Water emission reduction for front-loading Whirlpool Duet washer

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Erica Grysban, Gabriel Pak, Merry Shao, and Leonithas Volakis
Project Team #30

ABSTRACT

Whirlpool Corporation has provided the challenge of improving the eco-efficiency of the front loading Duet washer by reducing water emissions by 75%. The best solution was determined to implement a filtration system to clean and reuse water between each of the load cycles. Laboratory testing was performed on polypropylene and activated carbon filters in a total filtration (dead-end) configuration to provide proof of concept for the prototype. The prototype system was designed and fabricated using two dead-end filters: polypropylene and activated carbon. Due to lifetime issues with the polypropylene filter, a final filtration system was proposed. The final design replaced the polypropylene filter with a ceramic cross-flow filter to allow for easy self-cleaning and prolonged lifetime. Future work includes further research, laboratory testing, and cost analysis of the ceramic cross-flow filters.

EXECUTIVE SUMMARY

Whirlpool Corporation has provided us with a design problem to develop and design a solution to improve the eco-efficiency of the current Whirlpool Duet washer system. Due to the limited time scope of the project, the team focused on the proof of concept for a filtration system to reduce water consumption while minimizing additional energy consumption. This reduction in water consumption must not forgo the quality of the wash. In addition, the system must fit within the confines of the pedestal accessory and allow for attachment into the washer system.

The engineering specifications for this Duet re-design were developed with the sponsor requirements. These engineering targets include a 75% water consumption, or 45 liters, reduction in each wash cycle, an added maximum of 15 minutes to the system drain and recirculation, a T_{max} of 40°C, and a T_{min} of 25°C. Some key metrics of clean output water include obtaining a turbidity of 5-20 nephelometric turbidity units (NTU) and an alkalinity of 1.1-2.1 $^{mmol}/_{L}$. Robust filters are also necessary to extend the system lifetime. Therefore, the sponsors and design team defined a target lifetime of 6 months before replacement. The system must also fit within the existing washer and pedestal system of dimensions H 28 cm W 52 cm D 58 cm. Finally, the system must not leak and must have a total cost under $200. Additional design specifications are summarized in Table 1 on p.4.

In order to satisfy these engineering specifications, the team examined previously suggested concept designs in addition to brainstorming. The concepts were assessed and an alpha design was selected. The alpha design involved re-circulating the output water by a filtration system, thereby ridding the need to draw additional water in from the tap and reducing the total water usage of the system. Polypropylene filters were chosen for their low cost and ability to remove micron-sized particulates within a solution. Activated carbon filters were added for their ability to adsorb with organic compounds with the solution. Initial testing was performed on commercially available polypropylene (PP) and activated carbon (AC) filters. Testing results provided a sequence that passed detergent solution through PP then AC as effective in removing detergent and particulates from water within the given space constraints.

A prototype was manufactured to model the alpha design and provide proof of concept for the filtration system. However, the prototype did not satisfy the engineering specification of lifetime, due to clogging and pressure buildup in the PP filter. Therefore, a final design that replaced the PP filter was recommended. The final design uses a ceramic cross-flow filter and an activated carbon filter, as shown in Figure 23 p. 23. The cross-flow configuration of the final design will eliminate the lifetime issue by allowing the particles within the water to flow past the filter instead of building up on the filter surface, shown in Figure 6 p. 8. In addition, a self-cleaning operation was incorporated to increase ceramic filter lifetime up to 10 years.

Further research and testing on the ceramic filters and cross-flow filtration is necessary. Testing methods of biological oxygen demand (BOD) and turbidity should be performed to gain a better understanding of the effectiveness of the prototype and final design. By completing these additional tests and revisions, the Duet will be redesigned to meet all engineering specifications.

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INTRODUCTION

The United States uses more than 808 billion gallons of water each year to do laundry [1]. Therefore, there is tremendous room for improvement in the fabric care industry. The Whirlpool Corporation has proposed the design problem of improving the eco-efficiency of the Whirlpool Duet fabric care front-loading washer. A redesigned Duet with reduced water emissions will enable Whirlpool to remain one of the most innovative companies in the appliance market. The major goal was to reduce the Duet's water consumption by 75% while maintaining washer performance and keeping the additional costs under $200. If the redesign is successful the water-efficient Duet will appeal to environmentally friendly consumers and customers in regions were water shortages often occur. This project was done collaboration with Team 12.

ENGINEERING SPECIFICATIONS

To aid in the design process, customer requirements were gathered from Whirlpool Corporation and translated into engineering specifications. These specifications guided the research, development, and validation of the proposed product. A list of the specifications the corresponding engineering targets are shown below in Table 1.

Customer Requirements	Engineering Targets
Water Reduction	75 % Reduction
Maximum Addition to Load Time	15 Minutes
Hot/Cold Rinse Cycle Allowance	T_{min}=25°C T_{max}=40°C
Clean Water	Target Turbidity = 5-20 NTU Alkalinity = 1.1-2.1 mmol/L Blender Test = 0 mm foam height
Robust System	6 month min time between maintenance
Space Requirements	System must fit in pedestal H 28 cm W 52 cm D 58 cm
Energy Consumption	Maximum increase of 10%
Affordable	<$200/system
No Leakage	0 L water/cycle leaks
Noise/Vibrations	No additional noise or excessive vibrations

Table 1. Customer requirements and the associated engineering targets

The engineering target of 75% water reduction was employed by Whirlpool. This target will put the Duet at the top of the market as most water-efficient washer. The additional time that would be added to a wash load is not to exceed 15 minutes and was a specification provided by Whirlpool. To be compatible with the washer system, redesign must be able to withstand current washer temperature conditions of a maximum temperature or 40^{O}C and a minimum temperature of 25^{O}C. The water quality used in the cycles of the washer is to have specified measurements of turbidity, alkalinity and blender test as shown in Table 1 above. The redesign will must be robust, requiring maintenance at most every 6 months. Currently, the Duet is sold with an optional pedestal drawer accessory that fits underneath the washer with dimensions of 28 cm high by 52 cm wide by 58 cm deep. The final design is to fit within the volume of the Duet and pedestal system. The specification for the redesign cost stems from the cost of the pedestal addition which is $200 dollars. Total energy consumption of the final redesigned system is to be less than 10% of the current Duet's energy consumption (18.2 kWh/year.) The redesign must not leak. Finally, the noise and vibrations are to be minimized.

The project requirements were examined in more detail and relative importance levels were assigned based on the market demands and the customer needs. These importance levels were related using a Quality Functional Diagram (QFD). The QFD combines customer demands with their importance weights with the translated engineering specifications to determine the most significant aspect in the product development of the new Whirlpool system. In the QFD, it is seen that the filter material is the most important technical requirement with an importance percentage of 30% as seen in Table A.1 in Appendix A.

CONCEPT GENERATION

Many concepts were researched and generated as possible problem solutions. Initially, these concepts were compared in their ability to reduce water emissions. Later, they are narrowed down based on the specifications. These concepts are outlined in the following section as primary and secondary methods. Primary methods reduce water consumption by a large margin. Secondary methods are not stand-alone; they are methods that can be paired with the primary water reduction methods to make water reduction more effective.

PRIMARY METHODS

Reverse Osmosis Reverse osmosis uses pressure to force a solvent through a membrane which contains the solute, while letting the solvent pass. In this case, water from the wash cycle must be forced through a reverse osmosis system which would require the pressure levels of up to 250 psi. Given the scope of the project and the cost limitations, reverse osmosis would not be feasible. Also, water is needed to operate the system. Thus, potentially more water would be used to clean the water [2].

Alternative Water Sources Reusing water from alternate sources within the house, or rain water gathered from outside the house are other viable options. The storage of the water drained from the shower or the sinks in the house, or the gutters on the outside of the house, would provide a large reservoir of water which could be filtered and used in the Whirlpool Duet. Figure 1 on p.6 depicts this alternative water source system. This system would almost eliminate the water drawn from the tap. However, this system requires a complex piping infrastructure to set up in the house but would be a feasible option when constructing new houses and buildings.

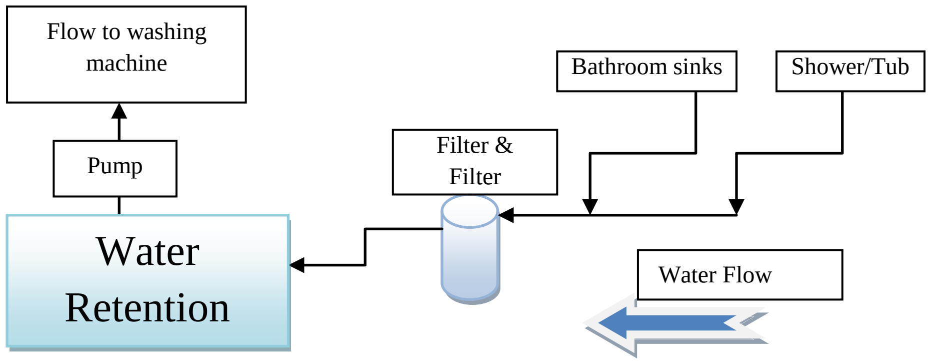


Figure 1. Depiction of system utilizing alternative water sources within the house

Weight Sensors The use of sensors to weigh the clothes placed in the washer drum before the cycle begins may decrease the water use by increasing or decreasing the water intake. Since most customers do not normally pay attention to the size of the load they use and the setting on the washer, water is wasted. These weight sensors would provide a simple solution that decreases the water intake. Figure 2 below represents such a sensor device placement on the drum. For example, when a large load requires 60 liters and a family places a small load of clothes within the drum, they automatically waste approximately 20 liters of water. This design will decrease the water use, but it is not adequate at reducing large levels of water. Therefore, this system must be implemented concurrently with another water cleaning design.

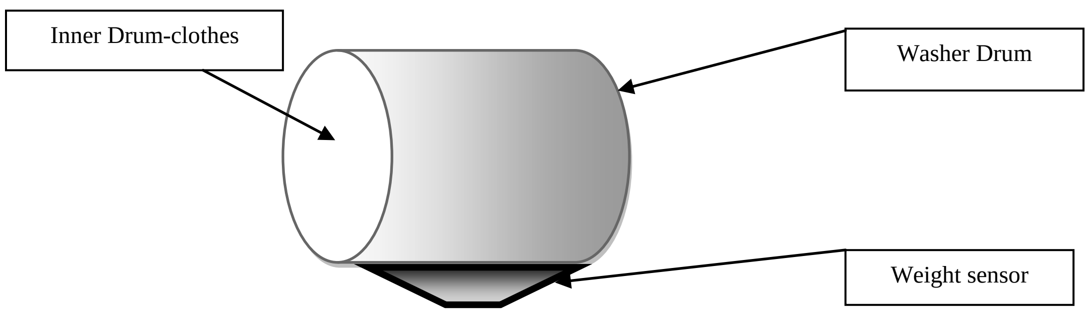


Figure 2. Depiction of the sensor placement on a drum to measure clothes content

Cartridge Total Filtration The main function of this design is to remove detergent and dirt particles from the wash cycle output water so the filtered water is clean enough to be reused in the rinse cycle. This can be accomplished by utilizing a filter. Figure 3 on p.7 shows a filter housing with a cartridge inside. Unfortunately, filters clog over a period of three to six months while an average washer life is 11 years [8]. Therefore, a method to clean the filter is necessary. Self-cleaning filter methods can be implemented to solve the clogging problem.

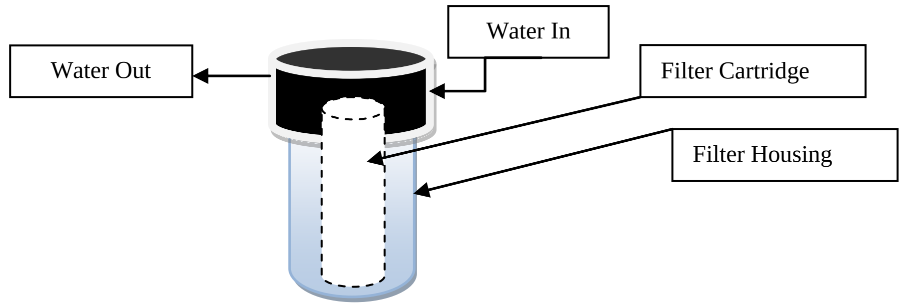


Figure 3. Filter housing and filter cartridge placed inside

These total (also known as dead-end) filters can be placed in series. This would hypothetically remove a higher percentage of impurities and allow for different contaminants to be removed at different stage which could improve the life of the filters. The dual-stage filters will also allow for cleaner output water. Another possibility for multi-stage filtration is to include a filter with different levels of filtering at different depths within the cartridge. Such a design would require less space requirements and would perhaps cost less. Figure 4 below shows the placement of the dual-stage filters and a single filter with two material layers in the form of cross-flow cartridges.

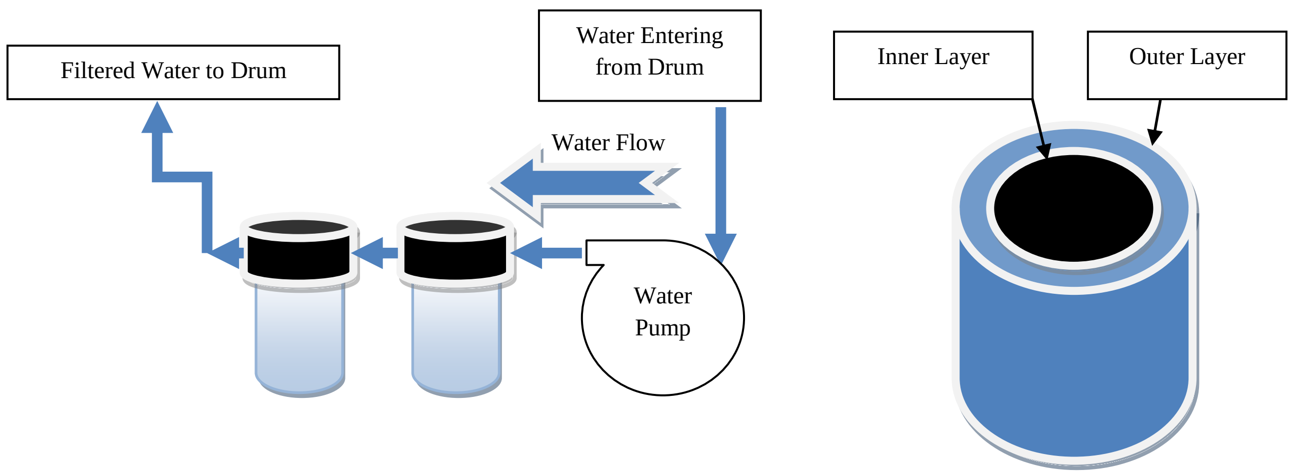


Figure 4. A dual-stage filtration system (left) and a single filter with two filter levels (right)

Perpendicular-Flow Filtration The previous total filtration method utilizing cross-flow (or cylindrical) cartridges to filter water can also be implemented with total flow cartridges. There exist differences in content filtered, availability in the market, and filter life between cross and total flow filters. The cross-flow filters will have a longer life due to a size and thickness, and are readily available as standard filters. In addition, cross-flow filter housings are often sold in nearby hardware stores in case a defective product is sold. Total flow filters are able to remove a larger amount of impurities due to the pressure gradient aiding the desire of water to flow at a constant flow rate through a pipe. However, this would decrease filter life compared to the cross-flow filters. Figure 5 on p.8 shows how a total flow filter would be placed within a system.

