decrease any additional wear on the cleaning station, increasing its longevity. Finally, a simple design with minimal parts will help prevent breakdowns by keeping the assembly of the cleaning station uncomplicated and limiting the place for error in its production. It will also decrease the amount of places open to wear and failure during the use of the machine. The other area involved in assuring the machine's dependability, maximizing the efficiency, originates from nozzle placement and minimizing the rotation needed in cleaning the shroud. Placing the nozzles in such a way that will cover a maximal area will help ensure the shroud is cleaned every cycle. Also, rotating the nozzles around the shroud a minimal amount of times will decrease the wear on the machine and the shroud, decrease energy usage, and decrease cleaning time per cycle.

Figure 3: FAST Chart



5.2 Morphological Chart

After defining the basic and subsidiary functions of the design, a morphological chart is used to create high-level design concepts to perform the functions (Table 2, p. 11). It is then analyzed and combined to generate several complete designs of the cleaning station (Table 3, p.11). From the FAST chart our team took three major functions to design concepts around: spraying water, drying the shroud, and containing the water spray-out. From these concepts, we combined them into five major design concepts.

5.2.1 Concept Chart

The methods that our team considered to spray the water include variations using a ring of nozzles that run continuously around the shroud and two or three arrays of nozzles that extend vertically next to the shroud inside the machine. The ring of nozzles could be stationary inside the cleaning station and the shroud could rotate, or the shroud could enter into the machine and the ring could mechanically rise and fall around the shroud while it remains stationary. The arrays of nozzles could also remain stationary while the shroud spins, or the shroud could remain stationary and the arrays could rotate around it to cover all the areas of the shroud. Rotating the shroud was eliminated because our sponsors at General Motors informed us that the robotic arm could not spin the shroud inside the machine. Another idea was to use multiple stationary nozzles throughout the entire interior of the machine; however this idea was also eliminated because another company, Durr, already uses that design concept and it is a proven unsuccessful way to clean the shroud. An arrangement of two spiraling nozzles down the interior of the machine was another idea added to our concepts. All these concepts could include angled nozzles in the design to enhance the area covered by the nozzle spray.

Next we considered a few different methods to dry the shroud after cleaning. Our first idea of using the air ring came from the Durr model. It is a ring at the mouth of the cleaning station that blows air downward through many small holes, drying the shroud as it leaves. Using air nozzles at the opening is another variation. They could be stationary or rotate around in unison with the water nozzles. Another idea was using heated air in the process, but this was eliminated after determining it would increase energy costs unnecessarily. Using a wiper to dry the shroud was another idea that was eliminated since this would increase the chances of the shroud being contaminated with different color paints from previous cycles.

To contain the water spray-out, the design concepts our team came up with were to use the air ring previously mentioned, using a shield, making a seal for the top, and making the entire machine closed. The idea for a seal at the top was eliminated since it could be another source of contamination to the shroud like the wiper in the previous section.

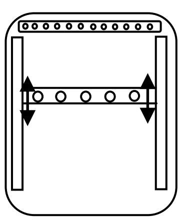
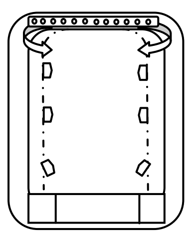
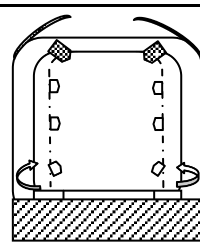
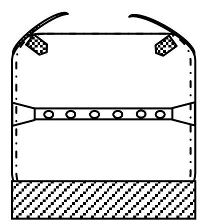
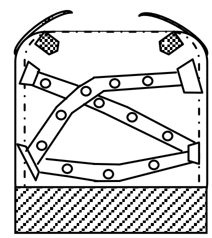
Table 2: Morphological Chart—Step 1

Function	**Concepts**						
Spray Water	one ring of nozzles	2 or 3 arrays of nozzles that rotate	Spiral nozzle arrangement (2 lines)	multiple stationary nozzles	2 or 3 arrays of nozzles with rotating shroud	angled nozzles	ring of nozzles that moves up and down
Dry Shroud	air ring	air nozzles at top for rotating	heating air	wiper	stationary air nozzles at top		
Contain Spray-out	air ring (Venturi)	shield (shell)	close	seal at top			

5.2.2 Concept Designs Chart

After eliminating the concepts that were not feasible for our project, we combined the remaining concept ideas to make five major concept designs seen in Table 3 and described individually below.

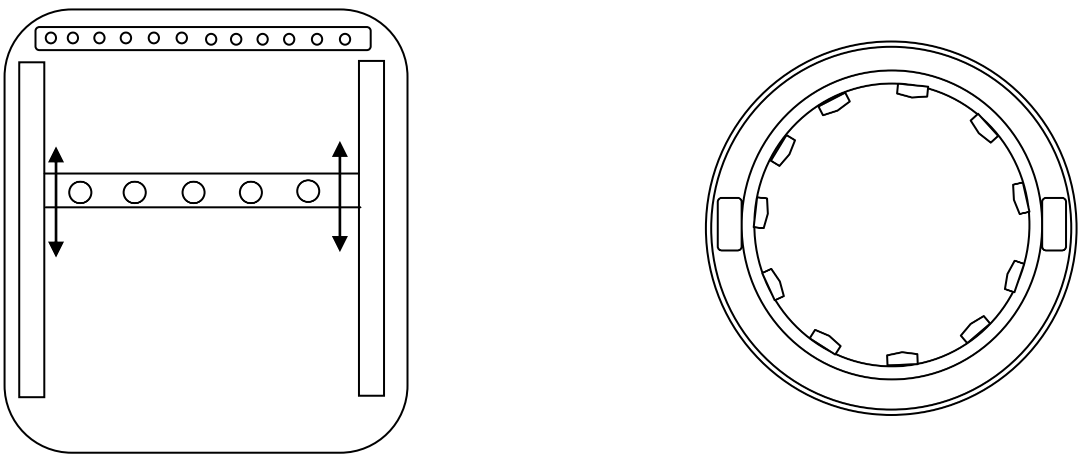
Table 3: Morphological Chart—Step 2

Function	**Design 1**	**Design 2**	**Design 3**	**Design 4**	**Design 5**
					
Spray water	Ring of nozzles that moves up and down	2 or 3 rotating arrays of nozzles	2 or 3 rotating arrays of nozzles	Stationary ring of nozzles with shroud passing through	2 spiraling rings of nozzles with shroud descending completely past all nozzles
Dry Shroud	Air ring	Air ring	Stationary air nozzles at top	Stationary air nozzles at top	Stationary air nozzles at top
Contain spray-out	Air ring	Air ring	Shield	Shield	Shield

5.2.2.1 Design 1

Design 1 (Fig. 4) features a horizontal ring of nozzles which are mounted such that they deliver a horizontal flat spray of water that spans the entire circumference of the atomizer shroud. Upon insertion of the shroud into the cleaning station, the ring of nozzles starts at the bottom of the shroud and moves up (possibly pneumatically) until the spray has covered five vertical inches of its surface, at which time the water spray stops. This design also features an "air ring" that is situated at the top of the cleaning station. The air ring dispenses air downward into the cleaning station during both the washing and drying processes. During the washing of the shroud, the air flow from the air ring creates a Venturi effect that forces all of the water that might escape out of the top of the cleaning station to exit out the bottom. When the washing is complete and the shroud is exiting the cleaning station, the air ring dries the shroud.

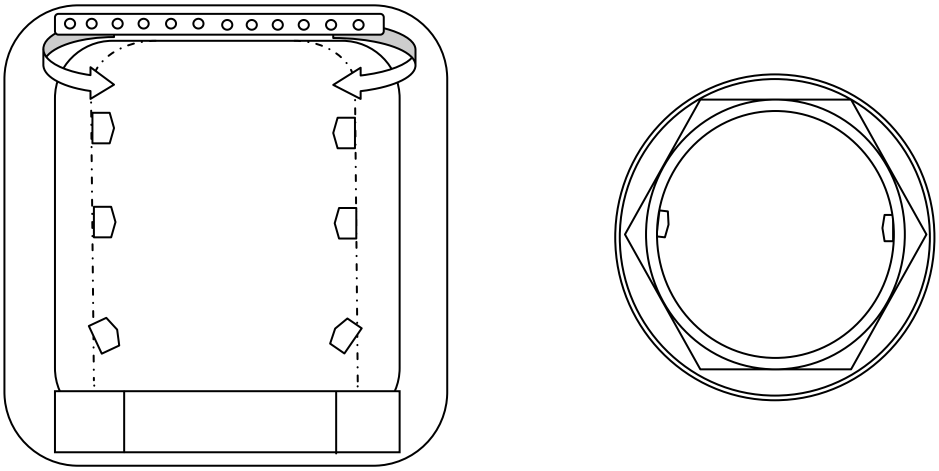
Figure 4: Design 1 Sketch



5.2.2.2 Design 2

Design 2 (Fig. 5, p. 13) features two vertical arrays of three nozzles each of which are mounted such that they deliver a vertical flat spray of water that spans the entire five desired inches of coverage on the shroud. Upon the insertion of the shroud into the cleaning station, the water is turned on and the entire station rotates 180° in one direction, then 180° back the other way until it reaches its original position. Since the arrays of nozzles will be positioned at opposite ends of the cleaning station, this 180° rotation (using a pneumatic actuator) will give complete coverage of the shroud. This design also features the same air ring as in Design 1, which again assists in containing the spray-out and drying the shroud.

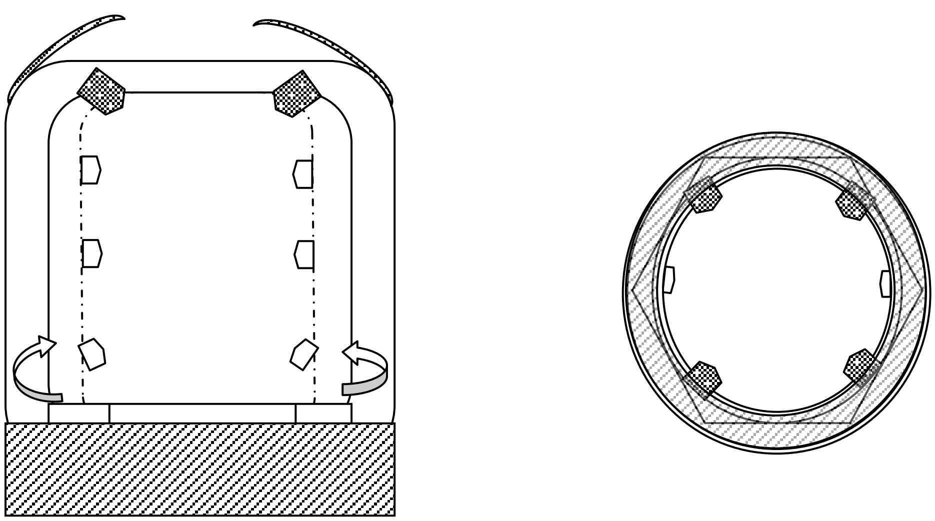
Figure 5: Design 2 Sketch



5.2.2.3 Design 3

Design 3 (Fig. 6) consists of the same arrangement and application of nozzles as in Design 2; however, the drying process in Design 3 is not completed using an air ring. In Design 3, the top of the cleaning station will house four air nozzles that will force air at the shroud in order to dry it. These air nozzles would have a much higher flow rate of air than in the air ring of previous designs; they would be comparable to the air jets that appear in most car washes. These air nozzles would most likely not be able to create the same Venturi effect as the air ring, so there would also be a need for some sort of additional shield just above the air nozzles for spray-out containment.

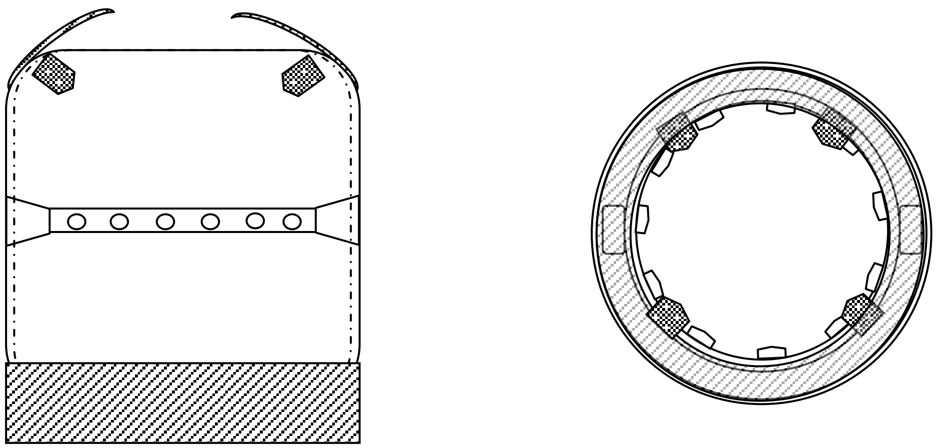
Figure 6: Design 3 Sketch



5.2.2.4 Design 4

Design 4 (Fig. 7, p. 14) consists of the same arrangement of nozzles as in Design 1 (the horizontal ring), except in this design there is no vertical motion of the nozzles. Instead, the shroud is slowly lowered through the nozzles by means of the robotic arm that it is attached to. Design 4 also uses the same arrangement of air nozzles for drying as in Design 3, as well as the same shield for spray-out containment.