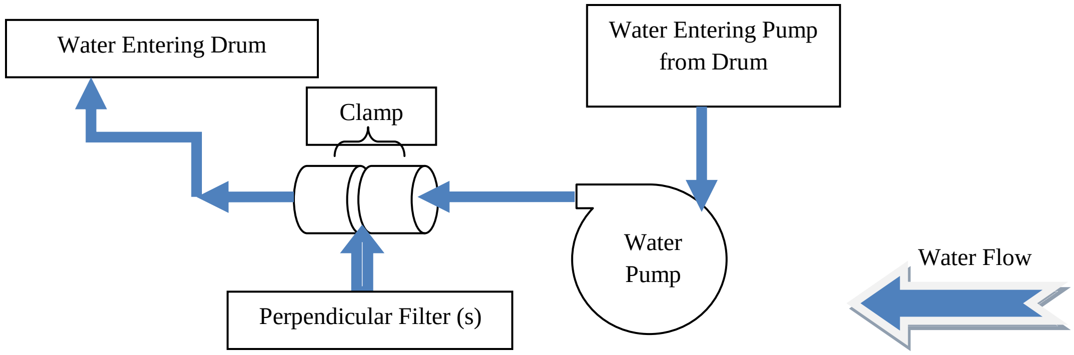


Figure 5. Perpendicular-flow filter placed within a system similar to a cross-flow filter

Cross-Flow Filtration The impurities in water are removed by cross-flow filters by feeding water across the filter at a high velocity. Due to the pressure across the filter the water then permeates perpendicularly across the filter membrane at a low velocity. The dirt within the water is then able to flow past the filter and out of the housing instead of being forced into or onto the filter. Any buildup that might occur on the filter can be easily removed by backwash. Figure 6 below shows the basic functionality of a cross-flow filter.

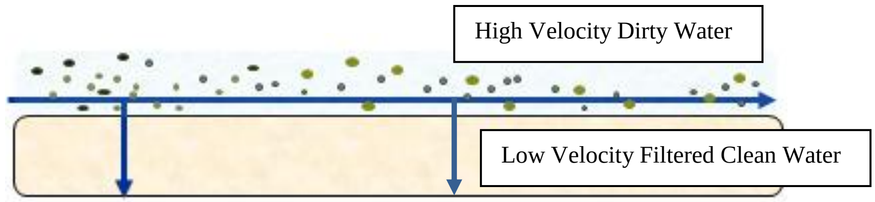
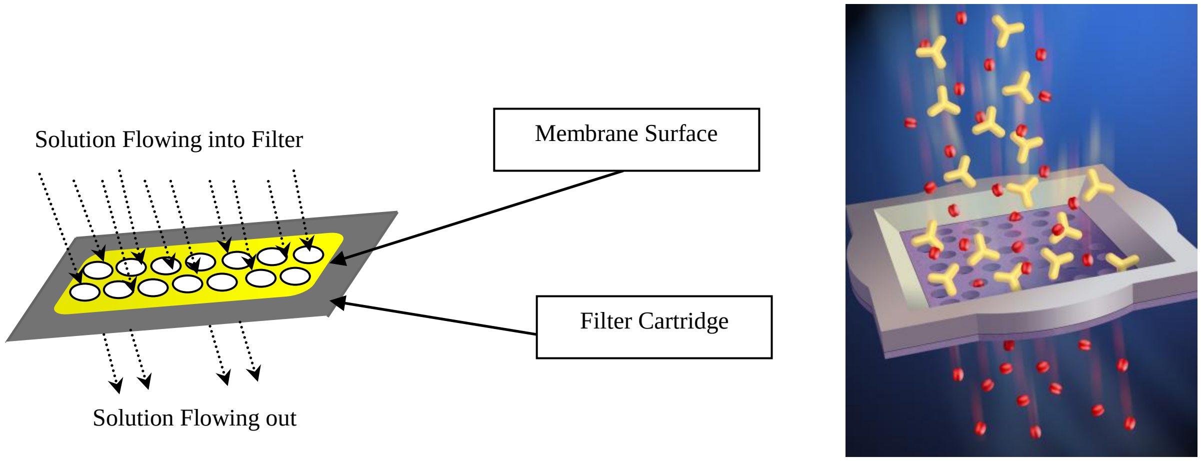


Figure 6. Cross-flow filtration showing areas of high and low water velocity

Membrane and Nano-Filtration Another filter that can used for removing impurities and compounds on a smaller scale within water is an organic filter. This can be a nano or a membrane filter. These filters are similar to the previously mentioned filter cartridges and sheets, with a change in pore size from the micron to the nano-scale in Figures 7 on p.9. The image on the right in Figure 7 shows a nano-filter with particles flowing through. In addition, many nano and membrane filters are specifically designed to filter microbial cysts, protein solutions, and other microscopic molecules. Current processes that use nano-filters include water treatments, medical purification methods, and gas separation. The product is also readily available in the current market commonly sold in packs of 40-100 filter discs. These filters are effective, but are out of the price range of this project.



*www.rochester.edu

Figure 7. Images of membrane (left) and nano (right) -filters that removes molecules and solutes within a solution based on particle size

SECONDARY METHODS

Blending and Siphoning The foaming agent within detergent can create issues when trying to reuse water. Therefore, one of the primary objectives must be to fully remove the foaming agent. Blending and siphoning off the foam from a blended sample of filtered detergent water can further decrease the soap content and foaming agent within the filtered water reintroduced into the rinse cycle. Figure 8 below shows a schematic of the blending and siphoning method. This process will aid in a primary filtering method for the detergent and dirt particles within the water.

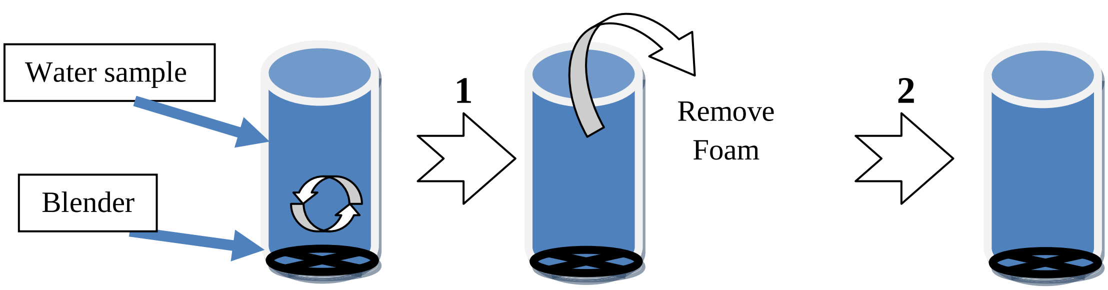


Figure 8. Represents the different steps that are necessary to siphon off the foam created by blending the water and detergent samples within a blender: (1) Blend the water and detergent together, (2) Siphon/Remove the foam from the blender canister by using a paper towel or a cup

Nozzles and Jets Incorporating jets in the rinse cycles may also aid in decreasing the water required. Figure 9 on p.10 shows a possible design incorporating nozzles and jets. By continually pulling the water at the base of the drum and cycling it through tubes that return the water to nozzles at the top of the drum, the water will pass through the clothes faster and pull more dirt and soap from the clothes by binding the water and dirt particles to the amphipathic detergent molecule.

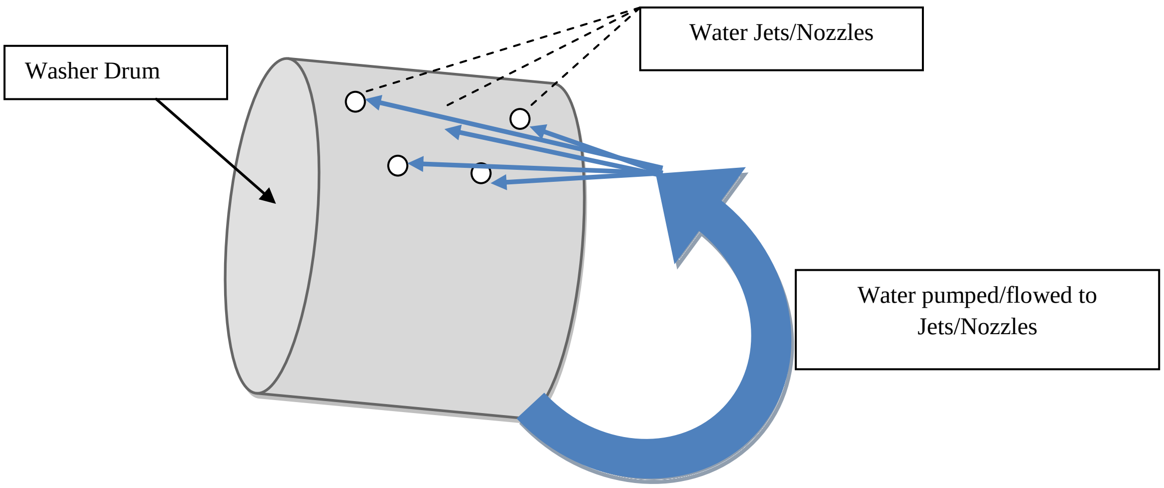


Figure 9. Washer drum with jets placed on top being pumped from the bottom

CONCEPT SELECTION

To determine which concept to choose the team analyzed which of the generated concepts met the engineering specifications. Reverse osmosis requires high pressures of around 250psi. Pressures this high will require pumps that would not meet the cost or energy consumption specifications. Using alternative water sources such as rain water or water from other areas of the house requires rerouting of a household's plumbing system which is not something that Whirlpool is able to market. The Duet already incorporates a weight sensor to measure the mass of clothes and therefore use the necessary water but the redesign is to reduce the water even further. Filtration methods satisfied more requirements than any other concept. The initial types of filtration that were considered included: membrane filtration, nano-filtration, cartridge total filtration and cross-flow filtration.

Membrane filtration technology is becoming more available and the applications are wide-ranging in recovering chemicals or products and even water from wastewater. With improvements in design and decreasing costs for these systems, the team investigated the application of membrane filtration for the washing machine [3]. The advantage of these new membrane filtration systems are the size of the contaminants that can be removed at high pressure levels [4]. Nano-filtration seems promising to meet the specifications of the project. Nano-filters micron size is at an average of 0.01 micron, thus filtering particles as small as 200 g/mol. A cross-flow design that allows fluids to flow parallel to the membrane surface is implemented in these nano-filters to help reduce contaminant clogging and fouling of the membrane. Nano-filters and membrane filtration must operate at pressures around 1,000 psi to be effective. Due to this large pressure requirement, these technologies are neither cost nor energy effective for this redesign.

Cartridge filters were considered for their ability to clean water. These filters are simple to use and do not require complex housings or high pressures to operate. Some are designed to remove large and micron sized dirt particles. Others focus on the removal of bacterial cysts within the water, as well as organic impurities/compounds which are found in detergent and surfactants. Effectiveness of the cartridge filter will ultimately depend on material, pore size and the ability to remove solutes within the dirt/detergent solution.

Two types of filters that the team researched were polypropylene (PP) and activated carbon (AC). Polypropylene filters with standard 20-35 micron pore size would be useful for their ability to remove large particles from the water. The design could take advantage of the AC filters ability to effectively adsorb organic compounds and bacteria since these will be two main components to remove from the wash water [5]. Self-cleaning filtration systems were investigated because they allow for little to no maintenance on the system by simply utilizing a backwashing of the filter by reversing the flow of the pump [6].

Cartridge total filtration was chosen to be used in the prototype and cross-flow filtration will be use in the final design. Due to the given constraints of time and budget, cartridge cross-flow filtration, also known as dead-end filtration, was used for the prototype since the PP and AC filters were commercially available and could be acquired at any hardware store for relatively low-cost. These dead-end filters could be used for the proof-of-concept that the system does in fact meet the majority of the specifications. Thus, cross-flow filtration will be used in the final design, since functionally cross-flow filters have similar performance as dead-end filters and are designed to improve the lifetime of the filter since the surface of the filters are cleaned from the flow of filtrate into a separate reservoir tank. In this design, the reservoir tank would require maintenance instead of the filters, allowing for the system to maintain its performance.

The final design system will utilize the same basic flow as shown in the flow diagram in Figure 10 on p.12. First, the washer drum will be filled with tap water as normal. After the wash cycle is complete, the water will be drained into the reservoir and then pumped through the filtration system. The output from the filtration system will go back into the washer drum to be used in the first rinse cycle. Output water from the first rinse cycle follows the same filtration path and the output from the wash cycle. After the second rinse the water is drained from the drum into the reservoir and out the disposal drain.

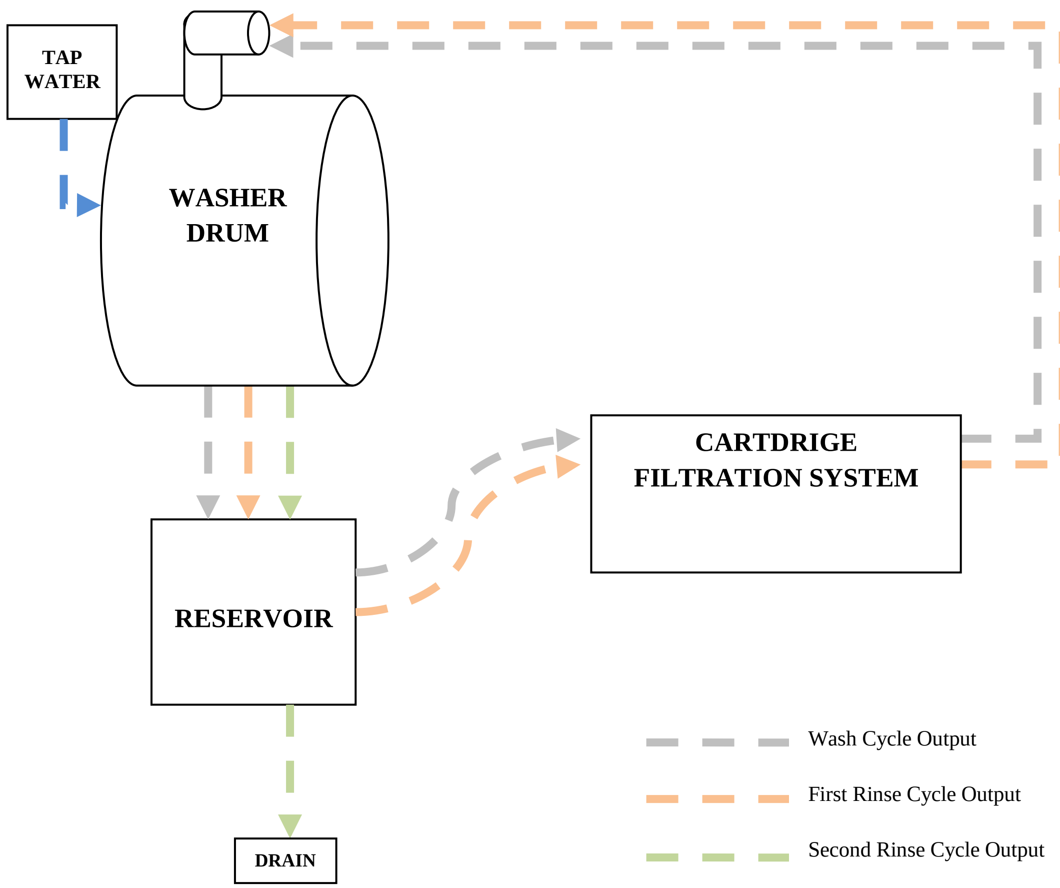


Figure 10. Flow diagram of the prototype and final design for the Whirlpool Duet filtration system

Once the prototype and final design were chosen, laboratory testing was performed to prove that filtration is a feasible and effective way to clean washer water.

ALPHA CONCEPT VALIDATION

The validation of the alpha filtration concept included material selection to determine which filter and filter housing materials would satisfy the operating conditions and the customer requirements. Additionally, a laboratory model of the alpha concept was assembled using the chosen materials and connected to a provided test pump in the available laboratory. Using this laboratory model, the output water quality was assessed obtainable testing techniques and then analyzed to resolve on a filter, or a series of filters, that was effective at creating clean enough water to meet the engineering specifications. Furthermore, the pressure input and output flow rate were correlated and that relationship was extrapolated to determine what input pressure would be required to generate the specified output flow rate. Lastly, a geometrical analysis was conducted to ensure that the functioning system would be able to fit within the provided constraints and still be customer friendly.

MATERIALS SELECTION Since there was not much existing literature about filtering detergents from water, the filter and filter housing materials for the alpha concept were chosen based on commercial availability. Filter housing materials were chosen to be made out of PVC because those were the most cost effective and commercially available filter housing materials. Though ideally, the filter housing material would be constructed from CPVC because of the high temperature and corrosion resistance of CPVC. Using this information, the connection piping material was chosen to be CPVC. The two main filter materials in the marker are polypropylene (PP) and activated carbon (AC) and were total (also known as dead-end) filters. These filters materials both satisfied the wash cycle operating temperature engineering specification and were low cost. Both of the filter manufacturers' claimed that the filters were effective for removing sediments, organic materials including bacteria, and reducing the turbidity of the filtered water. Due to the lack of information about the ability to remove surfactants and detergent from water, the next task was the alpha concept laboratory validation.

LABORATORY VALIDATION Several factors can measure the water composition and quality:

1) Water turbidity: This measures the clarity of the water—the higher the turbidity, the murkier the water.
2) Water conductivity: This measures the ability of the water to pass an electric current—the more conductive, the denser the water.
3) Biological oxygen demand (BOD): This measures the oxygen used by microorganisms to decompose organic waste—the higher the BOD level, the more bacteria there is in the water.
4) Alkalinity: This measures the ability of a solution to neutralize acids to the equivalence point of a carbonate--the lower the alkalinity, the less detergent present in the water solution.
5) Blender test foam height: This measures the amount of foaming solution in a fluid—the lower the foam height, the less the detergent present in the water solution.

The laboratory equipment needed to perform turbidity and BOD tests were not available or affordable during the scope of this project so they were not conducted. For the remaining tests, the following procedures were conducted.

<u>Water Conductivity Test:</u> Zero a digital conductivity meter. Take conductivity meter and put it in the fluid sample so that the conductivity meter sensor is completely submerged in the fluid. Wait 30 seconds for the meter reading to stabilize. Record the conductivity reading (in $^{\mu s}/_{cm}$).

<u>Alkalinity Test:</u> Measure out a small (10-50 mL) amount of the sample fluid into a beaker. Place the sample on a stir plate and begin stirring the fluid using a stir bar at a medium speed. Fill a buret with 0.01 N HCl solution nearly full. Prime the buret by letting all of the air out of the bottom of the buret. Place the buret in the holder, with the end of the buret directly over the beaker. Record the initial amount of HCl solution in the buret. Clean and calibrate a digital pH meter and place the pH meter so that the sensor is completely submerged in the sample fluid. A figure of the alkalinity testing set up can be seen in Figure 11 on p.14.

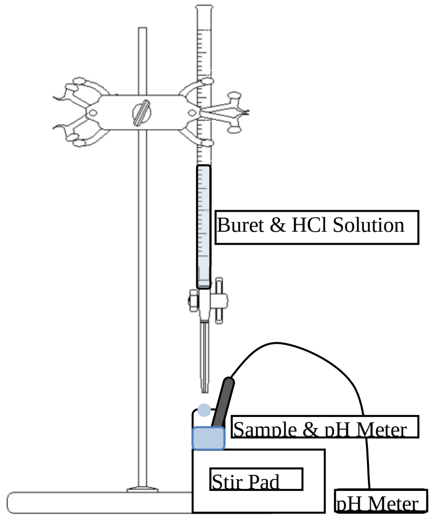


Figure 11. Set up of alkalinity test titration

Allow the HCl solution to drip slowly from the buret into the sample container. While the HCl is dripping into the sample, watch the pH meter readings. When the pH meter readings reach 4.3, stop the drips from the buret. Record the remaining amount of HCl solution in the buret. Next, use the following equation to determine the amount of $CaCo_3$ in $^{mg}/_{L}$.

$$CaCO_3\ ^{mg}/_{L} = \frac{mL(HCl) * 0.01N * 50000}{mL(sample)} \quad \text{[Equation 1]}$$

Finally, convert the amount of $CaCO_3$ in mg to mmol to find the final alkalinity of the tested sample in $^{mmol}/_{L}$.

<u>Blender Test:</u> Take 400 mL of the sample fluid and pour it into the blender. Run the blender for 15 seconds on the “Whip” setting directly followed by 15 seconds on the “Liquefy” setting. Turn the blender off and allow the blended fluid to settle for 3 minutes. Measure and record the height of the foam on top of the fluid from where the foam was present to where the foam disappeared. A photo of this measurement and the blender test set up is shown below in Figure 12 on p.15.

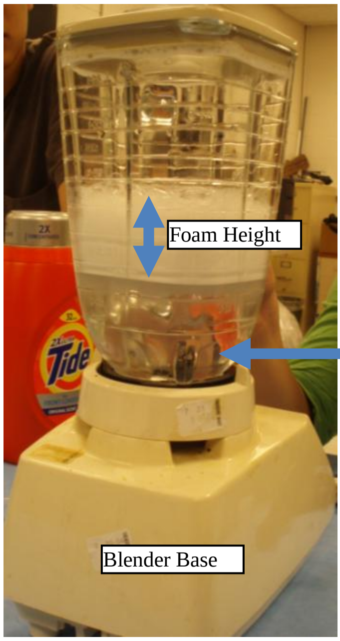


Figure 12. Blender testing set up and foam height measurement

In order to obtain samples to test the effectiveness of the commercially purchased filters, a laboratory model of the alpha concept filter system was assembled and is shown below in Figure 13. This model used General Electric brand filter housings with a GE water filter, CPVC pipe fittings, and other various pipe fittings connected to the provided pump in the available laboratory.

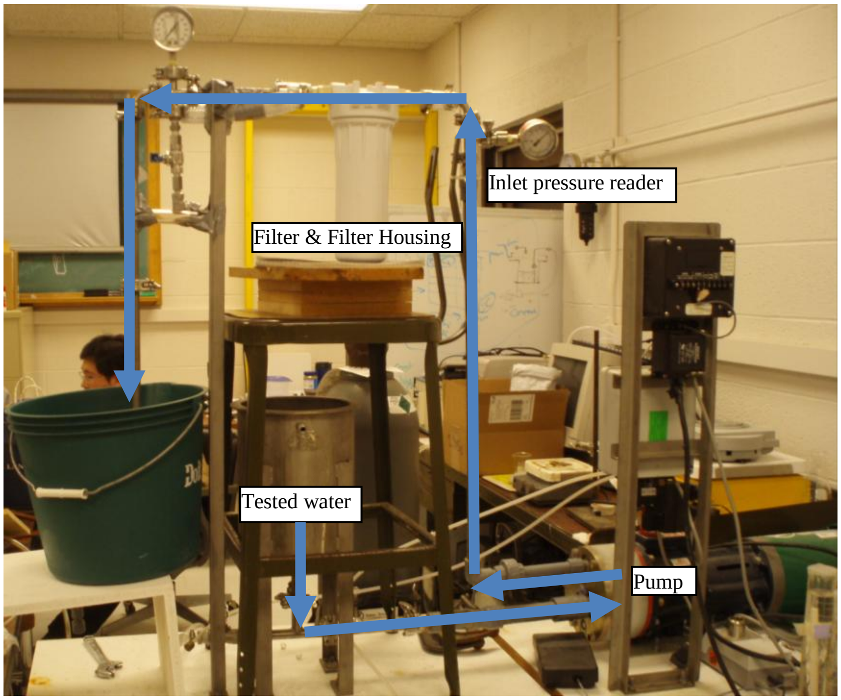


Figure 13. Laboratory set up of alpha concept illustrating flow of water though the system

Before testing any water quality tests from the laboratory alpha concept mock up could be conducted, the typical soapy solution used in front-loading laundry washes was reproduced. This solution will be referred to as the normal solution. The normal solution was created by blending Tide HE detergent and tap water according to the recommended package amounts. In order to have a baseline for how much detergent remained in filtered water, the normal solution was diluted down with tap water into $^{1}/_{2}$, $^{1}/_{4}$, and $^{1}/_{8}$ of the original concentration. Each of the solutions underwent the conductivity and blender tests. The results from these tests are summarized in Figure 14 and Figure 15 below. Next, the conductivity and blender test results were correlated Figure 16.

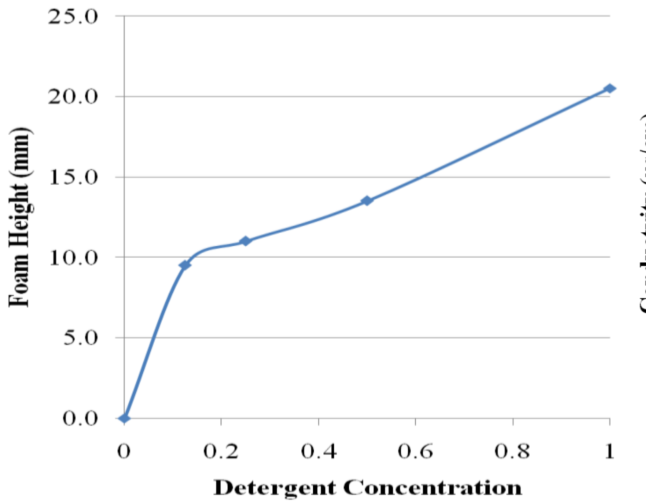


Figure 14. Foam height (mm) increases in a linear fashion in comparison with normal solution detergent concentration after 12.5% concentration.

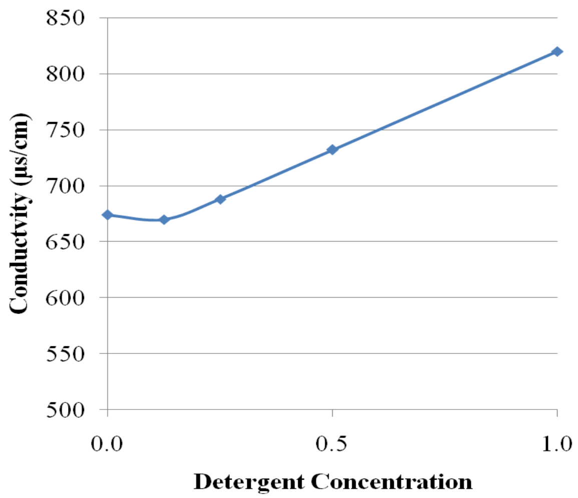


Figure 15. Conductivity (µs/cm) increases in an almost linear fashion in comparison with detergent concentration.