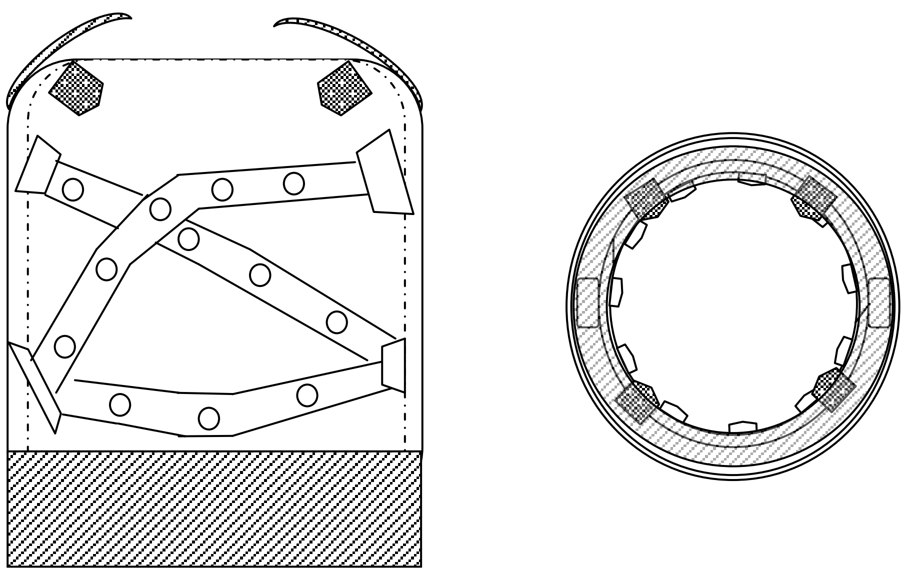
Figure 7: Design 4 Sketch



5.2.2.5 Design 5

Design 5 (Fig. 8) is almost identical to Design 4, except that instead of a horizontal ring of nozzles, it features two spiraling lines of nozzles through which the shroud is lowered during washing. Design 5 also features the same arrangement of air nozzles and containment shield as in Designs 3 and 4.

Figure 8: Design 5 Sketch



5.3 Design Comparison – Pugh Chart

After the final five design concepts were selected, they were inserted into a Pugh chart (Fig. 9, p.15). The Pugh chart helped in the comparison of the designs, as well as in the selection of the final design.

The Pugh chart lists the customer requirements and their weights, taken from the QFD (Fig.2, p.7), in the two leftmost columns, and the next five columns contain the five final design concepts. A plus (+) sign means that we expect the design to satisfy the corresponding customer requirement, while a minus (-) sign means that we don't expect the design to completely satisfy the corresponding customer requirement. A blank box means that we are not able to determine the information without actually testing the design.

All five concepts were designed to completely clean the shroud, use only water and air, and stay within the size limitations; therefore, all designs received equal ratings in those categories. Designs 1 and 2 (featuring the air ring) are believed to do a better job of drying the shroud than the remaining designs, which are worse in that category because the air nozzles are not believed to be sufficient for drying. Similarly, Designs 1 and 2 (which feature the air ring) are believed to do a better job of containing water spray-out than the remaining designs (which feature the containment shield). The two designs that would likely be the cheapest are Designs 4 and 5 because there is no movement of the nozzles, and the most expensive design would be Design 1 because of the complexity of its pneumatic vertical motion. Finally, Designs 2 and 3 would do the best job of cleaning the shaping air ring because of the angled nozzles near the bottom of the cleaning station that point upward at it. Designs 1, 4, and 5 all have nozzles pointed horizontally, which would likely not clean the shaping air ring sufficiently.

Figure 9: Pugh Chart

Customer Requirement	Weight	Design 1	Design 2	Design 3	Design 4	Design 5
Completely clean shroud	6	+	+	+	+	+
Completely dry shroud	2	+	+	-	-	-
Use only water and air	7	+	+	+	+	+
Complete in specified time	4					
Stay within size limitations	1	+	+	+	+	+
Contain water spray-out	2	+	+			
Minimize cost	1	- -	-	-	+	+
Clean shaping air ring	5	-	+	+	-	-
Sum of Positives	Σ+	23	23	19	15	15
Sum of Negatives	Σ-	-3	-1	-3	-2	-2
Total Sum	Σ	20	22	16	13	13

After the analysis of each design against each customer requirement was completed, the final scores were totaled on the Pugh chart and Design 2 was selected as the final design with which to proceed.

6 Selected Concept

After concept evaluation and discussion with our GM sponsor, our team has chosen Design 2 (Fig. 5, p.13) as the best possible option to satisfy all design criteria. This design features a rotating nozzle assembly. Six nozzles are rotated approximately 180 degrees and are to be arranged in two vertical arrays to effectively clean the specified shroud area. The design also includes a drying air ring and a water containment shell.

6.1 Cleaning Process

The cleaning process involves six nozzles that will rotate around the paint applicator shroud. Per the design constraints, these nozzles will spray only water at 600 psi. A pneumatic rotary actuator generates the 180-degree rotation of the cylindrical nozzle mount assembly.

6.1.1 Suggested Nozzles

Six stainless steel nozzle assemblies manufactured by Spraying Systems Co. (Fig. 10) were originally chosen for our prototype. These TP650050-SS nozzle tips include a spray angle of 65 degrees and deliver a flat fan-shaped spray pattern. These nozzles were chosen because they performed the best in high pressure tests which were conducted previous to our acquisition of this project. Also, the stainless steel with which the nozzles are manufactured from will minimize wear associated with this high-pressure application. Full-scale production applications might consider a nozzle with tungsten carbide inserts for additional wear resistance.

Figure 10: Spraying Systems Co. TP650050-SS spray nozzle assembly

6.1.2 *First Iteration of Nozzle Mount Assembly*

In order for 180 degrees of rotation to fully clean the shroud, the design will feature a cylindrical rotating assembly made out of PVC tubing (Fig. 11). PVC was chosen as the material due to its low cost, ease of machinability, and its toughness. The rotating assembly will hold two vertical arrays of three nozzles each located on opposite sides of the PVC cylinder. To optimize the cleaning process, the nozzles will be positioned so that they are normal to the surface of the shroud—the top 4 being flush with the side of the mount, while the bottom two are angled upward to clean the curved portion of the shroud. The upward angled nozzles also aid in cleaning the shaping air ring located at the bottom of the shroud. The positioning of the nozzles can be seen in Figure 12 below.

Figure 11: Nozzle Mount Setup

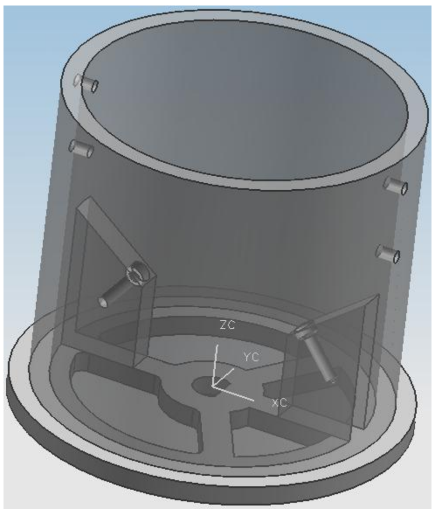
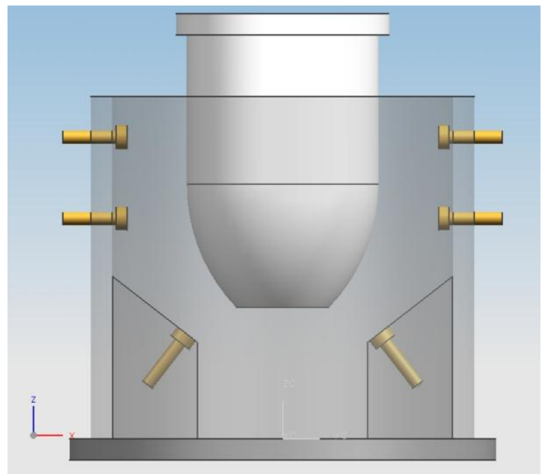


Figure 12: Complete Inner Setup



This entire setup is connected to a base that rotates on a pneumatic actuator that allows for the 180 degrees we need to fully clean the shroud. The base itself is made out of PVC, and it has holes machined into it to allow for water drain out.

6.1.3 *Pneumatic Actuator Used*

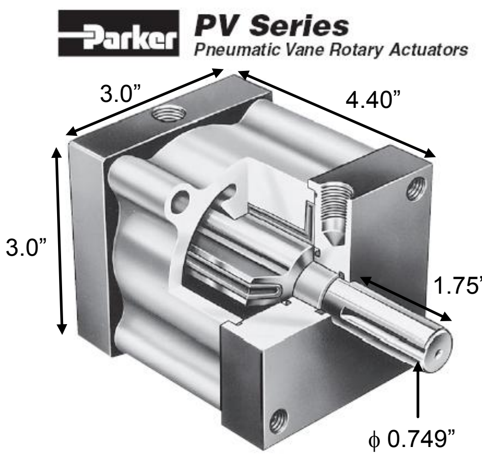
The initial design considerations to generate the rotation of the cleaning assembly involved (1) an electric motor and transmission system and (2) a pneumatic rotation system. Due to the aqueous environment the cleaning assembly would be exposed to as well as the level of complications that might arise with controlling an electric system, we eliminated this from our considerations. A pneumatic system offers simple controls and a high level of resistance to damage from water. With this decided the type of pneumatic system to use was then evaluated. The options were to use a rack and pinion type rotary actuator or a vane style one. Ultimately the vane style pneumatic rotary actuator was chosen as a result of the higher performance values for a given size.

Rotary actuators were considered from manufacturers SMC, Bimba, and Parker. Sizing the correct actuator meant calculating the torque output required to rotate the spraying assembly. This demand torque, T_D, for the actuator is given by:

$$T_D = T_\alpha + T_f + T_L \qquad \text{(Eq. 1)}$$

This is a summation of the torque required to overcome the inertia of the rotating assembly to provide acceleration, T_α, the torque required due to friction, T_f, and the torque required to overcome any shaft loads, T_L. Friction is minimal and no loads are being applied onto the shaft, so both the T_f and T_L terms were neglected. The acceleration torque is given as $T_\alpha = I\alpha$ where I is the mass moment of inertia for the rotating assembly and α is the angular acceleration required to rotate the cleaning assembly 180 degrees in 6 seconds. The torque requirement for the actuator is very low, less than 1 lb-in, and so physical size of the actuator became the primary consideration. The Parker PV33-180A-BB2-B (Figure 13) pneumatic vane style rotary actuator was selected.

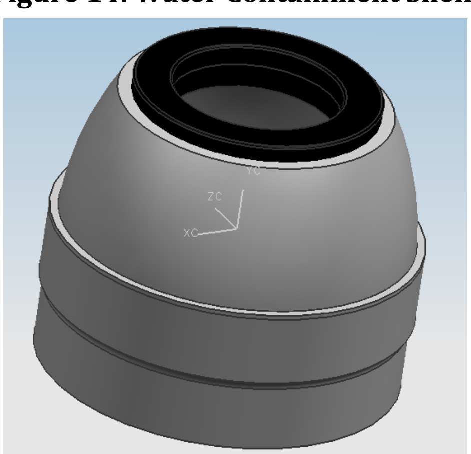
Figure 13: Parker PV33-180A-BB2-B dimensions [3]



6.2 Water Containment (Prototype)

The containment of the water is twofold (Fig. 14). First of all, a two-piece PVC water containment shell surrounds the entire cleaning setup. The nozzle mount is located and permanently mounted within the bottom piece, while the top piece is detachable for ease in maintenance. This shell should contain most of the spray rebounding off of the shroud at high velocity. Second, an air ring is located within the top piece of the water containment shell, and it will continually spray air at the shroud to contain any spray that may come toward the cleaner mouth. This air ring is discussed in detail below.