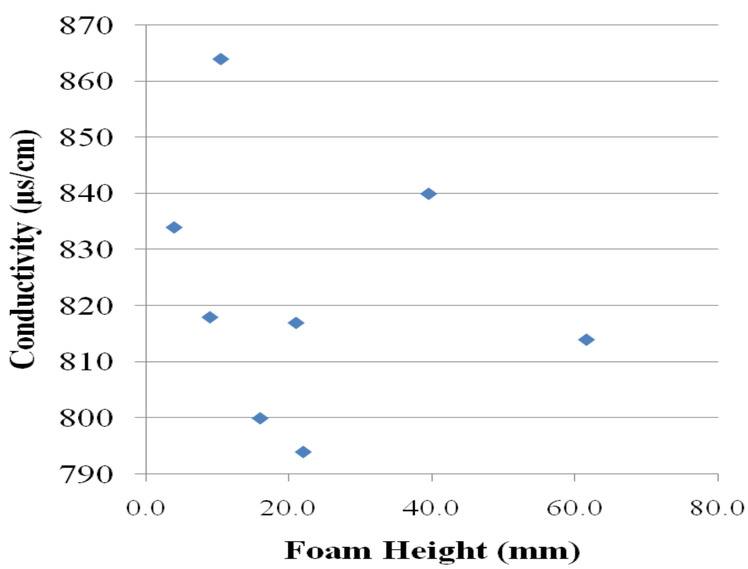


Figure 16. Conductivity (µs/cm) and foam height (mm) have no direct relationship

Figure 16 on p.16 demonstrated that there was no direct correlation between the conductivity and blender tests. In order to make a conclusion on which test was more accurate in correlating the concentration of normal solution to the test results, several factors had to be investigated. Since the relationship (shown in Figure 16 on p.15) between conductivity wavers between 0% and 25% concentration and does not show a steadily increasing or decreasing relationship in that concentration range, the team decided to only use the blender test to further quantify the concentration of detergent in sample solutions.

Initially, normal solution was run through an AC filter and then a blender test was performed on the filtered solution. The foam height of the blender test was translated using Figure 14 on p.16 into an estimated normal solution concentration. Since the result was a 100% concentration and did not come close to the engineering specification of 0 mm, the PP filter was tested. After evaluating the correlated normal solution and determining the result to be unfit, the team tested various combinations of filters in series for their effectiveness. Table 2 below illustrates the combination of the filters tested and their correlated normal concentration results based on the baselined blender test results. (See Appendix B for additional testing results)

	1st Cycle	**2nd Cycle**	**3rd Cycle**	**Corresponding Concentration**
Trial 1	Put normal solution through AC			100%
Trial 2	Put normal solution through PP			98%
Trial 3	Put normal solution through AC	Output of 1st cycle through AC		70%
Trial 4	Put normal solution through AC	Output of 1st cycle through PP		200%
Trial 5	Put normal solution through PP	Output of solution through AC		12%
Trial 6	Put normal solution through PP	Output of 1st cycle through AC	Output of 2nd cycle through PP	5%

Table 2. Estimated corresponding normal solution concentration in the output of the filtration cycles is the lowest for the PP→AC→PP trial

Trial 4 had an estimated corresponding concentration of 200% based on the blend test. This result was high due to the foam level generated by the blender test being greater than the normal dilution. The result was not possible unless the filter had actually deposited more detergent into the solution so the AC→PP filter order was further investigated. Understanding that AC environments have large surface area, the team hypothesized that the AC broke down the solution into smaller compounds, which caused the overall system to foam more. Thus, it was decided that using the AC filter would be the least ideal to reduce foaming in the system.

As seen in Table 2 above, the corresponding concentration of normal solution remaining after the normal solution was filtered through the PP→AC→PP filter sequence was only 5% of the normal solution. Using this data, the team concluded that the PP→AC→PP sequence was most effective for removing detergent from normal solutions. This proved the alpha design concept that using filters in series to filter normal soapy solutions was valid.

The next step was to attempt to recreate a “dirty solution” which related to a typical wash output. A new Whirlpool Duet front loading washer was used to wash a load of cloths and the output water from the initial spin cycle was saved. Next, generic potting soil was blended with normal solution in various amounts and visually compared by examining the color and turbidity of the two solutions. The closest solution was the result of adding 50 g of potting soil to 11 liters (3 gallons) of normal solution. This “dirty solution” was used to test the effectiveness of the filter sequence in real-life situations. There were some discrepancies in this “dirty solution” because it didn’t have all the ingredients in it that would correctly reflect a typical individual’s laundry water. Examples of components are dust particles, grass stains, ketchup, and more. To more accurately simulate real laundry output, future work would include conducting a market survey inquiring what people normally have on their dirty clothes and how soiled they are.

Once the “dirty solution” was run through the filter system, the filters clogged the flow of the system stopped after 11 liters (3 gallons), even when the input pressure was increased. To investigate the root cause of this clogging, the filters were removed. Photographs of the before and after-filtering PP filter are shown below in Figure 17.

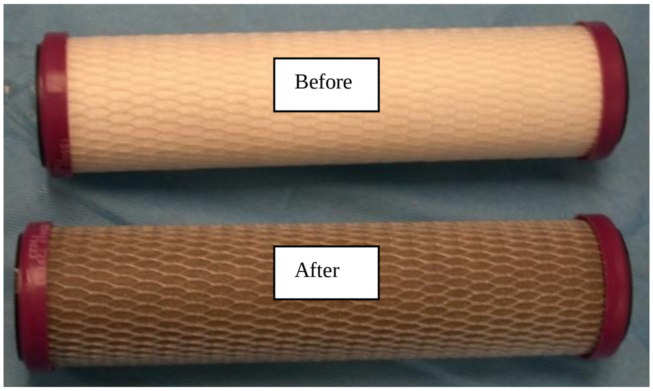


Figure 17. The PP filter was coated in dirt from the “dirty solution” and prevented the system from properly functioning

Then, the team hand-cleaned the grimy filter by running tap water around the outside surface of the PP filter to wash off the dirt. The hand-cleaned filter was then put back into the system with the other filters. “Dirty solution” was run through this cleaned system. The cleaned system began functioning again but the output flow was slightly reduced and clogged after just 11 liters (3 gallons). Using this knowledge, the team added an engineering specification to have the final design system incorporate a method for self-cleaning the filter.

GEOMETRY ANALYSIS Whirlpool Corporation allocated the pedestal space as geometrical restrictions for the filtration system. This space must accommodate for all of the elements of the filtration system including the pump, the storage tank, the filters, the filter housings, the piping, and valves. After Team 12 designed the layout of the pump, storage tank, piping, and valves, half of the pedestal volume was remaining for the filter and filter housing. This remaining space has the dimensions of (28 cm by 52 cm by 58 cm.) Figure 18 on p.19 shows the placement of the filter system in the pedestal.

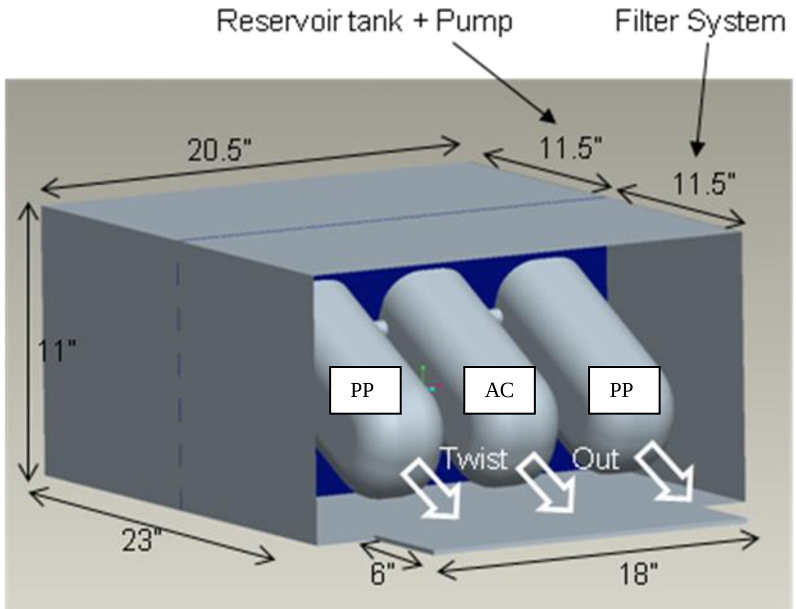


Figure 18. Alpha concept filter system and dimensions

The filters, connecting pipes and fittings, and the filter housings must fit into the remaining space. Since the height of the filter housing exceeded that of the allocated height, the filter housing system was designed to be on a 30^{o} angle from the vertical in order for the system to fit. In addition, the housing units must be easy to remove and must be placed so the consumer can reach and twist out the units without having to dissemble the system. After laboratory testing, it was concluded that the system could operate with the same effectiveness as if it was normally operating if it was on the tilt. Since the filter housings are not completely filled with liquid when the system is offline, the 30^{o} tilt on the system satisfies the no-leaking specification and does not splash out when removed.

FLUID DYNAMICS ANALYSIS There are two factors that constrain the required system inlet pressure:

1) Cost limitations for the pump
2) The pressure required to create the specified flow rate out of the system

Since the pump had be able to fit into the tank, the partner team, Team 12, was bounded by the commercially available market pumps. The initial pump that Team 12 chose was rated up to 18 psi of pressure. The pressure required to meet the specified flow rate of 3.8 $^{L}/_{min}$ (1 $^{gal}/_{min}$), a relationship between pressure and flow rate was extrapolated from experimental data. This relationship is expressed in the following linear relationship:

$$\text{Flow rate } (^{gal}/_{min}) = 0.036 * \text{Pressure (psi)} - 0.39 \qquad \text{[Equation 2]}$$

Using Equation 2 above, the necessary pressure is 39 psi. Since the provided pump did not reach the required pressure of 39 psi, the engineering specification will not be met. However, using the input pressure of 18 psi, the flow rate retained will be 1 $^{L}/_{min}$ (0.23 g $^{gal}/_{min}$), leading to a total cycle filtration time of 12 minutes, which is 2 minutes less than the target cycle time of 14 minutes. The safety factor is only 1.16. Considering that the time allocated to recirculate the water was not among the top of the specifications, adding time to the system would not be that important as long as the water was still cleaned. Also, if the system degraded over the lifetime of the system, the safety factor for this system would not be that important because it does not impact human safety or the safety of the surrounding environment, which would have higher safety factors between 3 and 10.

PROTOTYPE DESCRIPTION

Although the prototype does not physically model the final design, it provides proof of concept. The prototype utilizes a polypropylene (PP) filter in a total filtration configuration while the final design consists of a ceramic filter in cross flow configuration that will be discussed further in the following sections. As discussed in the testing methods section, in sequence the polypropylene and activated carbon (AC) filters effectively filter the washer water and output water at a quality that is acceptable for reuse in the rinse cycles as shown in Figure 19 below. The prototype allowed us to prove that the filtration method was a viable solution to the water reduction problem.

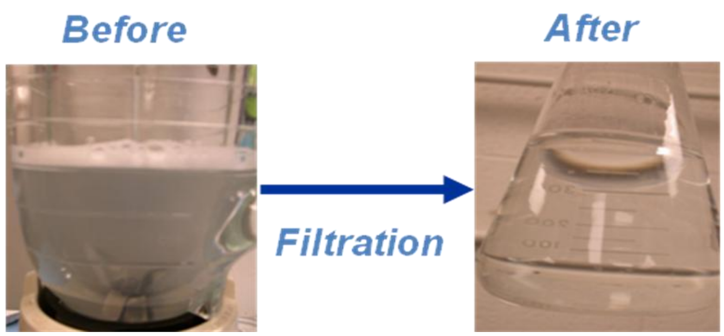


Figure 19. Picture of water before and after filtration

After testing was complete the prototype was constructed to implement all the components of the system together. The prototype was built in collaboration with Team 12 and it includes an integration of the test filtration system of the PP and AC filters in series and the pumps and retention tank designed by Team 12. A picture of the prototype with labeled components is shown in Figure 20 on p.21.

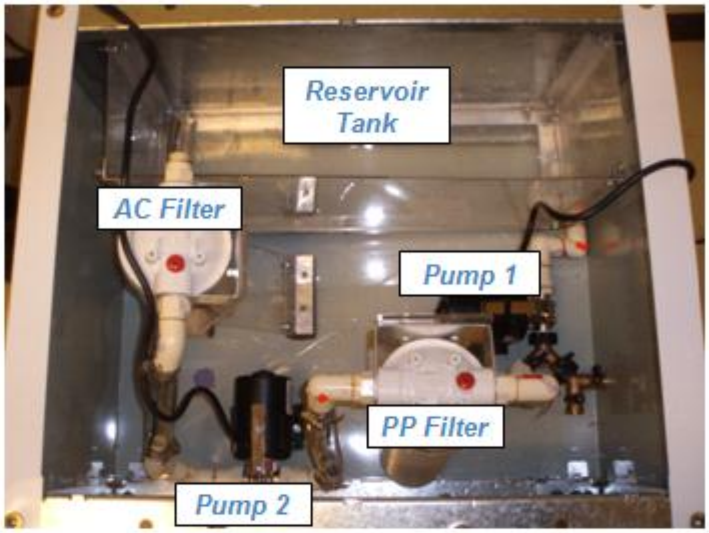


Figure 20. Picture of the prototype with components labeled

The total cost of the prototype, including components supplied by Team 12, is approximately $175. This is below the engineering specification of $200. A bill of materials for the prototype is located in Appendix D.

An outline of the flow through the prototype is shown in Figure 21 on p.22. The design of the systems flow was primarily Team 12's responsibility; however, due to lack of communication between the teams, the flow of the prototype does not efficiently clean the water. Currently, the output of the washer drum enters into the retention tank, is pumped by pump one through the polypropylene (PP) filter and into pump two which pumps the water through the activated carbon (AC) filter and back into the retention tank. Ideally, this process is to be run until all the water has been filtered and the retention tank is full of clean filtered, however, as discussed in the testing results section, the PP filters quickly clogs so that the prototype is not able to run until the water is cleaned. One solution to this problem is to have the water pumped from the drum by pump one and then filtered through the filters and stored in the retention tank. Then when all the water has been cleaned, pump one can pump it back up to the washer drum. Other solutions to this problem can be found in Team 12's final report.

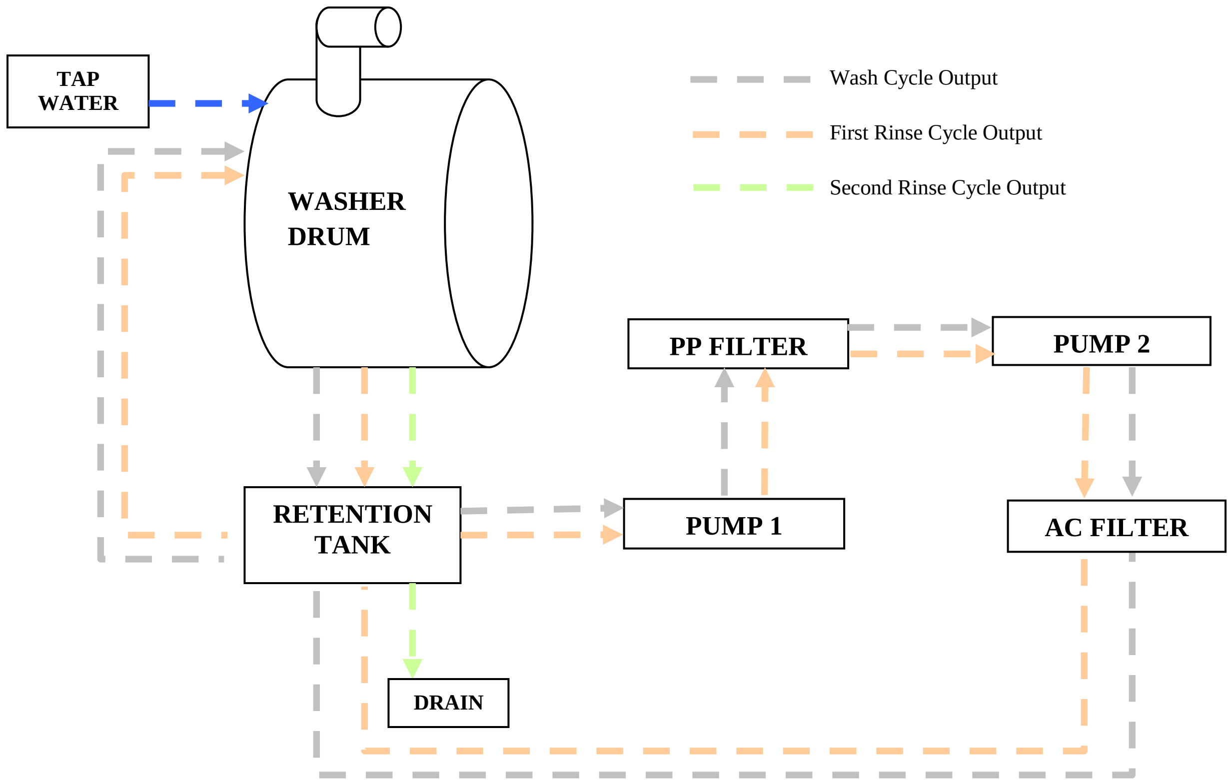


Figure 21. Flow of water through the prototype

A safety analysis was performed on the prototype to understand the risk it poses to operators and is outline in detail in Appendix C. The risk to the prototype user is relatively minimal if the filters are not clogged. Once the PP filter becomes clogged the user is at risk of system failure due to high pressure. The user will know when the filters are clogged, and that the pressure is increasing if the flow rate of the second filter becomes very low. When this happens the recommended action is to turn off the pumps and either clean of replace the PP filter.

FINAL DESIGN DESCRIPTION

The prototype of the washer water filtration system proved that the water can be filtered effectively with an alkalinity similar to normal tap water, as shown in the right image of Figure 19 on p.20. The prototype did not meet the lifetime design specification due to the primary filter, polypropylene (PP). The reason for the failure of the PP filter was due to a buildup of dirt particles that clogged the filter in 6 cycles or 2-3 loads. This clogging also led to increased pressure levels in the PP filter housing and the piping leading to the PP filter. Such a potential hazard to the user and possibility for system failure was detrimental to the manufacturing of the prototype without improvements.

The final design improves upon the prototype by changing the filter material and dead-end filtration configuration. In the final design a ceramic (α-Alumina) filter in cross-flow configuration will be utilized as the primary filter to prevent clogging and to extend the filter lifespan. Specifically the α-Alumina material was chosen because of its availability at pore sizes of 0.1 to 5.0 micron that is suitable for the filtration application. Ceramic membranes have been increasingly become popular in the areas of biotechnology, food and beverage, chemical and petrochemical, and metal finishing. The unique mechanical properties of ceramics allow for significant advantage over other commercially available filtration methods. The cost of ceramic filters is reasonable relative to their physically and chemically stable structures, allowing for a lifetime of up to 10 years, and their ability to handle a wide variety of substances at liquid and gaseous temperatures. [7,8]

Ceramic filters are often included in cross-flow filtration as a continuous process to increase the rate of the water to permeate through the filter pores. As shown in Figure 6 on p. 8, cross-flow filtration removes the dirt particles by feeding water at high velocity across the filter membrane. Then, the water will permeate through the filter at a lower velocity. The clean filtered water would exit the holes in the center of the ceramic filter, as shown below in Figure 22.

Figure 22. Picture of ceramic filter showing the outlet holes where filtered water exits

The final design will implement a re-circulating flow within the feed water part of the final design. The water will be taken from the drum, using the existing Whirlpool pump from the original Duet components, into the reservoir tank, then filtered through the system, and re-introduced into the washer drum. A CAD model of the final design showing water flow through the system is shown in Figure 23 on p.24. The first filter housing includes three ceramic filters placed in parallel with the water flow to increase the filtration rate into the AC filter. This may be altered based on the testing in future work.

As previously mentioned, the first pump will circulate the feed water into the cross-flow ceramic filter housing. The cross-flow configuration will continue to re-circulate water back into the reservoir tank to remove all the dirt particles and detergent compounds that would clog the filter. The impurities left from the water will reside in the feed water loop until a flush is performed with a back-pulse, which will jar any particles clogging the pores of the ceramic filter.

Meanwhile, the filtered water will be pumped by the second pump into the activated carbon (AC) filter and into the washer drum for the next cycle of the load.

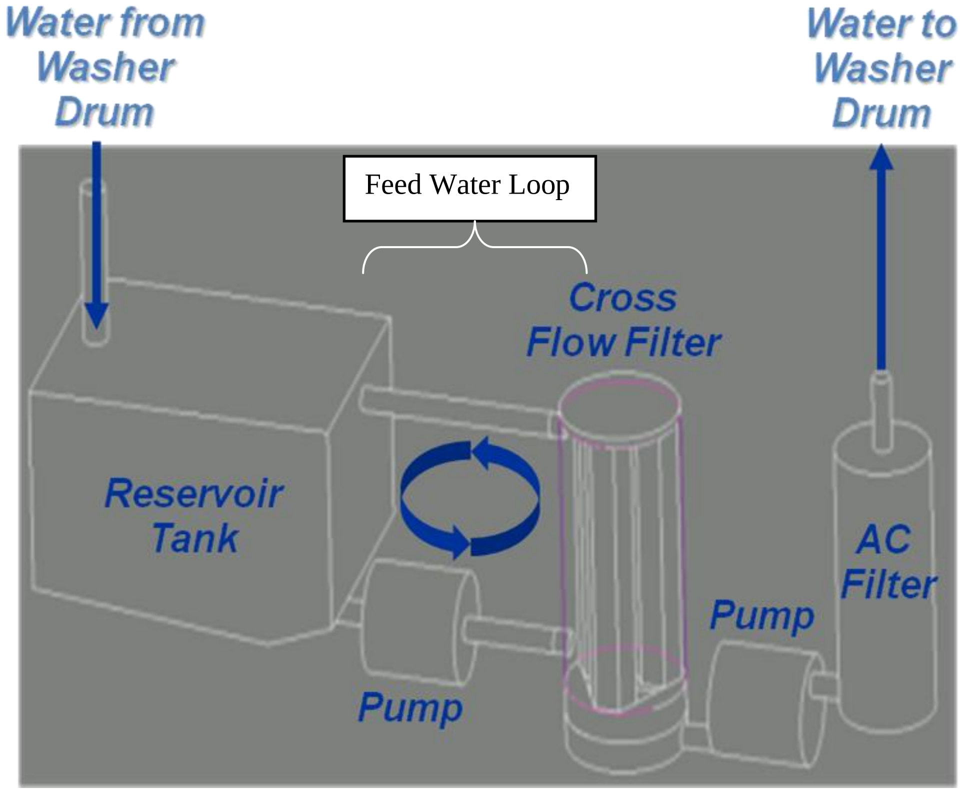


Figure 23. CAD model of the final design

Fluid dynamics analysis was performed to validate whether the ceramic filter would be an effective replacement for the PP filter from the prototype. Reynolds number, shown in Equation 3, was used to characterize the flow of the water through the system as laminar. The assumptions for this system include incompressible fluid, conservation of mass and momentum, and neglecting osmotic pressure due to enclosed system.

$$\mathrm{Re} = \frac{\rho \upsilon_s L}{\mu} << 1 \,, \qquad \text{[Equation 3]}$$

where ρ- density, V_s -mean fluid velocity, L -characteristic length, μ -dynamic viscosity

Since the density increases and the dynamic viscosity increases proportionally due to accumulating levels of dirt particulates and detergent, the Reynolds number calculated above, for the water, can be assumed as the same Reynolds number for the dirty solution. This allows us to assume laminar flow for the entire fluid system. Now that an analysis has been performed for the system fluid dynamics, Darcy's law will be used to characterize the flow of the water through the filters to understand how cross-flow ceramic filter compares to the PP and AC filters. Equation 4 on p. 25 will be used to characterize PP and AC filters and Equation 4 on p.24 will be used to characterize the pressure-driven membrane ceramic filter. Permeability for PP is $4.3\text{x}10^{-16}$ m^2 and for AC is $3\text{x}10^{-13} m^2$.

$$Q = \frac{-\kappa A \Delta P}{\mu L} \qquad \text{[Equation 4]}$$

where Q -total discharge, k –permeability, A -filter cross-sectional area, ΔP-pressure drop, μ - dynamic viscosity

$$J = \frac{\Delta P}{\mu(R_f + R_m)} \qquad \text{[Equation 5]}$$

where J -volumetric flux, R_f -fouling resistance, R_m -membrane resistance, ΔP-pressure drop, μ - dynamic viscosity

Using Equations 4 and 5, we find that the discharge through the PP filter is $5.97\text{x}10^{-12}$ m^3/s, the discharge through the AC filter is $4.17\text{x}10^{-9}$ m^3/s, and the discharge through the ceramic filter is $9.44\text{x}10^{-8}$ m^3/s. Therefore, by using Darcy's law, the discharge rate through the ceramic filter was found to be within one order of magnitude of the PP and AC filters, thus the ceramic filter is shown to be effective for the system. The analysis to obtain discharge through ceramic filter allowed the assumption that the rates are similar to the PP filter and that the time to filter the water would be similar for the final design and prototype.

To determine the material used for the piping and the filter housing of final design, CES software constraints were created. The constraints entailed a fixed diameter of the material, max. temperature of 40^oC, min. temperature of 25^oC, high strength to withstand pressure levels within the system, corrosion resistant, and a cost of less than $5 per pound. The material that would satisfy the above constraints and had the lowest cost was PVC. Thus for the piping and filter housings, PVC was implemented. See Appendix C.1 for additional information.

In efforts to minimize manufacturing costs, Boothroyd Dewhurst charts were generated to create a design that would minimize the number of parts and the ease of assembly. The final design will implement several snap-fits and will combine other components to minimize the total handling and insertion times. Snap-fits would be incorporated for the filter brackets that would allow for the brackets to be assembled into the system easily and with less time. Also the brackets and housing will be combined into one piece to minimize the number of parts and assembly times needed. With these design for assembly changes, the final design had a design efficiency of 44% compared to 10% in the original design. See Appendix C.2 for additional information.

Estimating the production volume of the Whirlpool Duet at 400,000 per year, the proposed water filtration would need to be mass produced to cover the US market. Using the CES manufacturing process selector, injection molding for thermoplastics was found to be the ideal process for the PVC components. The injection molding process allows for complex shaping that would be used for the piping and filter housing. To manufacture the ceramic filter, the constraints differed from that of PVC in physical and process characteristics and led to the process of ceramic extrusion. The initial costs of this process will be relatively high, however, the tool life and accuracy makes ceramic extrusion the best choice. See Appendix C.4 for additional information.

In addition to specifying the production methods and the materials for this filtration system, safety remains the foremost concern due its impact on market sales. Safety was taken into account in relation to the filtering process by performing a risk assessment on the filter types, housing, and piping. Failure modes and effects analysis (FMEA) was performed to identify the potential system failures and the resulting effects. The major concerns with the final design were the filter lifetime of the ceramic filter. Generally, the higher the risk priority number (RPN), the higher the risk for failure of the component. As a whole, the only component in the final design that was found to 100% fail was the AC filter, signifying a low-risk system to the consumer. See Appendix C.5 for additional information.

DISCUSSION

Due to the time constraint given much of the work on the project was rushed in order to complete a final functional prototype. As seen from the changes from our prototype to final design recommendation, one large difference is the first filter configuration. The prototype used a dead-end polypropylene filter, while the final design will incorporate a cross-flow ceramic filter and these polypropylene filters were chosen and used due to their availability. These filters were known to have a low lifetime and thus would not be feasible for the washing machine application. However, the polypropylene filters were used to prove the concept of the system. Also, the system was never implemented within the washing machine, thus the validation still needs to be done in terms of compatibility. If the project were to be done again, we would have done more extensive research on the cross-flow filters and had been able to buy a custom ceramic filter for use within the system. The system would have been incorporated with the Whirlpool Duet washer to see how the system would function under the actual conditions. Then the testing and validation would have proved the final design rather than just the concept of the system.

Testing methods were also limited due to our own knowledge and resources available to us. The validation approach was taken using only a blender and alkalinity tests that only gave us an idea in terms of how much detergent was being removed from the water. If the project were to be repeated, the testing would need to include the biological oxygen demand (BOD) and turbidity testing that would allow for a complete analysis of the water cleanliness of the filtered water.

The preliminarily research of this project’s work was developed by previous team and was not reliable. Much of this semester’s team spent time and money validating incorrect concepts from the previous semester. If the project was to be repeated, the project would begin with a larger scope and have room for more creativity and brainstorming.