Figure 14: Water Containment Shell



6.3 DRYING PROCESS

The main feature in the drying process is a drying air ring located in the top piece of the water containment shell. It continually sprays air at a slight downward angle onto the shroud. During the cleaning process, this air aids in containing the water spray, and, after the cleaning process, it dries the shroud as it is extracted from the cleaner in a fashion similar to that of a hand dryer. Currently, an air ring produced by Durr has proven to work with their low pressure, solvent based cleaning station. Ideally, we would like to use this design as our model; however, given the complexity of this design as well as our time and manufacturing constraints, this would be impossible. Instead, we plan to line the inner rim of the water containment shell with a metal ring and drill holes into it on a downward angle. The exact size of these holes will be decided upon once we know more about what air volume flow rate and velocity will dry the shroud in the shortest amount of time.

6.4 POWER SOURCES

The main sources of power for our prototype are an electric air compressor and a gasoline power pressure washer. The air compressor is necessary to run the pneumatic actuator that will allow our design to rotate the required 180 degrees, as well as pump air into the drying air ring. The pressure washer will be necessary to meet the volume flow rate and pressure demands for the six spray nozzles.

6.5 ISSUES TO CONSIDER

Without having any nozzles or manufactured parts, we have not been able to test how quickly our design will clean and dry the shroud. Experimentation once we have the necessary parts will allow us to decide if further brainstorming is needed.

7 ENGINEERING ANALYSIS

After determining our final design concept of our cleaning station, our team has quantitatively and qualitatively analyzed the design, manufacturing, and assembly. Through this process we have been able to mathematically confirm the details of our design. We have also been able to simplify and optimize various components of the design, manufacturing, and assembly.

7.1 QUANTITATIVE ANALYSIS

This analysis includes an optimization of the pressure, flow rate, and nozzle placement. Also from this analysis we were able to determine the ability of the inner shell (nozzle mount) to support the nozzle spray's normal force impact.

7.1.1 PRESSURE ANALYSIS

We performed calculations to determine if there was a significant difference in pressure between each nozzle. We consulted *Fluid Mechanics 6th Edition* [4] by F.M. White for all necessary equations and fluid properties. Before we started, we made two key assumptions: 1) the water pressure inside the entire hose-to-pipe manifold is a constant 600 psi, 2) the water properties can be approximated at STP. We then calculated the water velocity (V) through the pipe based on the flow rate (Q) needed to produce 600 psi (Eq. 2). Using this velocity, we calculated the Reynolds Number (Re) (Eq. 3) and determined that the flow was laminar.

$$V = \frac{Q}{\pi R^2} \quad \text{[ft/s] (Eq. 2)} \qquad\qquad Re = \frac{V \cdot d}{v_f} \quad \text{(Eq. 3)}$$

Laminar flow meant that we could use the simple friction factor equation (Eq. 4) and subsequently solve for the headloss (h_f) (Eq. 5) and the change in pressure (Δp) (Eq. 6).

$$f = \frac{64}{Re} \quad \text{for Laminar Flow} \quad \text{(Eq.4)}$$

$$h_f = f \frac{L}{d} \frac{V^2}{2g} \quad \text{[ft]} \quad \text{(Eq.5)}$$

$$\Delta p = \left[(z_2 - z_1) + h_f\right]\rho g \quad \text{[psi]} \quad \text{where } (z_2 - z_1) = \text{nozzle height [ft]} \quad \text{(Eq.6)}$$

The change in water pressure from manifold to nozzle was significantly less than 1 psi, ranging from 0.1 psi for the bottom nozzle to 0.3 psi for the top nozzle. We concluded that this was not a significant difference when dealing with pressures of around 600 psi. Based on this conclusion, we were able to assume the same pressure for each nozzle when calculating the impact momentum.

7.1.2 Optimum Flow Rate Analysis

Upon selection of our 65 degree flat fan spray nozzle, we obtained the nozzle flow rate (Q) and pressure (P) specifications from the website of the Spraying Systems Co. Next, we found an equation for the theoretical spray impact (I) delivered out of a nozzle from a Spraying Systems Company article [5]. We will use this equation to calculate the force impact later on in our analysis.

$$I = K * Q \text{ [gpm]} * \sqrt{P} \text{ [psi]} \qquad \text{[pounds]} \qquad \text{(Eq. 7)}$$

For calculations, we also needed to find the velocity of the spray, which was obtained using equation 8, below, where V is the velocity and A is the cross-sectional area.

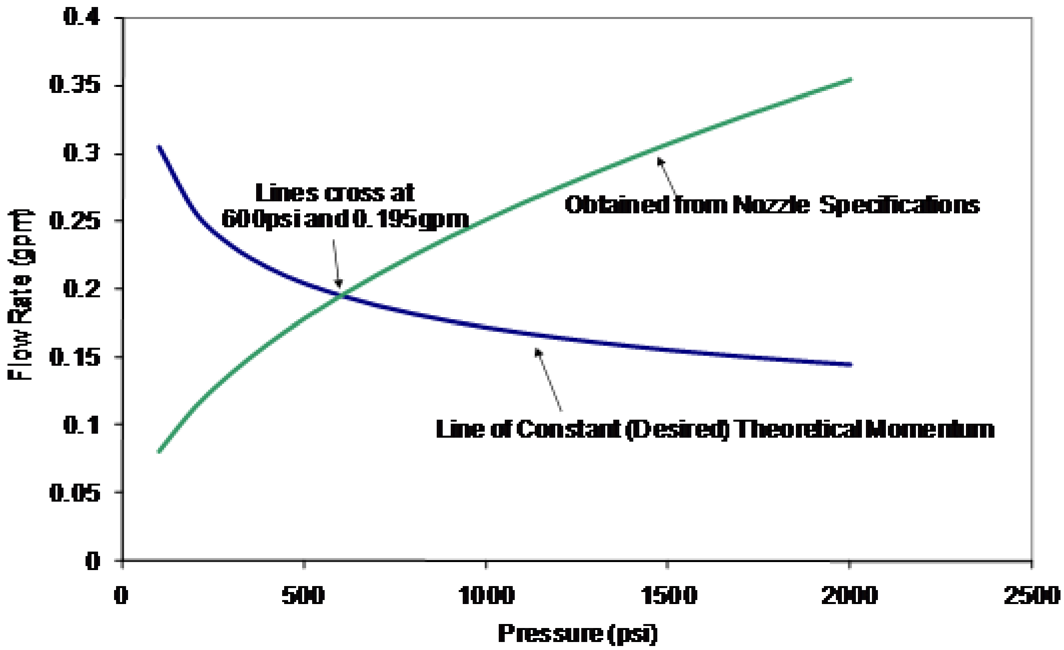
$$Q = V * A \qquad \text{[gpm]} \qquad \text{(Eq. 8)}$$

Next, using equation 7 (where *K is a constant 0.0526)* along with the velocity obtained in equation 8, we were able to determine the theoretical momentum that the spray delivered to the shroud (equation 9); setting that value of momentum constant, we backed out an equation relating pressure and flow rate.

$$\text{Theoretical Momentum} = I * V \qquad \text{[lb*in/min]} \qquad \text{(Eq. 9)}$$

Figure 15 (p. 21) is a plot of pressure versus flow rate of both equations: the one obtained from nozzle specifications and the one derived using our goal momentum. It is clear from these plots that the only pressure/flow rate combination that can produce the goal momentum from the selected nozzles is about 600psi and 0.194gpm. An initial goal for our design was to consume less than 0.5 gallons of water per cleaning cycle. Using these specifications, the cleaning station will only consume 0.117 gallons per cycle, which is well within our limit.

Figure 15: Flow rate vs. Pressure plot for both equations



7.1.3 *NORMAL FORCE IMPACT ANALYSIS*

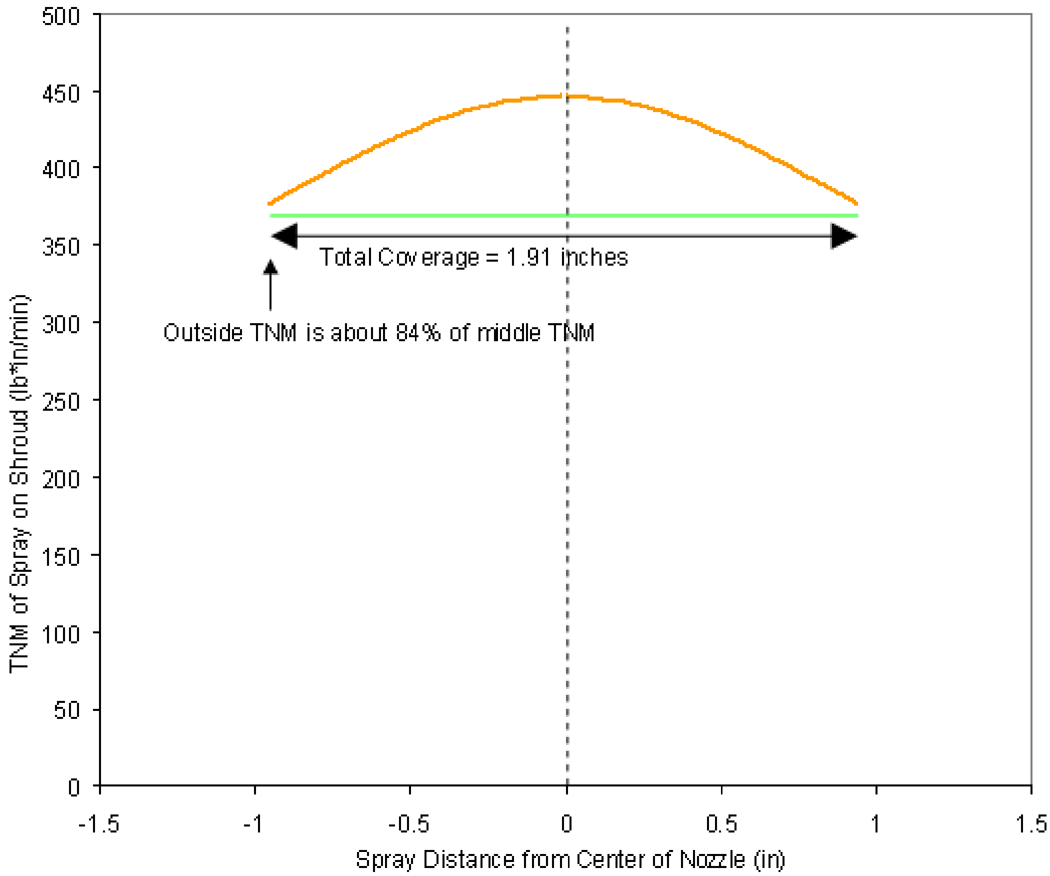
These six nozzles are going to be mounted on a cylindrical tube, and, in order to determine the optimal material for this cylinder, our team needed to determine the forces exerted by the nozzles. From Equation 7 (p. 20) above and using the optimal pressure and flow rate, our team was able to determine the normal impact force created from the water spray out of the nozzle onto the inner cylinder (nozzle mount). The calculated impact force was only 0.25161 lbs.

Wall thicknesses of 0.5 inches are standard for PVC tubing of the size we are considering and should prove to resist any crack propagation do to the forces applied by the high-pressure nozzles. However, we decided that a steel cylinder would ensure stability as a mount for the six nozzles and prove to be easier to obtain in the sizes we require.

7.1.4 *OPTIMUM NOZZLE PLACEMENT ANALYSIS*

The nozzle placement was determined with consideration to the 65° spray angle of the nozzles as well as the 5 vertical inches of desired shroud coverage. We also calculated the theoretical normal momentum of the spray on the shroud over the 1.9 inch range of coverage for a nozzle. This was done using Equation 7 (p. 20) along with three major assumptions: (1) the nozzle produces rectangular shaped flat spray, (2) there is an even drop distribution over the entire rectangular spray pattern, and (3) the energy losses for the spray between the nozzle tip and the shroud are negligible. From this, we determined that the theoretical normal momentum at the edge of the spray is approximately 84% of that in the middle; we consider this to be an acceptable value that will be sufficient in removing paint. A plot of the theoretical normal momentum of the spray on the shroud over the entire nozzle coverage is shown below in Figure 16 (p.22). It was determined that the nozzles will be placed 1.5 inches away from the shroud surface (see Fig. 12, p.17), making the inner diameter of the nozzle mount assembly 9 inches.

Figure 16: Theoretical normal momentum of spray on shroud vs. spray distance from center of nozzle



7.2 QUALITATIVE ANALYSIS

For this part of our analysis of the cleaning station, we used several charts to optimize the efficiency in manufacturing and assembly, reduce the impact the cleaning station has on the environment, and determine the areas of our design that are open to failure.

7.2.1 DESIGN FOR MANUFACTURING AND ASSEMBLY (DFMA)

Through this analysis, we were able to optimize the manufacturing functions involved in building our cleaning station as well as simplify the assembly. Listed below in Figure 17 (p. 23) are the design guidelines our team found to be important and apply most to our design. Then the direct applications of those guidelines on our design are explained. The cost for the production and assembly processes are lowered through these alterations; however, since only 300 units are expected to be manufactured with a maximum possibility of 1500, a mass production cost analysis is not applicable for such a small scale manufacturing possibility.

Figure 17: DFMA Chart

Guidelines	Implementation
Quality vs. Cost	Nozzles lower quality, less lifespan but still functions the same
	Base plate cheaper/easier machine as polyethylene instead metal
	Air ring machined with copper tubing cheaper and lower quality than CNC shaped but performs same function
Minimize Part Count	Keyway notch used to fasten plastic base plate and actuator eliminating additional fixtures
	Minimal fasteners used since parts machined to fit tight
Assemble In Open Spaces and Minimize Rotation	Components are attached inside to outside and bottom to top
Standardize/Reduce Part Variety	Only two different threaded fasteners for entire design
	Use standard cylinder sizes for the inner and outer cylinders to add ease in manufacturing
Symmetry	Symmetrical nozzle placement and drain slots in base plate
Features added to Facilitate Orientation	Added feature to align screw holes on steel cylinder and plastic base plate
	Added feature to align attachments for outer enclosure and fixture on the actuator
Easy Attachment Feature	Rounded edges on the plastic base plate for the steel cylinder to slide over, making attachment easier
Allow Access for Tools	Instead of using a set screw to attach the plastic base plate to the actuator, we used a keyway system so areas are accessible
Use Standardize Size tools	Used a standard 3/16'' keyway
Place Holes so does not Weaken Structure	All holes are placed on smooth surfaces on the cylinder, no corners and by no bends
Minimize Tool Changes	The base plate was machined with one 1 ½ '' end mill
	Two drills used for holes in metal cylinder

7.2.2 DESIGN FOR THE ENVIRONMENT (DfE)

In this qualitative analysis, the environmental impact of our design's lifecycle is optimized. Below is the DfE Chart (Fig. 18, p. 24) which lists the important guidelines that were taken into consideration for the lifecycle of the cleaning station from manufacturing to disposal. The intended effect on the environment for each step in the lifecycle is then explained, and, for each effect, the specific application onto the design is then listed. After this analysis, our design has become a more environmentally friendly machine and should save our sponsors money since they will be able to recycle many of the resources used.

Figure 18: DfE Chart

Lifecycle Guidelines	Intended Effect	Implementation
New Concept Development	Increase performance so less energy needs to be used	Simplifying and optimizing each feature of cleaning station
Physical Optimization	Combine functions of components to decrease parts	Air ring will both dry shroud and be used to keep splash off inside station
	Ease ability to inspect, repair and replace parts to avoid unnecessary part failure and excessive replacement costs and material use	Both the steel encasement and cylinder are attached with bolts for easy disassembly
Optimize Material Use	Use same material for different parts to limit suppliers and shipment of materials	Steel can be used for both the inner and outer cylinders in standardized sizes
Optimize Production Technique	Simplifying model to use less parts for assembly and machine less parts limiting energy usage	Use fewer nozzles then previous designs
		Bottom nozzle is being angled with common fixtures instead of a machined piece
		Only four pieces and a fixture need to be manufactured and the rest are standardized parts
Reduce Impact During Use	Limit the energy consumption and make waste recyclable	Only water and air at room temperature will be used for cleaning no chemicals so water can be recycled
		Using pneumatic actuator instead of electrical, less energy used
		High pressured water is used to clean shroud faster and use less water
Optimize End-of-Life Systems	Recycle parts	Recycle the steel, aluminum, and polyethylene materials

7.2.3 Failure Mode and Effect Analysis (FMEA)

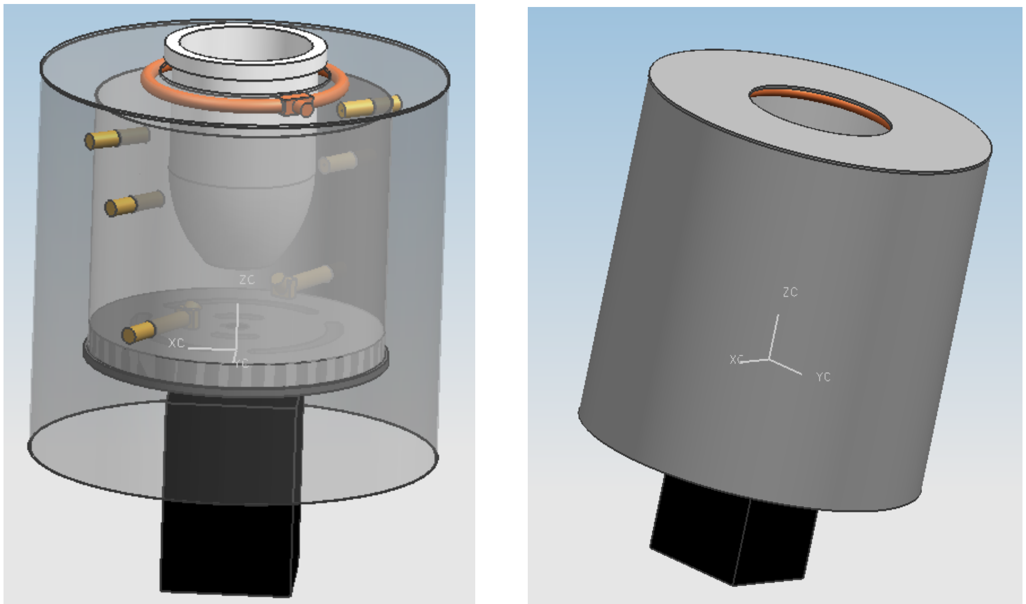
This is the final qualitative analysis method our team used, designed to determine where potential failures in our model could occur. It also helps determine what the effects of these failures would be to our model's overall performance. Finally, it will help us identify and create preventative actions to take in the design and manufacturing stage, during the commercial use of our model, and actions to be taken after these failures occur. This analysis is summarized in the charts in Appendix A (p.34). Each subsystem of the entire cleaning station is evaluated and broken down into each component. Each component is then analyzed and all possible failures, causes of failures, and the preventative measures to be taken are listed. The RPN number is used to help determine which failure needed to be prevented the most.

8 Final Design

As mentioned in the selected concept section, our design team has chosen a design that involves a rotational cleaning process. A cylindrical shell with two vertical arrays of three nozzles will rotate

180 degrees around the paint applicator shroud for cleaning, and an air ring situated within an outer containment shell will aid in water spray out control (Figure 19). This entire system will be positioned at standard locations within the assembly line floor.

Figure 19: Inner cleaning assembly and outer containment shell



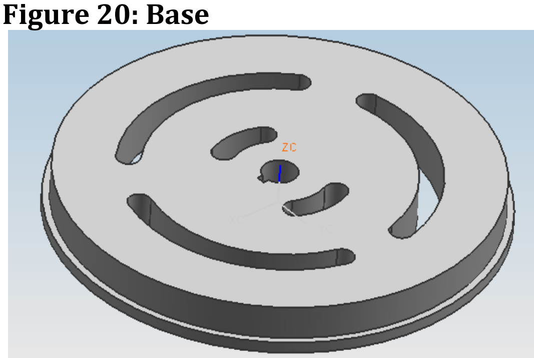
8.1 MACHINED COMPONENTS AND MATERIAL CHOICE

The following outlines each manufactured component, as well as their purpose and material choice. For complete dimensioned drawings and tolerances, see Appendix B (p. 38).

8.1.1 BASE

The base (Fig. 20) is a critical piece in the rotation process, designed to properly support the inner nozzle set-up and allow for water drainage. We have chosen an UHMD polyethylene for our prototype based upon cost and manufacturing constraints; however, we suggest the use of a more durable and sturdy material (like steel or aluminum) for long term use in the plant. Roughly, the base is 1 inch thick with a diameter of approximately 9 inches.

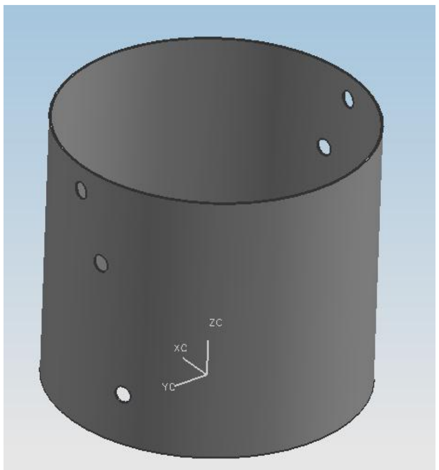
Figure 20: Base



8.1.2 *INNER SHELL (NOZZLE MOUNT)*

A cylindrical inner shell (Fig. 21) was decided upon as the best option for holding the vertical arrays of rotating nozzles. These vertical arrays were slightly offset so that separate water lines could run straight down to the base. The cylindrical shape was chosen to balance the reaction forces exerted on the shroud by the high velocity water spray. Also, 13 gage cold rolled steel was chosen as the proper material due to its high yield strength and ability to be easily shaped and rolled to size. The inner shell is approximately 9 inches in diameter and 8 inches tall.

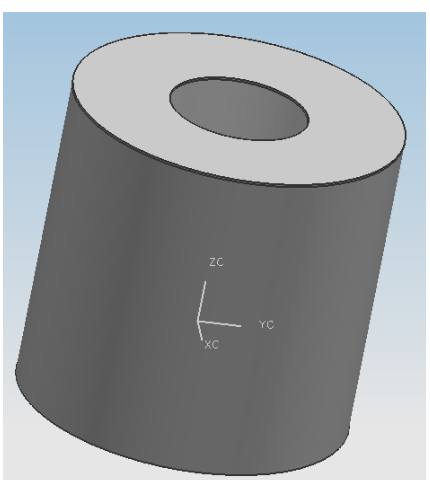
Figure 21: Inner Shell (Nozzle Mount)



8.1.3 *OUTER SHELL (CONTAINMENT SHROUD)*

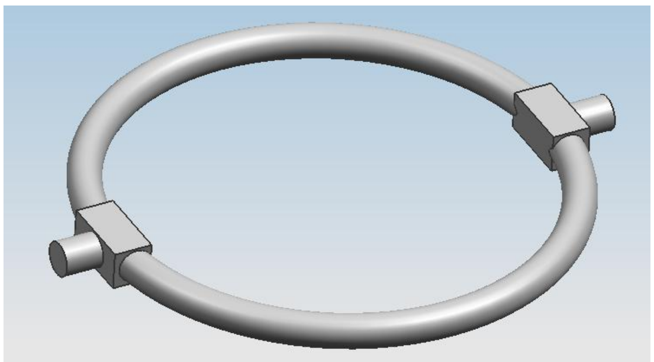
The cylindrical outer shell (Fig. 22) encloses the entire cleaning assembly and houses the drying air ring. The main function is to contain water spray-out, therefore protecting the freshly painted vehicles. It also provides a protective cover for the nozzle mount components. Like the inner shell, it is rolled from 13 gage cold rolled steel. The outer shell has an approximate diameter of 12.5 inches and is 1 foot in height.

Figure 22: Outer Shell (Containment Shroud)



8.1.4 AIR RING
The air ring (Fig. 23) is a circular tube of ½" diameter 6061-T6 aluminum pipe located within the top of the outer containment shell. A circular array of small holes is located on the inside of the ring, angled slightly downward to direct air flow onto the paint applicator shroud. The continuous air flow dries the shroud and aids in the containment of the water spray out of the top of the containment shell. Aluminum is the proper material for this application because it is easily machined and can be welded.

Figure 23: Air Ring



8.2 PURCHASED COMPONENTS AND MATERIAL CHOICE
The following outlines each purchased component, as well as their purpose and material choice.

8.2.1 ROTARY ACTUATOR
As mentioned in the selected concept section, a Parker pneumatic vane-type rotary actuator (Fig.13, p. 18) was chosen to provide the necessary 180 degrees of rotation. Out team purchased this particular part off of eBay, therefore saving close to 500 dollars. It provides a high torque output for the slow and steady rotation, and has a compact size (4in x 4in x 6in) that easily fits into our design.

8.2.2 NOZZLES
Six 303 stainless steel water nozzles (Fig. 24) were purchased from BETE Fog Nozzle Inc. for the high pressure cleaning of the paint applicator shroud. They were able to produce the necessary 65 degree spray angle that we designed for. Due to cost constraints, the carbide tip, multi-part-assembly nozzles spoken about in the selected concept section were not used. The stainless steel replacements were evaluated to be very similar in spray performance; however, long term wear may be a problem. The solution to this problem will be discussed later in the section on future improvements (p.32).