With that said, the strengths of the system filtration concept can be seen in its versatility and customer-friendliness. The system is able to incorporate various filters yet still maintain the same cleaning performance and function. In addition, the components of the system are relatively low cost and readily available. Overall, the main weakness of the filtration concept as discussed in previous sections is the lifetime of the filters. This issue is addressed in the final ceramic cross-flow filter configuration (calculations shown in Final Design Description from p.21 to p.25).

CONCLUSIONS AND RECOMMENDATIONS

The Whirlpool Duet has been successfully redesigned and a prototype was created to validate the final design. Initial concept generation and selection lead the team to implement a filtration system into the washer that would filter the water from the output of the wash cycle for use in the rinse cycle. Testing was performed to provide a proof of concept for a filtration system composed of a polypropylene (PP) filter and activated carbon (AC) filter in series. This sequence of PP and AC filters satisfied most of the design requirements required for the filters. One important specification that was not met was the lifetime of the system due to clogging of the PP filter. To solve this problem the final design implements a ceramic cross-flow filter configuration. Table 3 below outlines the engineering specifications met by the prototype and the final design.

Sponsor Specifications	Engineering Targets	Prototype	Final Design
Water Reduction	75 % Reduction	Yes	Yes
Maximum Addition to Load Time	15 Minutes	No	Yes
Hot/Cold Rinse Cycle Allowance	T_{min}=25°C T_{max}=40°C	Yes	Yes
Clean Water	Target Turbidity = 5-20 NTU Alkalinity = 1.1-2.1 $^{mmol}/_{L}$ Blender Test = 0 mm foam height	Yes	Future Work
Robust System	6 month min time between maintenance	No	Yes
Space Requirements	System must fit in pedestal H 28 cm W 52 cm D 58 cm	Yes	Yes
Energy Consumption	Maximum increase of 10%	Yes	Future Work
Affordable	<$200/system	Yes	Future Work
No Leakage	0 L water/cycle leaks	Yes	Yes
Noise/Vibrations	No additional noise or excessive vibrations	Yes	Yes

Table 3. Engineering Specifications met by the prototype and final design filtration systems

In the future, more water quality testing should be performed. These tests include those that the team was not able to perform due to lack of resources as time such as biological oxygen demand (BOD) and turbidity testing. Additionally, more alkalinity testing should be performed to reduce the precision error in research. Research and development should be performed on ceramic cross-flow filters to ensure that the final design will satisfy all of the engineering specifications. Based on the current project progress, the team is unable to complete the final design fabrication and validation. Therefore, another ME 450 class group should should concentrate on testing and prototyping the ceramic cross-flow filtration of the final design.

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APPENDIX A. Quality Functional Diagram

Customer Needs	Customer Weights	Kano Type	Dimensions	Number of Parts	Total Cycle Time	Durability/Strength of Material	Filter Capability	Filter Material	Water Usage
Water Reduction	4		3	3				3	9
System Drain Time	3			1	3			3	
Hot/Cold Rinse Cycle Allowance	4					9	3	9	
Clean Water	4					3	9	9	
Robust Filters	3					9		9	
System Fits	2		9	9					
Affordable	3		3	9				9	
Easy to Manufacture	2		9	9		3			
No Leakage	4		3	3		3			1
	Raw score		69	90	9	93	48	147	40
	Scaled		0.469	0.612	0.061	0.633	0.327	1	0.272
	Relative Weight		14%	18%	2%	19%	10%	30%	8%
	Rank		4	3	7	2	5	1	6

Table A.1. Quality Functional Diagram (QFD) for the improved Whirlpool Duet washer system.

APPENDIX B - Additional Testing Results

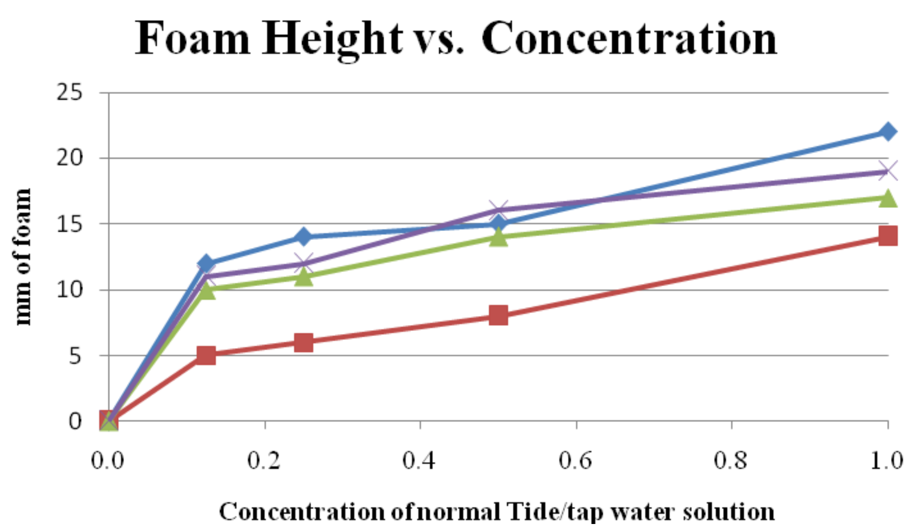

Figure B.1. Foam height (mm) vs. Concentration of detergent in the solution for various trials.

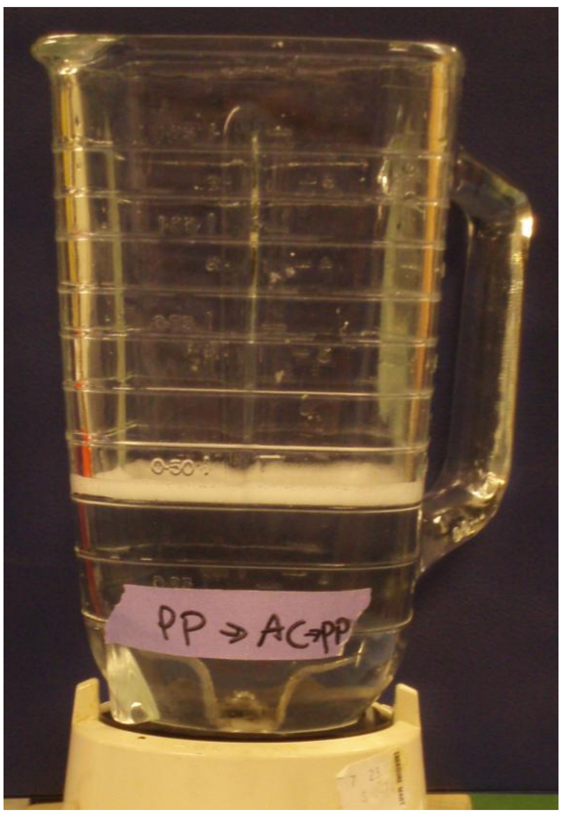

Figure B.2. Shows a foam test with the least amount of foam from Trial 6 in Table 4.

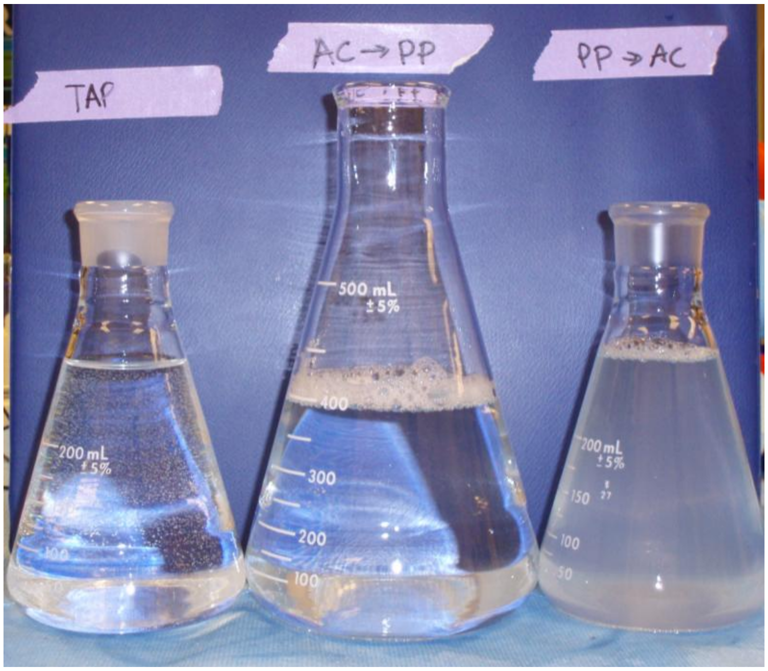

Figure B.3. Shows Trials 4 (AC→PP) and 5 (PP→AC) compared with tap water. Trial 4 can clearly be seen as similar to tap water turbidity.

APPENDIX C: Design Analysis of Prototype and Final Design

1. MATERIAL SELECTION

The two components from the final design that were chosen to be analyzed for material selection are the piping and the filter housing. The constraints for both of these components are similar because they are both part of the filtration system and must operate under the same conditions. CES software was utilized for material selection. The material index for both the piping and the housing is defined in Equation C.1. This index expresses that the strength is prescribed but that the cost should be optimized.

$$M = \frac{\sigma_y^{2/3}}{C_m \rho} \qquad \text{Equation C.1}$$

Where σ_y is the elastic limit, C_m is the cost per mass, and ρ is the density.

Piping The function of the piping is to move the water throughout the system. The objective for material selection is to minimize the cost. The following are the constraints on the material:

- Fixed diameter
- Maximum operating temperature of 110^{O}F
- Minimum operating temperature of 60^{O}F
- Strength
- Cost < $5/lb
- Durability (Corrosion)

The CES software helped to determine which materials satisfy the above constraints and the top five materials are:

- Poly Vinyl Chloride (PVC)
- Polyethylene (PE) (20-30% Long Glass Fiber, High Density)
- Polyphenylene Oxide/Polystyrene Alloy (PPO/PS) (15% Glass Fiber)
- Polybutylene (PB)
- Polyamide(PA) (Nylon) (Type 66, 40% Aluminum Flake)

We chose to use PVC as the piping material in the final design because the objective was to minimize cost and it was the cheapest of the five materials at 0.6495 – 0.7145$/lb.

Filter Housing The filter housings function is to aid in pushing the water through the filter. The objective for material selection is to minimize the cost. The following are the constraints on the material:

- Fixed Dimensions
- Maximum operating temperature of 110^{O}F
- Minimum operating temperature of 60^{O}F
- Cost < $10/lb
- Strength
- Durability (Corrosion)

The CES software helped to determine which materials satisfy the above constraints and the top five materials are:

- Poly Vinyl Chloride (PVC)
- Polyethylene (PE) (20-30% Long Glass Fiber, High Density)
- Polyphenylene Oxide/Polystyrene Alloy (PPO/PS) (15% Glass Fiber)
- Polybutylene (PB)
- Polyamide(PA) (Nylon) (Type 66, 40% Aluminum Flake)

We chose to use PVC as the filter housing material in the final design because the objective was to minimize cost and it was the cheapest of the five materials at 0.6495 – 0.7145$/lb.

2. DESIGN FOR ASSEMBLY
Using the manual handling and manual insertion codes we generated a Boothroyd and Dewhurst DFA Chart for the original filtration system design as seen in Chart C.1.

DFA Chart for Original Design:

	1	2	3	4	5	6	7	8
Part Name	Part ID	Number of Times	Manual Handling Code	Handling Time per Part	Manual Insertion Code	Insertion Time per Part	Op. Time (2) x [(4)+(6)]	Theoretical Min. Parts
Plexiglass base	1	2	20	1.8	08	6.50	16.6	2
Plexiglass support	2	2	20	1.8	08	6.50	16.6	2
Connecting bracket	3	2	30	1.95	18	9.00	21.9	0
Base bracket	4	2	30	1.95	06	5.50	14.9	0
Filter bracket	5	2	20	1.8	06	5.50	14.6	2
0.25" Screws	6	20	06	2.17	39	8.00	203.4	0
Lock washers	7	20	06	2.17	31	5.00	143.4	0
Filter housing cap	8	2	30	1.95	06	5.50	14.9	2
Filter house	9	2	83	5.6	39	8.00	27.2	2
Polypropylene filter	10	1	00	1.13	22	6.50	7.63	1
Activated carbon filter	11	1	30	1.95	22	6.50	8.45	1
Rubber stoppers	12	3	00	1.13	00	1.50	7.89	1
0.75" Inlet tube	13	2	05	1.84	39	8.00	19.68	2
0.75" Outlet tube	14	2	05	1.84	39	8.00	19.68	2
TOTALS:		Parts: 63					Time: 536.83	Min. Parts: 17
				Design Efficiency: 9.50%				

Chart C.1. Boothroyd and Dewhurst DFA chart for the original design filtration system prototype

The original design will take an estimated 8.95 minutes to assemble and the theoretical minimum number of parts is 17 out of 63; this yields a design efficiency of 9.50%.

To eliminate components and improve the efficiency of the original design we utilized the test for minimum number of parts as listed below:

1. Do parts move relative to each other?
2. Must these parts be made of different materials?
3. Would combination of these parts prevent assembly or disassembly of other parts?
4. Has servicing of the assembly been adversely affected?

If the answer to all the questions above is "no", then we considered eliminating the part. Overall, we eliminated the following seven parts:

Part Name	Part ID	Method of Elimination
Plexiglass support	2	Combined with part 1
Connecting bracket	3	Combined with part 1
Base bracket	4	Introduce snap fit
0.25" Screws	6	Introduce snap fit
Lock washers	7	Introduce snap fit
Polypropylene filter	10	Replaced with cross-flow ceramic filter
Rubber stoppers	12	Replaced with cross-flow ceramic filter

Table C.1. List of parts eliminated from the prototype to improve the assembly efficiency

First off, the plexiglass support and base could be combined and manufactured as one injection molded piece that would meet the functional needs of the previous two components. By combining these components, both the plexiglass support and connecting bracket parts would be eliminated, thus leaving only the handling and insertion time of the plexiglass base.

The screws and washers were replaced with a snap fit design that would allow for easy handling and assembly. For snap fits, we ensured that the component material, geometry limitations, and load constraints are all suitable for the redesign.

Lastly, the polypropylene filter would be replaced with a cross-flow ceramic filter for the final design. Though the implementation of the ceramic filter was more for increased filter performance rather than to improve assembly efficiency, the ceramic filter would in fact improve assembly efficiency by reducing the number of rubber stoppers that are needed for the filters since the cross-flow filtration requires a different set-up than the original dead-end polypropylene filters.