Figure 24: 303 Stainless Steel Water Nozzle

8.2.3 MISCELLANEOUS PARTS

The rest of the small fastener and facilitator parts (Fig. 25) were ordered from McMaster-Carr. The two manifolds split the single water line from the water source into three separate lines to the spray nozzles. The high pressure hydraulic hoses and steel piping facilitate the high pressures we need to put the cleaning water under. Also, multiple fittings, bolts, screws, pipe elbows, etc. help hold the entire assembly together.

Figure25: Miscellaneous Parts

NOTE: The bill of materials for the final design appears in the Appendix C (p.42).

9 MANUFACTURING

9.1 MANUFACTURED COMPONENTS

Manufactured components will include the rotating shroud base, containment shroud base, both shrouds, and the drying air ring. Due to material and equipment constraints, the inner rotating shroud will be rolled from 13-gage cold-rolled steel sheet metal by an outside contact (personal friend). The seam will be tig-welded to form a complete cylinder. The rotating shroud will have six 9/16" holes drilled to accept the nozzle assemblies and four ¼" holes to attach the water manifolds.

The circular rotating shroud base will be machined from ultra high molecular density (UHMD) polyethylene material on a manual mill equipped with a rotating table fixture. Five ½" slots will be milled into the base to allow water to drain freely from the system. A central ¾" hole will be drilled with a 3/16" keyway slot to accept the rotating actuator shaft. Four 10-24 by 1/2" machine screws will be used to attach the base to the rotating shroud.

The outer containment shroud will be manufactured from the same material and using the same process as the rotating shroud. A top cover will be cut from the same 13-gage material and tig-welded into place. Four holes will be drilled to accept ¼" machine screws to attach the containment shroud to the shroud base.

9.2 Purchased Components

Purchased components include the rotary actuator, UHMD polyethylene material, nozzles, manifolds, various high-pressure hoses and fittings, all listed in the project bill of materials, Appendix C (p.44). Most of the components are held in stock at the suppliers so that a 1-week advance ordering time is sufficient. The exception to this is the rotary actuator, which could have a lead-time of up to several weeks, depending on the distributor consulted.

9.3 Mass Production

In a mass production scenario, several features of the device could be changed to ease manufacturing and reduce cost. First of all, rather than rolling from sheet metal and rolling the shrouds, cutting these cylinders from aluminum pipe of the similar dimensions should be considered. The base plates should be manufactured from a stiffer material than the UHMD polyethylene used for the prototype. Aluminum plate could be a good option. This will provide a more secure attachment to the keyed shaft of the rotary actuator. Also, a sealed thrust bearing should be placed between the actuator surface and rotating base plate to relieve any friction between the two surfaces. The drying air ring should be CNC machined to provide a more accurate hole pattern, resulting in a more consistent flow distribution over the atomizer surface. Several fittings and hoses may be eliminated by instead using threaded pipes that are cut to the appropriate lengths. Last, tougher nozzles that feature carbide inserts should be considered because they will not wear out as quickly as the 303 stainless steel nozzles used for the prototype.

10 Testing

In this section, we will be describing our initial procedure for testing the cleaning station and then the actual testing process and observations. From the tests we were able to establish some conclusions about the abilities of the cleaning station.

10.1 Testing Procedure

Testing should begin by setting up the cleaning station with valves and regulators to control the pressures and flow rates of both the water and air that are supplied to the nozzles, drying air ring, and pneumatic rotation systems. A steady 180-degree rotation of 6-seconds for the actuator should be adjusted. The atomizer should be coated with paint by simulating a production painting cycle. The atomizer should be lowered into the cleaner and the air supply to the drying air ring should be turned on. Pressurized water starting at 100 psi and increasing in 50 psi increments to 600 psi should then be used to simulate a cleaning cycle. If the theoretical 600 psi does not clean the surface entirely, water pressures should be increased to a maximum to 1000 psi until a successful cleaning cycle is obtained. Airflow rates through the air ring should be adjusted until no residual water remains on the surface after the atomizer is extracted from the cleaning station. A 100% clean and 100% dry surface indicates satisfactory performance that meets the requirements for production application.

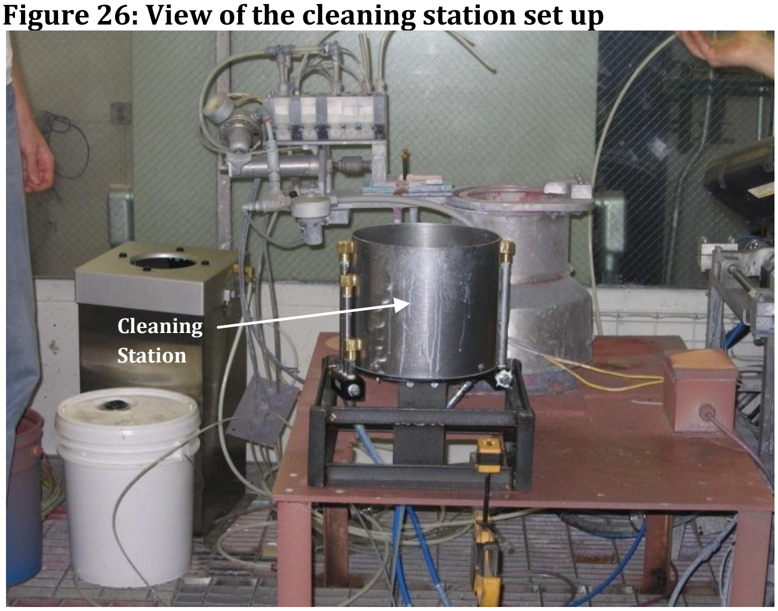
10.2 First Test – Low Pressure Water

The first testing was done at a team member's house. The cleaning station's nozzles were connected to a hose sending a low pressure water flow through the system. This test was to make sure the nozzle system was in good working order and to determine if there were any major changes needed before high pressure testing began. We discovered that some tube connections needed to be resealed because the tape we used allowed some water leaks. We also found that some of the nozzles had been clogged from debris during the construction of our cleaning machine. However, after cleaning out the nozzles we found that the spray coverage appeared to be adequate. We also determined that the outer shell enclosed the water spray very well, and the draining slots in the base plate drained the water sufficiently. From this initial test, we concluded that the cleaning station was ready to be tested with high pressure water after resealing the pipe connections.

10.3 Second Test – Cleaning Station Set-Up

For the second round of testing, we went to the Sames North America facility in Livonia, MI. Here we were able to connect our nozzles to a computer operated high pressure water supply and air compressor to rotate the actuator. Setting up the connections from the supply to the cleaning station and determining the best way to connect the actuator took the better portion of the day (Fig. 26).

Figure 26: View of the cleaning station set up



It was determined that the water could be connected directly to the supply outlets without extra regulating valves. However, the pneumatic actuator needed additional regulating valves in order to get the slowest rotation possible (which was achieved at an air pressure of about 10psi). It was also determined that in order to connect our prototype properly and put on the outer shell, a different base would have to be constructed to allow room for the hoses. The outer shell also needed to be slightly bigger in diameter by 2''- 4''. Still, we were able to run high pressured water through the nozzle system and the new seals handled the pressure and water flow successfully.

10.4 THIRD TEST – HIGH PRESSURE PAINT REMOVAL

For our last test, we were able to finally test whether or not our cleaning station will remove paint. We returned to the Sames North America facility and set up the cleaning station just like we had done in the previous test. Next, we obtained a bucket of red paint which is identical to the paint that is used on General Motors vehicles and fed a paint line into the robot which paints the vehicles. With the assistance of a Sames employee, we directed the rotary paint atomizer to spray paint directly into a five gallon bucket so that there would be paint bouncing off the bucket and sticking back onto the atomizer shroud, just like it would in a real painting. After deeming the shroud sufficiently dirty, we let the paint dry for several minutes so that we would be attempting to clean a shroud that was dirtier than it would normally be after a paint cycle. Finally, the robot arm directed the atomizer shroud into our cleaning station, and high pressure water attempted to clean while the station rotated. Due to time constraints, we were only able to run this test with two water pressures, the first of which was 480psi; the results of this test are shown below in Figures 27 and 28.

FIGURE 27: CLEANING TEST AT 480PSI (ONE SIDE)

FIGURE 28: CLEANING TEST AT 480PSI (OTHER SIDE)

The 480psi test did not clean the shroud enough, because there was still a large section of paint remaining at the top. Therefore, we increased the pressure of the water for our next test to 720psi, and followed the same procedure as above; the results of this test are shown in Figures 29 and 30.

FIGURE 29: CLEANING TEST AT 720PSI (ONE SIDE)

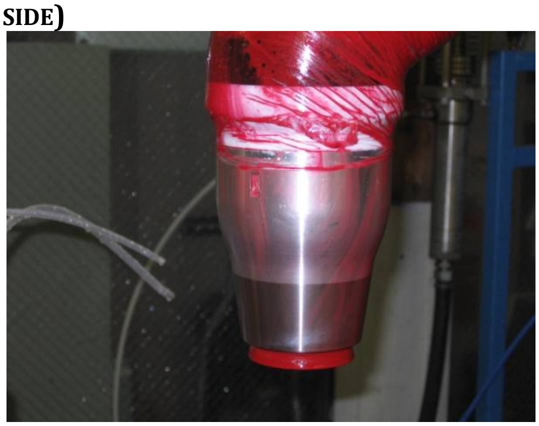
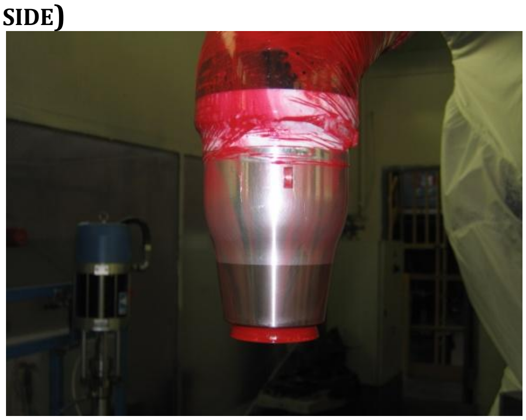


FIGURE 30: CLEANING TEST AT 720PSI (OTHER SIDE)



In this test, the entire shroud was completely cleaned. It should be noted that the paint that appears on the shroud in these pictures is due to the runoff from the paint above the shroud, which occurred because we did not use the containment shell or drying air ring in this test; this run off will not be an issue when the shell and air ring are used, so we concluded that this test was a success.

10.5 Future Testing

Based on the potential that this design has, as well as the success of our testing, General Motors has assured us that development of this project will be continued in the future.

11 Future Improvements

We were very satisfied with the performance of the prototype; there were no major problems or design flaws that we encountered during testing. One of the major strengths of the design is that it is very simple, which makes it easy to adjust or improve.

We did come across a few minor weaknesses to be improved upon. The first is that due to budget restraints, we were not able to include the nozzles that we originally wanted in our prototype. The nozzles used on the prototype are not designed to withstand the constant corrosion associated with high pressure applications. These nozzles were sufficient for our initial tests, but if long-term testing is to be done, we suggest that more expensive carbide nozzles that can endure high pressures are used.

Another minor issue we discovered was that the rotary actuator we purchased is not able to rotate as slow as we planned. We designed for each cleaning cycle to feature two slow 180 degree rotations, one in each direction; unfortunately, the slowest that the actuator can rotate is still much faster than we had hoped for. We suggest that a new rotary actuator be inserted into the cleaning station, one which rotates at slower speeds.

The next minor problem was that the UHMD polyethylene base that was used for our prototype will not be tough enough for its application. The base is connected to the actuator shaft using a metal press-fit key; during testing it became apparent that when the actuator spins, the key will wear away at the polyethylene base. We suggest that in the future, the base should be made of a tougher material, such as steel.

Another possible future problem to address is the seals between the various fittings and tubing. For our testing, we used pipe thread sealer to seal the connections, which worked fine; however, for long-term use of this design, we suggest that further steps should be taken in order to ensure that there are no leaks.

Finally, we suggest that more testing be done on the containment shell (including the air ring), because we were unable to conduct any high pressure testing on it. We do expect that some adjusting will need to be done, but General Motors already has a satisfactory air ring concept, so we are confident that they can have the containment shield up and running with minimal effort.

12 CONCLUSION

The main goal for our team is to produce a working prototype of a cleaning station for a rotary atomizer shroud that will be used during the painting process of General Motors' vehicles. In order for GM to reduce production costs and become a more environmentally friendly company, the prototype must use only water and air to completely clean and dry the atomizer shroud in 10 seconds or less. The benchmarking research for this project was started by a summer intern at GM who conducted optimization testing for the use of high-pressure water in the cleaning process. We spoke to our contacts at GM in order to gather a list of customer requirements that we needed to incorporate into our design; the requirements were then correlated with quantitative engineering specifications by means of a QFD diagram. From there we used the FAST Chart to breakdown the functions of the cleaning station and picked the three most important functions to design concept ideas for the Morphological Chart. We created five main design concepts, and using the Pugh Chart, selected our final design. This final design involved two vertical arrays of three nozzles mounted to a cylindrical base. This entire base would rotate 180 degree to clean the entire shroud, and a drying air ring would dry the shroud as well as aid in containing water spray-out. Manufacturing of the cleaning station concept was completed for the Design Expo held in Lansing, MI on December 4th, 2007. Initial testing of the system took place at Sames North America in Livonia, MI on December 6th, 2007 and was completed December 11th, 2007. An input water pressure of 720 psi was required to completely clean the surface of the rotary atomizer. Cleaning action was excellent and cycle time requirements were met. Additional testing of the concept will be performed by General Motors to further validate the concept. GM then plans to further develop our concept, come up with a manufacturing plan, and begin placing these cleaning stations in their automotive assembly plants around the world.

13 ACKNOWLEDGEMENTS

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Professor Bogdan Epureanu
Sames North Amercia Inc.

14 REFERENCES

[1] Intellectual Property Organization, 1997, "Method and apparatus for cleaning spray guns", http://www.wipo.int/pctdb/en/wo.jsp?wo=1997018903, accessed 25 Aug 2007.

[2] Crystal Cap Cleaners, http://www.crystalcap.com, accessed 25 Aug 2007.

[3] Parker, PV Series Pneumatic Actuators Catalog, www.parker.com, accessed 25 Oct 2007.

[4] White, F.M., 2007, *Fluid Mechanics 6th Edition*, McGraw-Hill, New York, pp. 341-367.

[5] Schick, Rudolf J., 2006, "Spray Technology Reference Guide: Understanding Drop Size," Spraying Systems Co, www.sprayconsultants.com, accessed 10 October 2007.

Appendix A FMEA Charts

Figure A.1 Nozzle Rotation

Product Name:	Cleaning Station	Development Team		Page No.	1	of 4
System:	Remove paint	Michael Byrne	Hugh Churchill	FMEA No	1	
Subsystem Name:	Rotate Nozzles	Lynn Ciarelli	Nicholas Lynn	Date	11/18/2007	

Component Part # Functions	Potential Failure Mode	Potential Effects of Failure	Severity(S)	Potential Causes/ Mechanisms of Failure	Occurrence (O)	Current Design Controls/Tests	Detection (D)	Recommended Actions	RPN	New (S)	New (O)	New (D)	New RPN
Parker Pneumatic Vane Rotary Actuator PV33-180A-BB2-B Rotates base plate and steel cylinder, therfore rotating the nozzles attached to the cylinder 180 degrees in 6 secs (30 deg/sec) Allows the nozzle rotaion necessary to fully clean shroud	Rotational Failure	Actuator rotation decreases and does not rotate specified 180 degrees or fast enough and cleaning quality decreases	8	1)Water leakage into actuator 2)Insufficient pressure supplied to operate actuator, loose fittings	1	Repeatedly flush the system with water to detect areas of leakage and lifespan	7	1)Design a container to enclose the actuator to keep water off 2)Run tests to see how the actuator and fittings lasts under the pressure demands	56	1	1	1	1
13-Gage Cold Rolled Steel Inner Shell (Nozzle Mount) Supports the 6 nozzles and their hose connections Connects them to the plastic base plate and allows them to rotate uniformly	Deformation of cylinder shape or holes cut for the nozzles and screw holes	Bending at holes would loosen fittings to the nozzles which may lead to detachment and inability to spray the shroud effectively	3	Too much force applied to edges of holes for nozzles	3	1)Force analysis on the water sprayed out of the nozzle onto the cylinder 2)Repeated use and record effects over time	3	1)If the analysis and tests prove shell will not be able to stand up to force load, may need to thicken shell or consider a different material	27	2	1	2	4
		Bent into an oval shape possiblly changing the spray distance and effectiveness of the nozzle spray	3	Inner shell not strong enough to handle spray force of all 6 nozzles	3		3	2) A washer can be added to spread the force over larger area	27	2	1	2	4
UHMD Polyethlene Plastic base plate supports steel cylinder and attaches it to the pneumatic actuator Allows the water to drain out of the cleaning machine through slots	Deformation and wear at the keyway attachment connecting rotary actuator and the base plate	Wearing at cut notch attachment would expand the notch, loosening it so the wedge does not fit as tight and the rotary actuator could not rotate the nozzles with as much precision	7	Too much force applied to the notch cut, not big enough to sustain forces	8	Repeated rotations to assess effects of weight on the plastic	7	1)More screws may need to be added to attach cylinder to base and decrease force on the notch attachment. 2)Using a different way to attach plastic base to actuator shaft would have to be explored to prevent the plastic from cracking.	392	3	2	1	6
	Stripping of screw holes attaching steel cylinder	Stripping holes would cause the steel cylinder fit to loosen and put more stress on the notch attachment, increasing likelihood of failure	3	Not enough srews used to secure steel cylinder to base plate	2		2	More screws may need to be added to increase support or a different material that will be less likely to strip.	12	1	1	1	1
	Clogging of drain slots	Clogging of the drain slots with paint residue may cause shroud to become contaminated from previous cleanings	8	Draining slots are not large enough for the paint and water to drain through	2	Simulate the paint removal process to see how the paint comes off and if blockage is a concern	1	The drain slots also may need to be enlarged but then the stability of the base will need to be reassessed.	16	3	1	1	3

Figure A.2 Nozzle System

Product Name:	Cleaning Station	Development Team		Page No.	1	of	4
System:	Remove paint	Michael Byrne	Hugh Churchill	FMEA No	1		
Subsystem Name:	Rotate Nozzles	Lynn Ciarelli	Nicholas Lynn	Date	11/18/2007		

Component Part # Functions	Potential Failure Mode	Potential Effects of Failure	Severity(S)	Potential Causes/ Mechanisms of Failure	Occurrence (O)	Current Design Controls/Tests	Detection (D)	Recommended Actions	RPN	New (S)	New (O)	New (D)	New RPN
Parker Pneumatic Vane Rotary Actuator PV33-180A-BB2-B Rotates base plate and steel cylinder, therfore rotating the nozzles attached to the cylinder 180 degrees in 6 secs (30 deg/sec) Allows the nozzle rotaion necessary to fully clean shroud	Rotational Failure	Actuator rotation decreases and does not rotate specified 180 degrees or fast enough and cleaning quality decreases	8	1)Water leakage into actuator 2)Insufficient pressure supplied to operate actuator, loose fittings	1	Repeatedly flush the system with water to detect areas of leakage and lifespan	7	1)Design a container to enclose the actuator to keep water off 2)Run tests to see how the actuator and fittings lasts under the pressure demands	56	1	1	1	1
13-Gage Cold Rolled Steel Inner Shell (Nozzle Mount) Supports the 6 nozzles and their hose connections Connects them to the plastic base plate and allows them to rotate uniformly	Deformation of cylinder shape or holes cut for the nozzles and screw holes	Bending at holes would loosen fittings to the nozzles which may lead to detachment and inability to spray the shroud effectively	3	Too much force applied to edges of holes for nozzles	3	1)Force analysis on the water sprayed out of the nozzle onto the cylinder 2)Repeated use and record effects over time	3	1)If the analysis and tests prove shell will not be able to stand up to force load, may need to thicken shell or consider a different material	27	2	1	2	4
		Bent into an oval shape possiblly changing the spray distance and effectiveness of the nozzle spray	3	Inner shell not strong enough to handle spray force of all 6 nozzles	3		3	2) A washer can be added to spread the force over larger area	27	2	1	2	4
UHMD Polyethlene Plastic base plate supports steel cylinder and attaches it to the pneumatic actuator Allows the water to drain out of the cleaning machine through slots	Deformation and wear at the keyway attachment connecting rotary actuator and the base plate	Wearing at cut notch attachment would expand the notch, loosening it so the wedge does not fit as tight and the rotary actuator could not rotate the nozzles with as much precision	7	Too much force applied to the notch cut, not big enough to sustain forces	8	Repeated rotations to assess effects of weight on the plastic	7	1)More screws may need to be added to attach cylinder to base and decrease force on the notch attachment. 2)Using a different way to attach plastic base to actuator shaft would have to be explored to prevent the plastic from cracking.	392	3	2	1	6
	Stripping of screw holes attaching steel cylinder	Stripping holes would cause the steel cylinder fit to loosen and put more stress on the notch attachment, increasing likelihood of failure	3	Not enough srews used to secure steel cylinder to base plate	2		2	More screws may need to be added to increase support or a different material that will be less likely to strip.	12	1	1	1	1
	Clogging of drain slots	Clogging of the drain slots with paint residue may cause shroud to become contaminated from previous cleanings	8	Draining slots are not large enough for the paint and water to drain through	2	Simulate the paint removal process to see how the paint comes off and if blockage is a concern	1	The drain slots also may need to be enlarged but then the stability of the base will need to be reassessed.	16	3	1	1	3

Figure A.3 Water Containment

Product Name:	Cleaning Station	Development Team		Page No.	3	of	4						
System:	Remove Paint	Michael Byrne	Hugh Churchill	FMEA No	3								
Subsystem Name:	Water Containment	Lynn Ciarelli	Nicholas Lynn	Date	11/18/2007								
Component Part # Functions	Potential Failure Mode	Potential Effects of Failure	Severity(S)	Potential Causes/ Mechanisms of Failure	Occurrence (O)	Current Design Controls/Tests	Detection (D)	Recommended Actions	RPN	New (S)	New (O)	New (D)	New RPN
13-Gage Cold Rolled Steel Outer Shell (Containment Shroud) Keeps water spray inside the cleaning machine and off the cars	Bending at connection of air ring and at connection to actuator	Change placement and size of shroud hole which may lead to the robotic arm bumping into the sides more	6	1)Attachments of the air ring cannot properly hold the force exerted by the air ring 2)Weight on the shroud enclosure too much to hold	1	1)Test the air ring attachment and see if creates any great change in the hole 2)Set up the attachment to the actuator and see if any part seems strained	6	1)Change the air ring and actuator attachments 2)Possibly pick a different material for the shroud enclosure	36	1	1	1	1
Steel Base Plate Connects the shroud enclosure to the actuator	Bending at connection to shroud encolsure	Make connection to the shroud not as sturdy and endanger the stability of the machine	2	Weight of the outer shell (containment shroud) on the connections from the shroud enclosure or actuator too great	1	Set up the connection to the actuator and see if any part seems strained	3	Change the way the shroud is attached to the actuator	6	1	1	1	1

Figure A.4 Air Ring

Product Name:	Cleaning Station	Development Team		Page No.	4	of	4						
System:	Dry Shroud	Michael Byrne	Hugh Churchill	FMEA No	4								
Subsystem Name:	Air ring	Lynn Ciarelli	Nicholas Lynn	Date	11/18/2007								
Component Part # Functions	Potential Failure Mode	Potential Effects of Failure	Severity(S)	Potential Causes/ Mechanisms of Failure	Occurrence (O)	Current Design Controls/Tests	Detection (D)	Recommended Actions	RPN	New (S)	New (O)	New (D)	New RPN
Air Ring Dries shroud on its way out of the cleaning machine and keeps water spray-out inside enclosure	Clogged	Water spray-out is no longer contained	5	Water spray-out too close to air ring	2	Mockup the water spray-out from the shroud onto the air ring to see what is too close	3	Make the outer enclosure taller so the air ring is not so close to the spray-out	30	2	1	1	2
Attachments Hold air ring to the shroud enclosure and to the tubes supplying air	Loosening at attachments to shroud enclosure and to air supply tubes	1)Drop in pressure of the air being sprayed, not drying shroud as effectively 2)Misdirected air spray, decreasing quality of drying the shroud	2	1)Improperly attached to supply tubes and connection may not be able to withstand pressure 2)Attachments cannot hold forces inflicted by air ring	2	1)Send the max air pressure through the connection and see if there is leakage 2)Set to max pressure it would be run at and see if forces could possibly loosen attachments	4	1)Look up details of a connector that can withstand the pressures used in the air ring and, if not, change material 2)Design a different way to attach air ring	16	1	1	1	1