Provided the design modifications from above, we developed a Boothroyd and Dewhurst DFA chart for the redesigned filtration system design as seen in Chart C.2.

DFA Chart for Final Design:								
	1	2	3	4	5	6	7	8
Part Name	Part ID	Number of Times	Manual Handling Code	Handling Time per Part	Manual Insertion Code	Insertion Time per Part	Op. Time (2) x [(4)+(6)]	Theoretical Min. Parts
One-piece plexiglass brace	1	2	30	1.95	30	2.00	7.9	2
Filter bracket	2	2	20	1.8	31	5.00	13.6	2
Filter housing cap	3	2	30	1.95	06	5.50	14.9	2
Hinged filter house	4	2	30	1.95	30	2.00	7.9	2
Cross-flow ceramic filter	5	1	00	1.13	22	6.50	7.63	1
Activated carbon filter	6	1	30	1.95	22	6.50	8.45	1
Rubber stoppers	7	1	00	1.13	00	1.50	2.63	1
0.75" Inlet tube	8	2	05	1.84	39	8.00	19.68	2
0.75" Outlet tube	9	2	05	1.84	39	8.00	19.68	2
TOTALS		Parts 15					Time 102.37	Min Parts 15
					Design Efficiency =			**44.00%**

Chart C.2. Boothroyd and Dewhurst DFA chart for the final design filtration system

The final design will take an estimated 1.70 minutes to assemble and the theoretical minimum number of parts is 15 out of 15; this yields a design efficiency of 44.00%.

3. DESIGN FOR ENVIRONMENTAL SUSTAINABILITY

PVC was the only material chosen for both the filter housing and the piping in the material selection part, but ceramic for the filter in the final design will be the other material used in this environmental sustainability analysis. The amounts of materials that will be needed in the final design are 2-5 lbs of PVC and 1-3 lbs of ceramic. For sustainability analysis we used 5 lbs (2.268kg) of PVC and 1 lbs (0.454kg) of ceramics. The closets materials available in SimaPro 7 were PVC Pipe E and Ceramics ETH U. Figure C.3 on p.36 shows a total mass comparison for the two materials. It is obvious from this graph that PVC has a much greater environmental impact. This is not surprising since PVC is a thermoplastic and made from unnatural materials while ceramic is much more natural in composition.

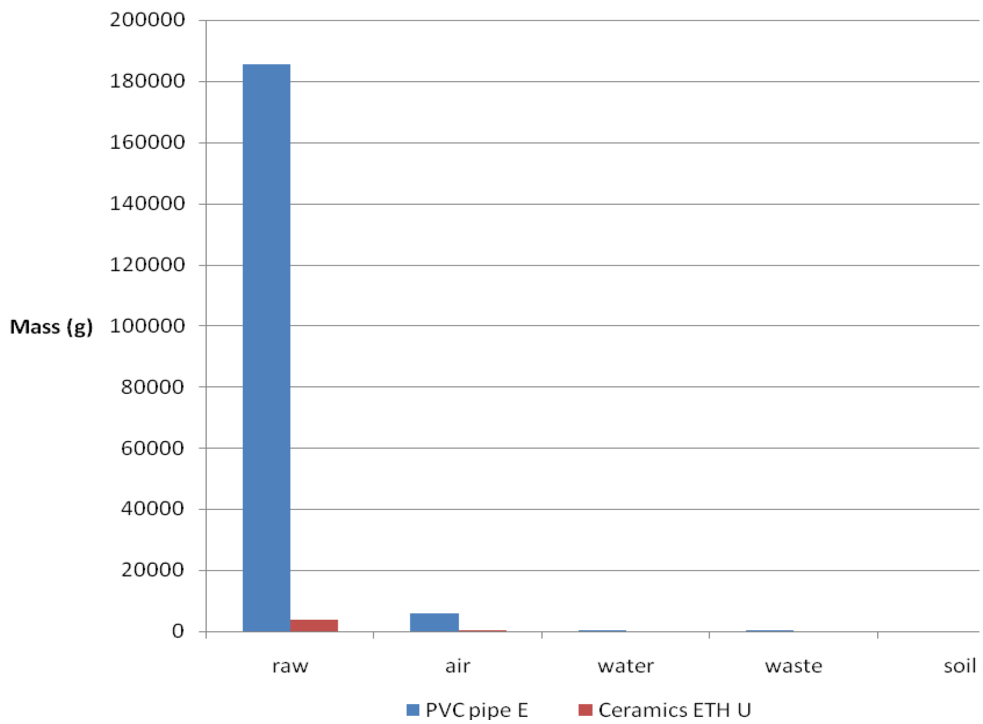

Figure C.3. Total mass comparison for materials of PVC and Ceramic of final design

Figure C.4 shows the relative impacts on disaggregated damage categories. This graphs implies that PVC is has a greater environmental impact since it shows PVC with a greater percentage in seven of the ten categories. Ceramic is has a greater impact than PVC in the radiation, ozone layer, and land use categories. The PVC doesn't even rank in these categories.

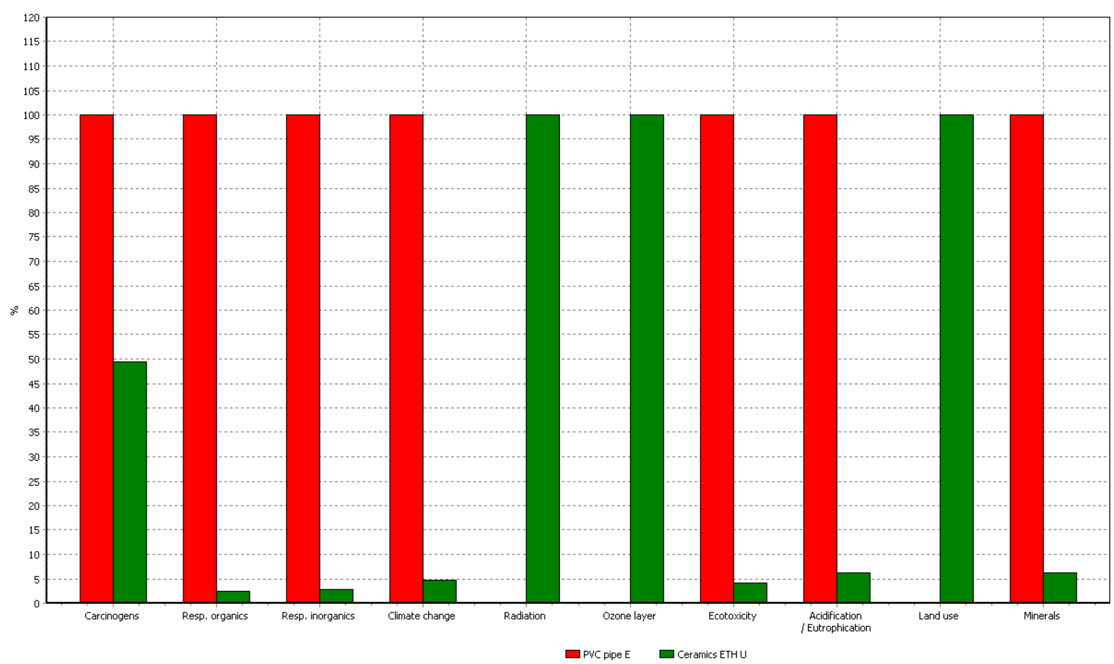

Figure C.4. Characterization comparison for materials of PVC and Ceramic of final design

Figure C.5 gives the normalized score of each material on human health, ecosystem quality, and resources. This graph also shows PVC having a greater environmental impact. PVC has a larger normalized score for all categories and ceramics are hardly a factor in any category.

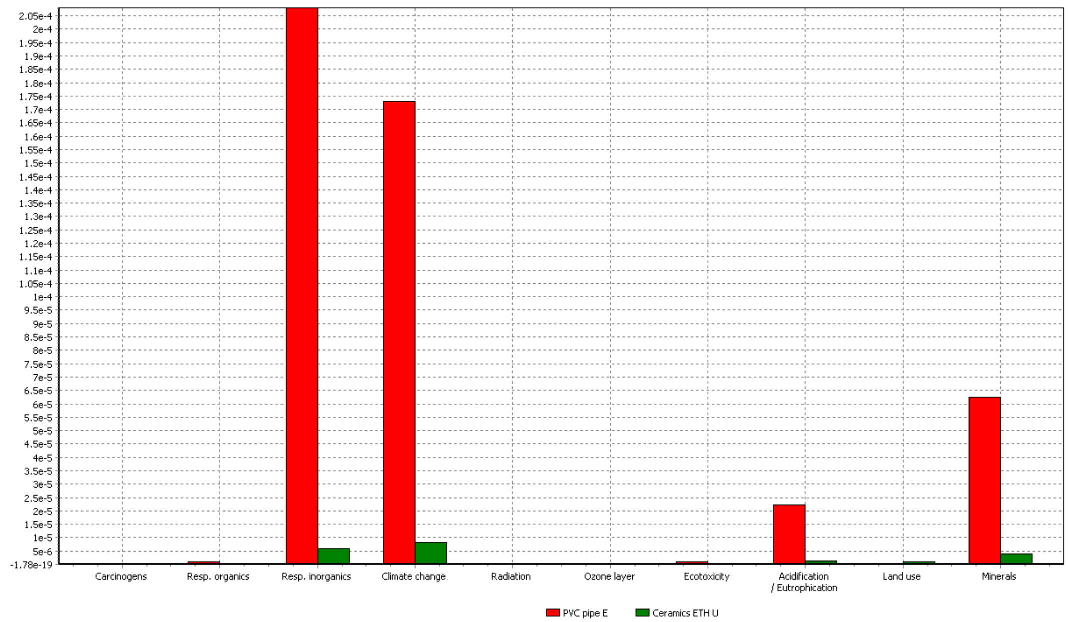

Figure C.5. Normalized comparison for materials of PVC and Ceramic of final design

Figure C.6 on p.38 shows a single score comparison of both materials in "points". Ceramics has about 10 points while PVC has 230 points. This is in agreement with the other methods of comparison, the indicating that PVC has a great environmental impact that ceramic.

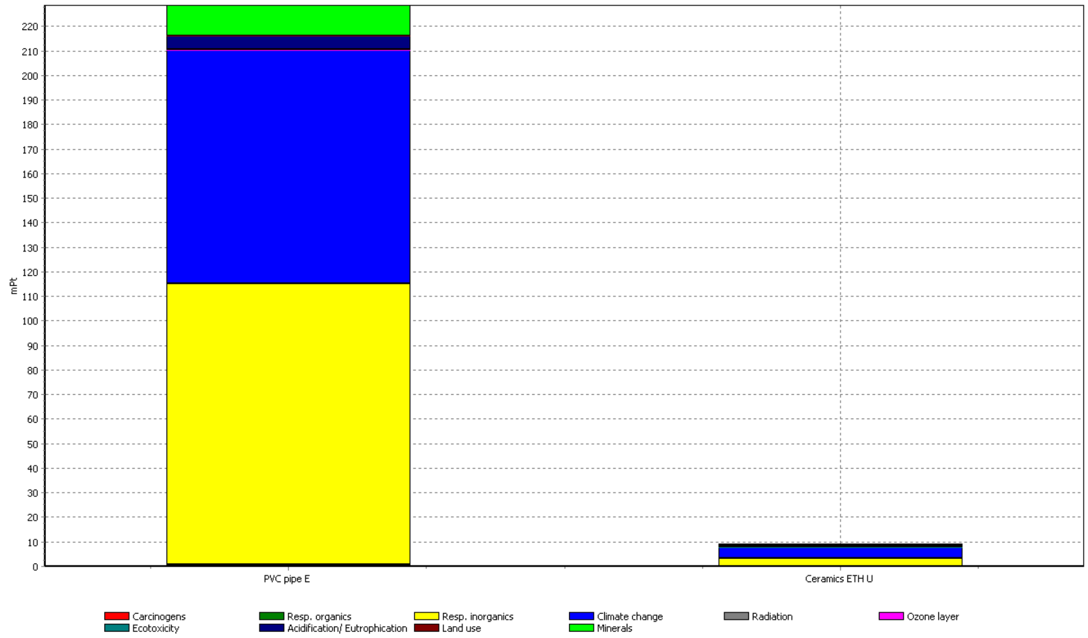

Figure C.6. Single score comparison for materials of PVC and Ceramic of final design

All the comparisons made in SimaPro show that the PVC used in the final design has a greater environmental impact compared to the ceramic material of the filter in the final design. When considering the fill life cycle of each material in the final design, it is clear that PVC will once again be the material with great environmental impact. PVC is recyclable and the ceramic is not, but at the end of the washer's lifetime the materials will not be harvested out before the washer is disposed. Since both materials are going to end up in a landfill the PVC will have a greater environmental impact even after the use stage because PVC is not biodegradable like ceramic. Based on these comparisons and analysis it might be smart to consider a different material for the piping and housing, other than the PVC. Since, ceramics have such a small environmental impact we will continue to use them in the final design, also they are specific to the filtration aspect of the design and therefore, the filter material cannot easily be changed without first testing to see what materials will be able to filter according to the design specifications.

4. MANUFACTURING PROCESS SELECTION

Estimated production volume for the modified Whirlpool Duet is 400,000 per year. This value was based by using the current USA population and number of households from the US Census Bureau as 303.4 million with approximately 110 million households. The production volume may increase or decrease within the first year depending on the washer market, the customer demand for a highly water-efficient washing machine, and the increase in the price of the Whirlpool Duet with what customers are willing to pay. We suggest a market survey to prospective customers to gain a better perceptive of the number of modified washers to produce. This would greatly decrease losses.

Injection molding is recommended to mass manufacture the filter housing of the system. As shown in Material Selection, PVC was decided for the material of the piping and the filter housing based on operating conditions. The CES Manufacturing process selector was used with the following design constraints for the filter housing to find that injection molding (for thermoplastics) was the ideal choice:

- Shape attributes: circular prismatic, non-circular prismatic, solid 3-D and hollow 3-D
- Physical attributes: less than 0.01 in. tolerances, 5 in. thickness
- Process characteristics: primary shaping process, forming a discrete product
- Cost of model: Relative cost index (per unit) max. $20, long lifetime of tools

The injection molding process allows for complex shaping of a product, i.e. varying angles, thickness, or hollow components. The PVC piping manufacturing process was found by entering the following constraints into the CES Manufacturing process selector:

- Shape attributes: solid 3-D, hollow 3-D
- Physical attributes: tolerances of 0.01 in.
- Process characteristics: primary shaping process, discrete product

Reviewing the possible choices for the pipe manufacturing process, injection molding was decided as the best choice due to the shape of the pipes, the threading of the pipe ends, and the relatively long lifespan of the tools necessary for the manufacturing process. Since both the filter housing and the piping are composed of PVC, a thermoplastic, a third system component was selected. The following are constraints for the manufacturing of the ceramic filter:

- Shape attributes: circular prismatic, non-circular prismatic
- Physical attributes: 1-3 lbs. mass, less than 0.001 in. tolerance, section thickness 3-5 in.
- Process characteristics: primary shaping process, continuous (to be cut later)

The selected mass manufacturing process yielded several possibilities. However, ceramic extrusion was preferred due to the choice of alumina for the cross-flow filter, and the typical uses of the process for creating uniform cross-sections in bars and rods, yielding a low-porosity component. The initial tooling costs may be slightly high, but tool life is several years before replacement. In addition, to the extrusion process, a furnace is necessary to sinter the ceramic once the extrudate is cut to length (9 in.). Lastly, a milling process through the center of the ceramic extrudate is necessary for the water to permeate.

5. DESIGN FOR SAFTEY

This design for safety includes components only relative to the filtering process, i.e. filter types, filter housings, and pipes between filter housings. Group 12 focused on the fluid flow through the system, creating the reservoir tank, and pump selection. Table C.2 and Table C.3 show failure modes and effects analysis (FMEA) and the risk assessment for the prototype and the final design, respectively. The FMEA component of the table focuses on identifying potential system failures and the potential effects of these system failures. In addition, the purpose of FMEA is to generate recommended actions to reduce the possibility of failure occurrence. Risk assessment is the identification of hazards/risks of operating the system and how to reduce such hazards. This may include automating a light when a replacement is necessary or automating the self cleaning process for the final design.

Product Name: Modified Whirlpool Duet. Prototype									
Subsystem: Filtration components									
Part # & Function	**Potential Failure Mode**	**Potential Effects of Failure**	Severity (S)	**Potential Cause of Failure**	Occurrence (O)	**Current Design Tests**	Detection (D)	**Recommend Actions**	**RPN: (SxOxD)**
5 µm PP Filter; General Electric, FXWPC	Clogging, pore size defect, defective rubber seal	Water flow stops between the filters, ineffective water filtration	8	Build up of dirt particles	10	Lifetime test, pressure relative to clogged filter	2	Change the filter material: the final design	160
Filter Housing; General Electric, GXWH04F	Leaking, material yield, loose cover	Lose of pressure, decrease filtering effectiveness, water damage	3	Not tightly closed cover, high pressure build-up, pipes not screwed into in/out-let sufficiently	2	Test general ability to withstand possible pressures in the system	2	Check the connections, tighten all pipe fittings and plate	12
Activated Carbon Filter; General Electric, FXSVC	Clogging	Filtering process is rendered ineffective (lifetime approx. 6 months)	8	Adsorption of filter with organic impurities is at the maximum	10	Lifetime test, water flow testing	2	None, since this filter type is necessary	160
0.75" piping PVC; Charlotte Pipe, CTS 12005 0600	Leaking, cracking, material yield	Pressure lose, water lose, water damage	3	High pressure, not fully screwed together	2	Test ability to withstand temperature and pressure	2	Tighten pipe connections	12

Table C.2. Risk assessment for the prototype of the filtering system

The major risks found from the prototype assessment, Table C.2, relate to the ability of the filters in the filtration system. The values of 160 for risk priority number (RPN) show that the system will fail for sure. The risk to the user or a human is relatively minimal as long as the filters have a setting to notify filter cartridge replacement. The major problem that may arise is a build-up of pressure in the polypropylene filter, which may cause the system to explode. This risk may be greatly reduced by a pressure release valve or a simple pressure meter that stops the cycle when the filter is clogged. When replacing the filters, the customer must be sure to press the pressure-release button on the housing to keep from being sprayed with water.

In order to reduce the risk of failure for the filter housing and the piping, the manufacturer must be sure to fully fasten the parts of the system together to ensure no leakage. The RPN for filter housing and piping components registers as highly unlikely as long as they are properly fastened. This is true as long as the PVC material for the filter housing and the piping is designed for the high temperatures found in the washer water and the pressure that may arise to push the water through the dead-end polypropylene and activated carbon filters.

Product Name: Modified Whirlpool Duet. Final Design											
Subsystem: Filtration components											
Part # & Function	**Potential Failure Mode**	**Potential Effects of Failure**	**Severity (S)**	**Potential Cause of Failure**	**Occurrence (O)**	**Current Design Tests**	**Detection (D)**	**Recommend Actions**	**RPN: (SxOxD)**	**Revised Occurrence**	**Revised RPN**
Ceramic (α-Alumina) Cross-flow Filter	Clogging, discontinuous pore size	Water flow stops between the filters, ineffective water filtration	8	Build up of dirt particles on the feed side of the PVC filter housing	10	Lifetime test, pressure relative to clogged filter	2	Set up a self cleaning cycle for the washer to be performed after a set number of loads	160	2	32
PVC housing for the cross-flow ceramic filter as shown in Final Design	Leaking, material yield, loose cover	Lose of pressure, decrease filtering effectiveness, water damage	3	Cover plate not tightly screwed, material defects, loose pipe connections	2	Test general ability to withstand possible pressures in the system	2	Check the connections, tighten all pipe fittings and plate covers	12	-----	-----
Activated Carbon Filter; General Electric, FXSVC	Clogging	Filtering process is rendered ineffective (lifetime approx. 6 months)	8	Adsorption of filter with organic impurities is at the maximum	10	Lifetime test, water flow testing	2	Additional lifetime analysis	160	-----	-----
Filter Housing; General Electric, GXWH04F	Leaking, material yield, loose cover	Lose of pressure, decrease filtering effectiveness, water damage	3	Not tightly closed cover, high pressure build-up, pipes not screwed into in/out-let sufficiently	2	Test general ability to withstand possible pressures in the system	2	Check the connections, tighten all pipe fittings and plate covers	12	-----	-----
0.75" piping PVC; Charlotte Pipe, CTS 12005 0600	Leaking, cracking, material yield	Pressure lose, water lose, water damage	3	High pressure, not fully screwed together	2	Test ability to withstand temperature and pressure	2	Tighten pipe connections	12	-----	-----

Table C.3. Risk assessment for the final design of the filtration system

The final design resolves this issue of lifetime with the primary dirt filter by incorporating a self cleaning system with a cross-flow ceramic filter. As shown in Table C.3, the incorporation of a backflow or a self-cleaning system allows for a reasonable RPN value of 32. In addition to the self-cleaning cycle, the filter lifetime may be increased to up to 10 years. The activated carbon filter still maintains a RPN of 160, which signifies a definite failure in filtration, requiring a replacement in approximately 6 months. Recommended action to reduce the risk of filtration failure is to set a self-cleaning cycle after a specific number of loads, and to set a light for activated carbon filter replacement.

The major risks that arise from the final design system are clogging. This may generate a pressure build-up, and a sharp decrease in filtered water flow rate into the drum. In the final design, the risk for pressure build up in the system is greatly reduced by using the cross-flow filter with a feed and a permeate side. As long as water can flow through the reservoir tank, as shown in the final design CAD, the risk to the user is minimal. This assessment also showed that the manufacturer must fasten all filter housing caps and piping into the system to prevent leaking and possible water damage to the user house. This will keep the filter housing and piping within a no-failure RPN value.

The prototype and the final design risk assessment in Table C.2 and C.3 show a relative low possibility for failure of the filter housing and the piping components, but a definite failure for the filtration system over a period of time. The prototype system has a definite failure for both filters, and a possible hazard of pressure build up in the system, which may lead to system explosion. Neither prototype nor final design can have zero risk due to the possibility of defects in system components: filters, filter housing, piping, threading, and ceramic filter pore size. The ability to maintain zero risk pertains to a system that will never fail and have no hazard to the user. Such a risk is unreasonable, since defects are a constant issue with mass manufacturing. Therefore, companies often aim for a reasonable likelihood for no failure in large-scale manufacturing, and a warranty is provided with the product based on the chance for failure.

APPENDIX D –Bill of Materials

PROTOTYPE						
Item	**Quantity**	**Source**	**Catalog Number**	**Cost ($)**	**Contact**	**Notes**
0.75" Pipe	1	Charlotte Pipe	CTS 12005 0600	3.12 ea.	Home Depot	Only sold by 10', need to cut.
CPVC Primer	1	OATEY	307560	3.49 ea.	Home Depot	Use for housing connections.
CPVC Cement	1	OATEY	311290	4.49 ea.	Home Depot	Use for housing connections.
0.75" elbow joints	3	---	C470734	0.34 ea.	Home Depot	Use before and after housing.
0.75" Slip Male Thread Adapter	4	---	C470434	0.39 ea.	Home Depot	Glue with piping between housing.
AC and PP Filters	1	General Electric	FXSVC	41.39 ea.	Home Depot	First and second stage filters.
Filter Housing	2	General Electric	GXWH04F	16.49 ea.	Home Depot	---
Tide HE	1	TIDE	---	6.99 ea.	Kroger	Liquid 2X concentration formula.

Table D.1. Bill of materials for components in filtration system of the prototype

FINAL DESIGN						
Item	**Quantity**	**Source**	**Catalog Number**	**Cost ($)**	**Contact**	**Notes**
0.75" Pipe	1	Charlotte Pipe	CTS 12005 0600	3.12 ea.	Home Depot	Only sold by 10', need to cut.
CPVC Primer	1	OATEY	307560	3.49 ea.	Home Depot	Use for housing connections.
CPVC Cement	1	OATEY	311290	4.49 ea.	Home Depot	Use for housing connections.
0.75" elbow joints	3	---	C470734	0.34 ea.	Home Depot	Use before and after housing.
0.75" Slip Male Thread Adapter	4	---	C470434	0.39 ea.	Home Depot	Glue with piping between housing.
Ceramic Filter	1	N/A	N/A	N/A	N/A	---
AC Filter	1	General Electric	FXSVC	25.00 ea.	Home Depot	Second stage filter.
Filter Housing	2	General Electric	GXWH04F	16.49 ea.	Home Depot	---
Tide HE	1	TIDE	---	6.99 ea.	Kroger	Liquid 2X concentration formula.

Table D.2. Bill of materials for components in filtration system of the final design

TEAM MEMBER BIOGRAPHIES

Erica Grysban was born in Ann Arbor and raised in Wayne, Michigan. In May, 2004 she graduated from Wayne Memorial High School. In September of 2004 she began attending the University of Michigan and will be graduating in April, 2008 with a B.S. in Mechanical Engineering. Erica chose mechanical engineering because she enjoys problem solving and fixing things. She has spent the summers of her college career as a controls engineering intern at the braking systems and component supplier ADVICS North America in Plymouth, Michigan. After graduation Erica hopes to become a full time engineer at ADVICS, which would keep her close Ann Arbor and family and friends in the metro Detroit area. In her free time Erica enjoys reading, running, golfing, watching college football, and spending time with her family.

Gabriel Pak is a 21 year old undergraduate student at the College of Engineering in the University of Michigan studying mechanical engineering. He was born in Hong Kong and soon after moved to Toronto, Ontario in Canada. There he began his primary education and moved to Ann Arbor, Michigan where he would finish his primary and secondary education and entered the University of Michigan. Gabriel first received interest in mechanical engineering through his passion for sports, especially ice hockey. He entered the College of Engineering with little background in the field and knowing only that he thrived in math and sciences and enjoyed problem solving. And wanting to tie in his passion for sports with his gifts in problem solving, Gabriel pursued a degree in mechanical engineering with hopes of working in the sporting equipment field in designing new equipment that would enhance the performance of athletes as well as lower costs of equipment to provide better equipment at more affordable prices. Today, Gabriel has changed his pursuits to more humanitarian work in wanting to use the education and gifts he has received in engineering to help those in developing countries to improve the standard of living or to even save life if given the opportunity. He hopes that even through this experience working with Whirlpool washing machines to improve eco-efficiency and sustainability will be an excellent way to improve his background to be used for work in the future.

Merry Shao was born in Ann Arbor, MI. She moved around quite a bit due to her parents graduating from grad school and getting new jobs, etc. In fact, she has moved around 16 times. However, she ended up back in Ann Arbor where she went to high school at Ann Arbor Huron High School. She then started school at the University of Michigan, College of Engineering in fall of 2004. She chose to go into mechanical engineering because of the broad aspect of the field. Her favorite topics covered in mechanical engineering were fluid mechanics and heat transfer. In the future, she plans on getting a job, a masters degree, having a family, and volunteering. She loves to run and has completed 2 marathons. Her goal is to complete 30 marathons by the time that she is 30 years old. Additionally, she likes to rock climb, play the violin, hike, mountain bike, camp, and travel. She has visited 12.5% of the world and plans on visiting 30% of it by the time she is 30 years old. Volunteering has always been a huge part of her life and she plans on being part of Engineers Without Borders when she graduates and also plans on participating in the Peace Corps once she retires.

Leonithas Volakis was born in Ann Arbor, Michigan. He graduated from Ann Arbor Huron High School in 2004. He is currently working towards a B.S.E. in Mechanical Engineering at the University of Michigan. He will graduate in the fall of 2008. The reason for his interest in Mechanical Engineering is the broad applications and solid foundation in fundamental engineering topics that the program offers. In the future, Leo Volakis' goal is to attend Medical School and apply this engineering knowledge in the field of Orthopedic Research and Surgery. His interest in this project is to gain a different perspective on the future of energy and material reduction devices, due to their increasing demand and necessity. Leo enjoys snowboarding, playing water polo, swimming, soccer, football, and volunteering at the UM hospital. He also hopes to volunteer for Peace Corps later in his life once he graduates from Medical School.