Appendix B CAD Drawings

*all dimensions in inches

Figure B.1 CAD drawing of base

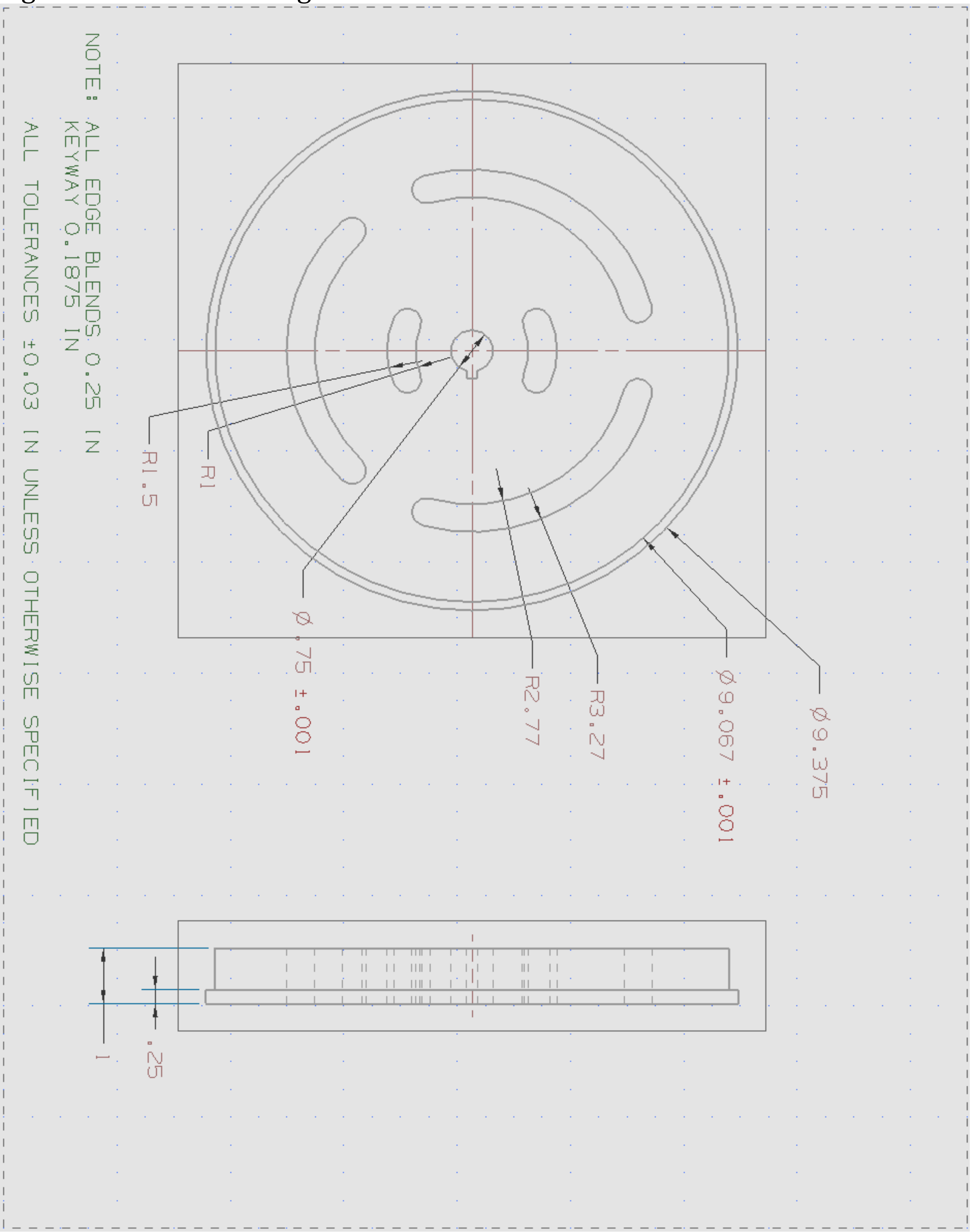


Figure B.2 CAD drawing of inner shell (nozzle mount)

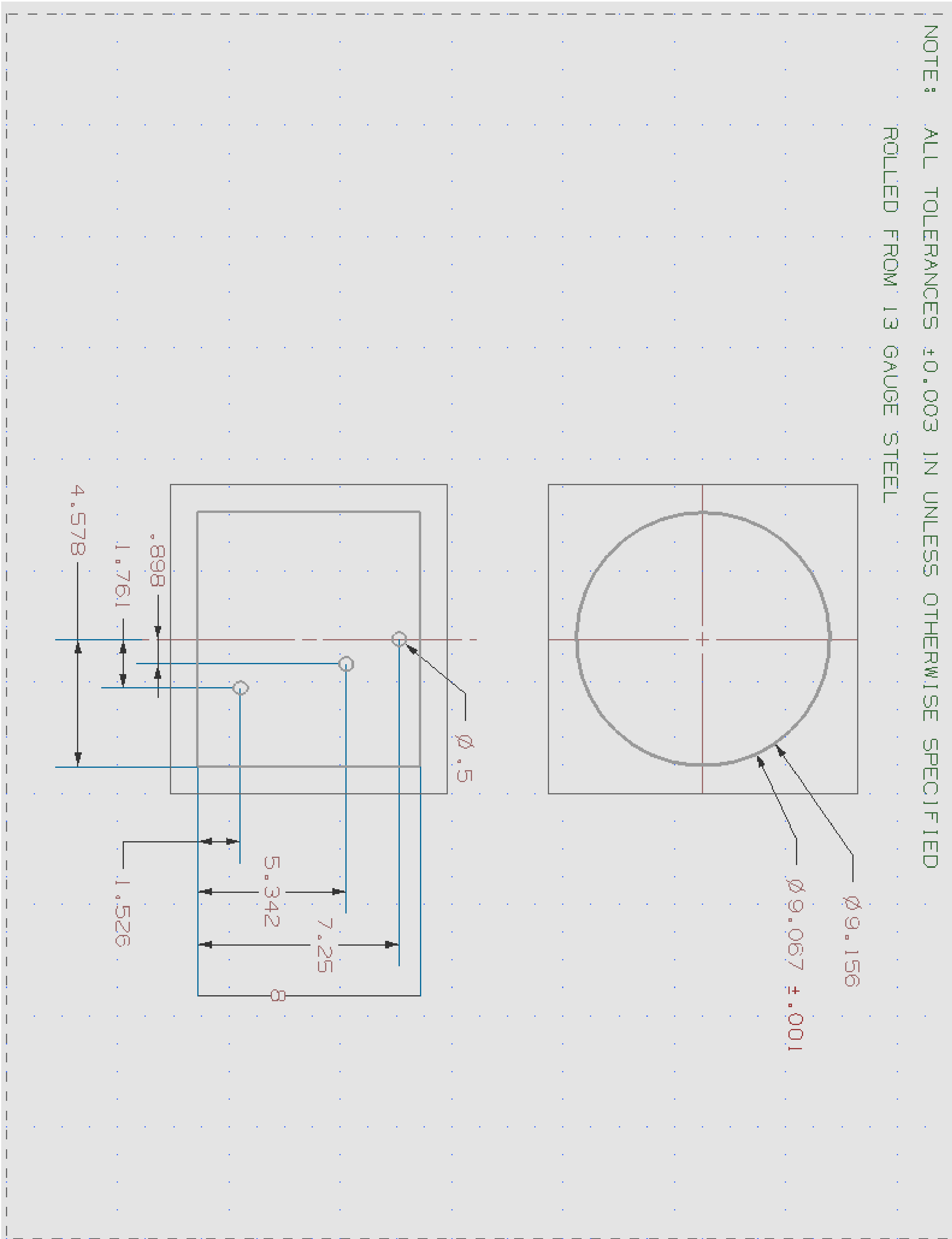


Figure B.3   CAD drawing of outer shell (containment shroud)

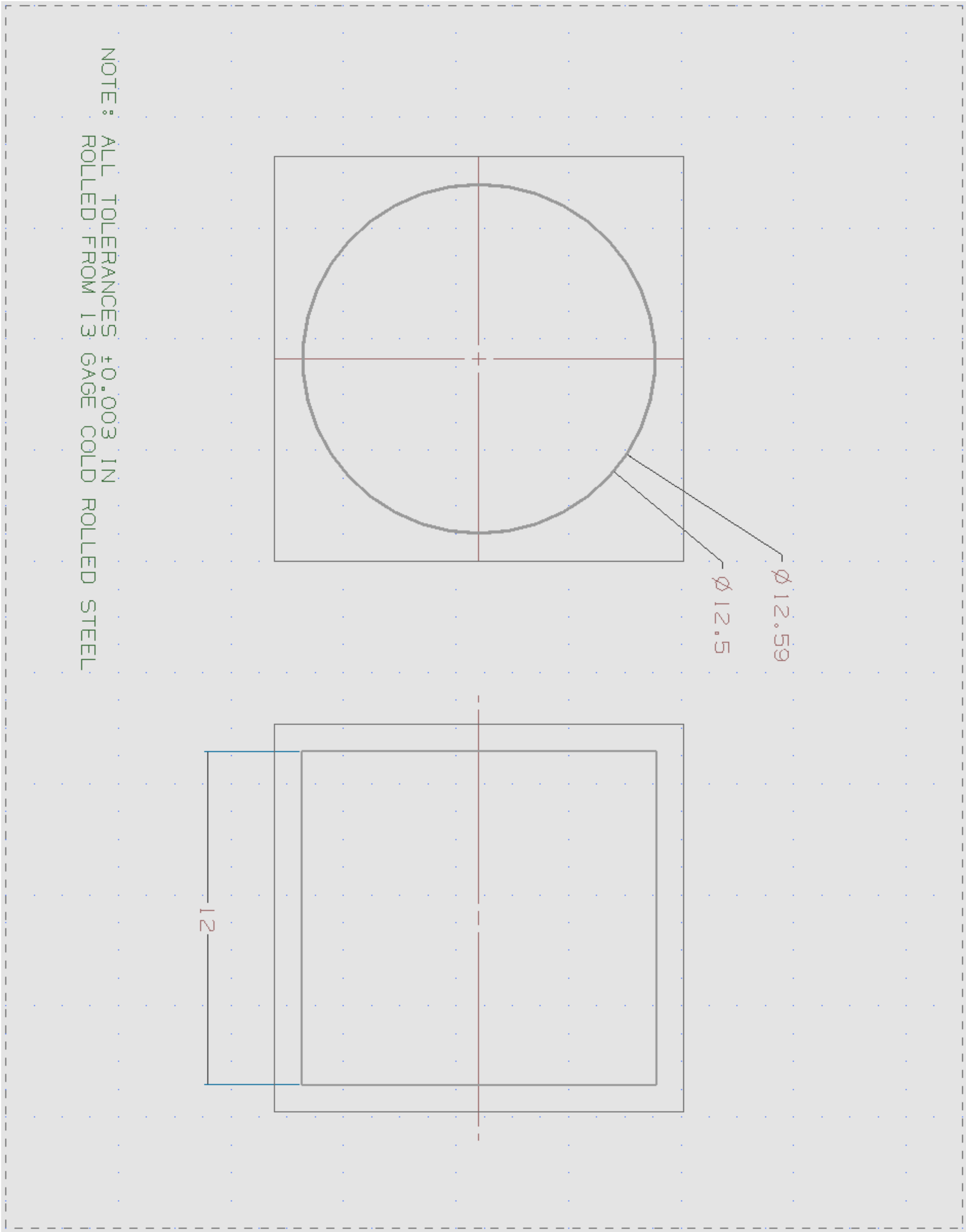


Figure B.4 CAD drawing of top of outer shell

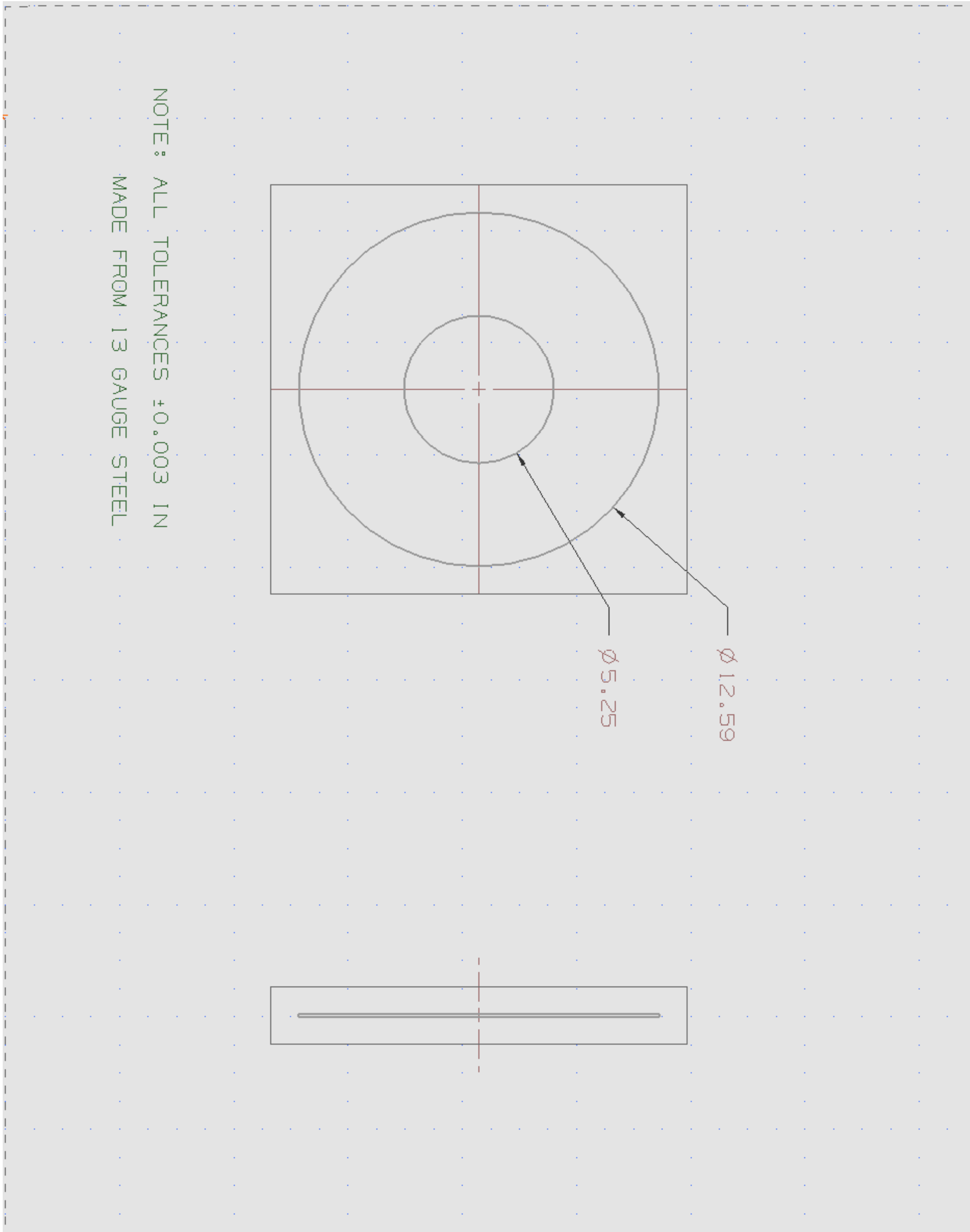
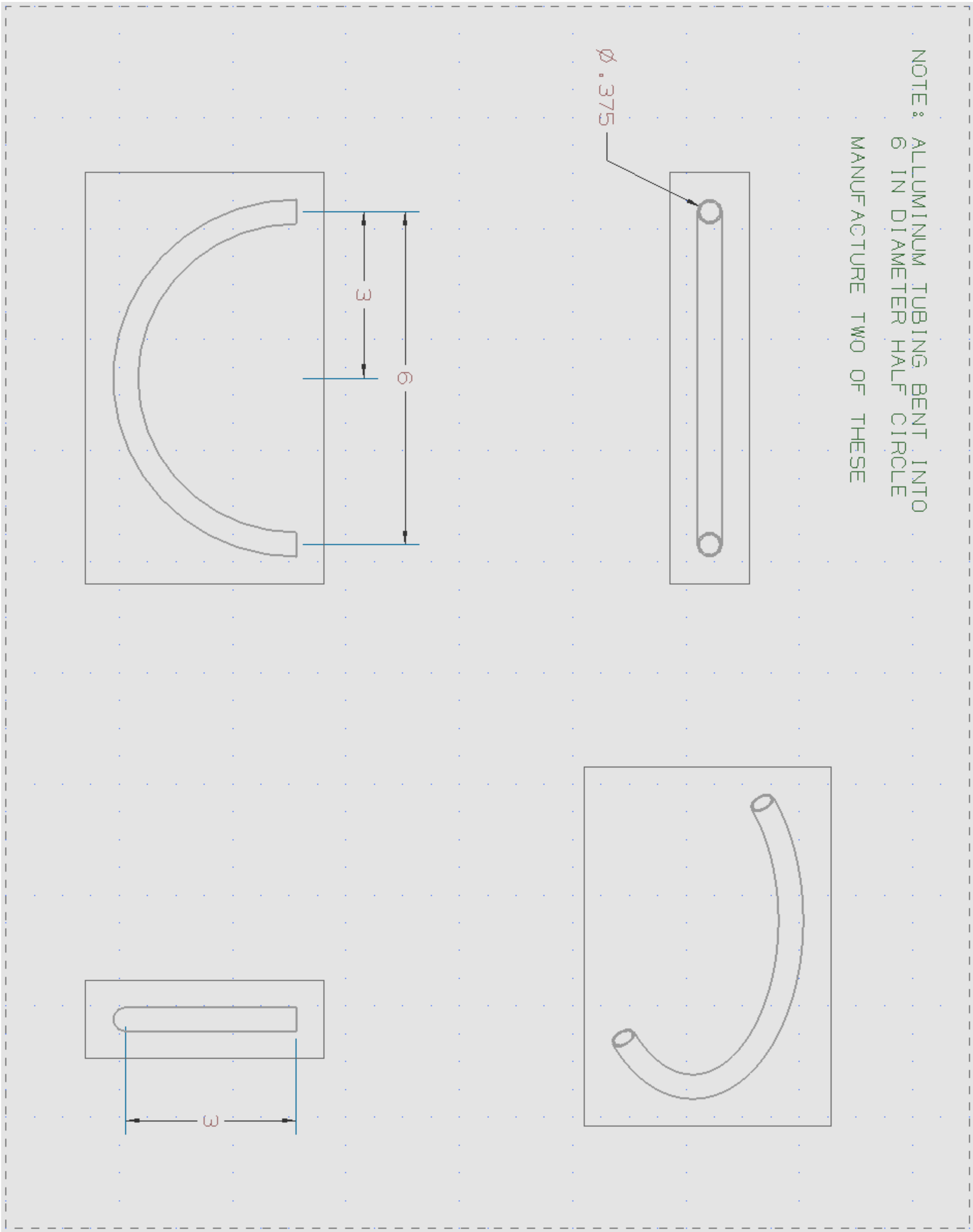
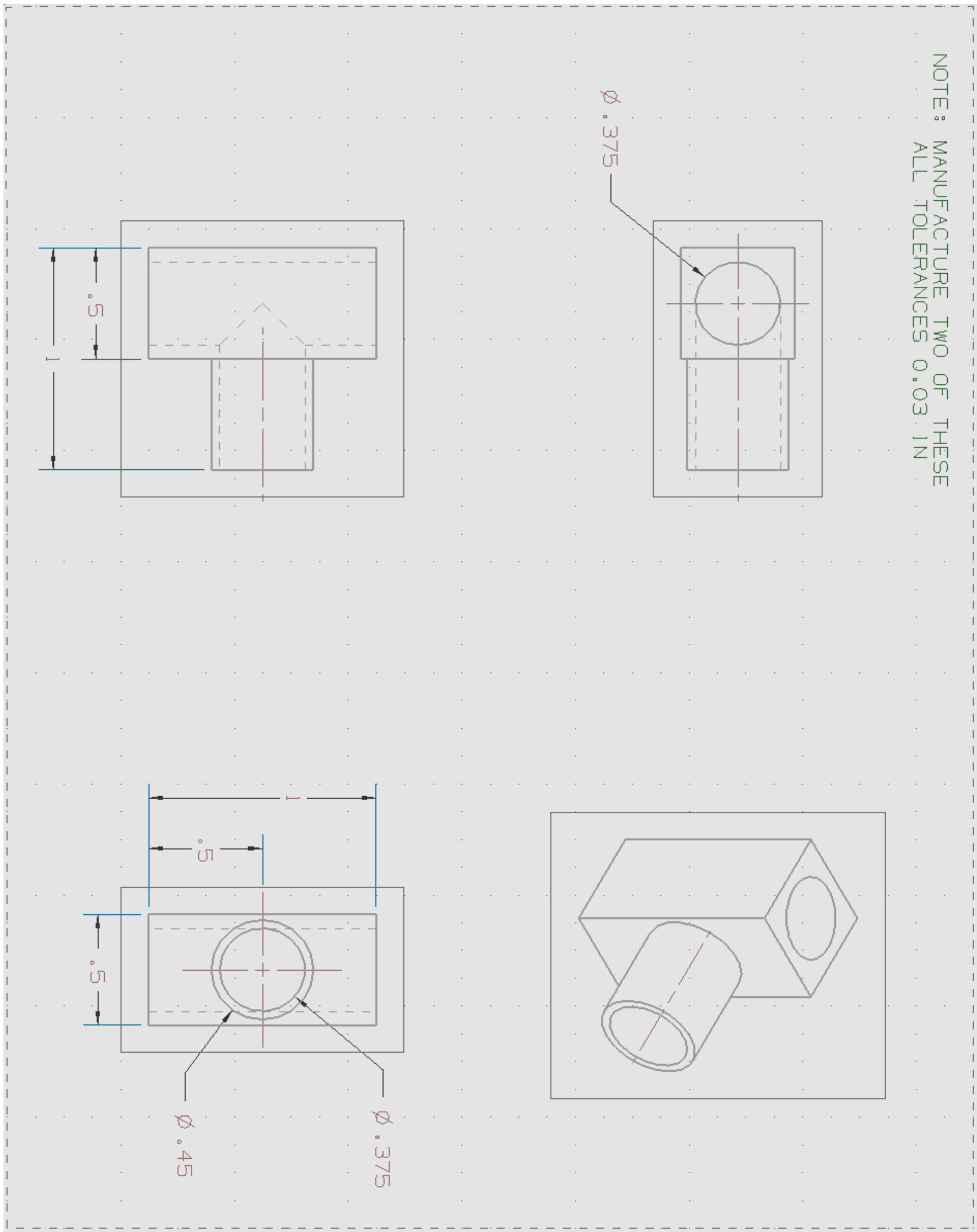


Figure B.5 CAD drawings for the two parts of air ring




NOTE: MANUFACTURE TWO OF THESE
ALL TOLERANCES 0.03 IN
Ø.375
.5
1
.5
1
.5
Ø.45
Ø.375

Appendix C

Bill of Materials

Quantity	Part Description	Purchased From	Part Number	Price (each)
1	Parker vane type rotary actuator	Ebay*	PV33-180A-BB2-B	$44.30
6	BETE 1/8" NPT 65-degree flat spray nozzle	BETE*	NF01	$28.00
1	13-gage steel shroud rolled to 9.3" diameter	Personal friend		
1	13-gage steel shroud rolled to 12.5" diameter	Personal friend		
2	6061-aluminum manifold, 3/8" NPT inlet, (3) 1/4" NPT outlets	McMaster-Carr*	5469K113	$13.63
6	90-degree 1/4" NPT socket wrench elbow	McMaster-Carr*	5021T14	$3.64
2	45-degree 1/4" NPT socket wrench elbow	McMaster-Carr*	50785K82	$1.82
1	(10 ct.) 1/4" NPT to 1/8" NPT hex bushing	McMaster-Carr*	5454K57	$11.24
1	42" x 14" x 1" UHMD polyethylene material	Alro Steel Co.	NA	$45.32
1	2-1/2" Pressure gauge, 1/4" NPT, 0-1000 psi	McMaster-Carr*	4003K11	$18.71
2	1/8" NPT aluminum pipe coupling	McMaster-Carr*	44705K36	$1.85
1	1/8" pipe size aluminum Sch 40 3' length	McMaster-Carr*	5038K51	$9.53
2	1/8" NPT aluminum pipe nipple 4" length	McMaster-Carr*	44665K117	$1.66
2	1/8" NPT aluminum pipe nipple 10" length	McMaster-Carr*	44665K551	$3.49
2	1/8" NPT aluminum 90 degree elbow	McMaster-Carr*	44705K266	$3.30
3	neoprene rubber edge trim	McMaster-Carr*	8507K63	$0.64
1	1/8" steel pipe (4' length)	Personal friend		
1	1/4" x 1" cold roll steel angle (8 ft.)	Personal friend		
3	3/4" flat washers	University of Michigan		
4	10-24 x 1/2" screw	University of Michigan		

*www.ebay.com
*www.bete.com
*www.mcmaster.com

Total = $372.36