FIB-LESS!

The Household Washing Machine Filtration Device for Microfibers

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Table of Abbreviations

℃	Degrees Celsius
γ	Specific gravity [N/m²]
f	Friction factor
ϱ	Density [kg/m³]
π	Pi constant
μ	Fluid viscosity [Pa*s]
ν	Kinematic viscosity [m²/s]
A	Area [m²]
ABS	Acrylonitrile-Butadiene-Styrene
CAD	Canadian Dollars (currency)
CEC	Canadian Engineering Competition
CSIRO	Commonwealth Scientific and Industrial Research Office
D	Diameter [m]
ft	Feet (or foot)
g	Gravity [m/s²]
GE	General Electric
GPM	Gallons per Minute
h_f	Head loss [m]
in	Inch
k	Permeability [m²]
kg	Kilograms
l	Length [m]

L	Litre
LED	Light-Emitting Diode
LEED	Leadership in Energy and Environmental Design
m	Meter
min	Minutes
N	Newtons
p	Hydrostatic Pressure [Pa] or [N/m²]
P	Pressure [Pa]
Pa	Pascals
PVC	Polymerized Vinyl Chloride
Q	Flow rate [gallons/minute] or [L/s] or [m³/s]
QEC	Quebec Engineering Competition
r	Radius [m]
Re	Reynold's Number
s	Seconds
UNEP	United Nations Environment Programme
US	United States of America
USD	United States Dollar (currency)
V	Velocity [m/s]
w	Width [m]
z	Elevation [m]

Executive Summary

Synthetic textiles release microplastic fibres during a washing cycle. As with all plastics, their decomposition can take thousands of years. Due to the lack of current industry standards, both in washing machine manufacturing and in wastewater treatment plants, these microfibres have become ubiquitous in our waterways and are being ingested by marine wildlife. Consequently, they are bioaccumulating in the food chain, thus causing harmful chemical and physical effects on ecosystems and living beings worldwide. To mitigate this perpetuating global issue and given several social, environmental, technical, and economic concerns, an award-winning filtration device for microfibers called Fib-Less! has been developed by a group of Bioresource Engineering students at McGill University. The user can easily install Fib-Less! to the end of their household washing machine drain pipe, addressing the problem at the source. Using an innovative technology, the fibres are filtered and collected within the device, thus allowing households to capture their fibre resources with little effort. This provides a guilt-free solution to the increasing trend of 'fast fashion'. Capturing microfibers is the purpose of the device, but it is also the team's vision to ensure their collection and repurposing. In attaining these goals, the users will be encouraged to participate in local and national upcycling programs. The proposed solution instantaneously addresses the problem and alleviates the perpetuation of microfiber pollution around the world.

1.0 Introduction

Synthetic materials, including polyester, rayon, spandex, and fleece, which make up 60 percent of all clothing articles around the world, are composed of petroleum-based, plastic microfibers (Salvador *et al*., 2017). These fibers range between 50 and 5000 microns in size and, unlike natural fibers, take hundreds of years to degrade due to the nature of their composition (Salvador *et al*., 2017). This becomes an issue during a wash cycle, when synthetic clothes release their microplastic fibers, which then persist in marine ecosystems (Boucher & Friot, 2017). The physical agitation and conditions during a cycle, as well as the addition of detergents and other chemicals into the washing load work simultaneously to weaken the textile fabric, damaging the molecular chain and reducing the strength of the bonds holding the polymer together, thus causing an inevitable release of microfibers (Browne *et al*., 2011; De Falco *et al*., 2017; Salvador *et al*., 2017).

The rate of synthetic textile degradation and microfiber release is contingent on multiple factors related to (1) the washing conditions and inputs and (2) the garments being washed. In the first case, the effects of cycle conditions – including the duration, temperature, and spin behaviour impact – and the washing machine inputs – such as type and amount of detergent used – on garment degradation have been tested in recent years, with results often conflicting.

Generally, higher temperatures are associated with increased fiber release, especially with the addition of detergents (Salvador *et al*., 2017). In fact, after determining that detergent had the most significant effect on the microfibers released relative to varying cycle durations and wash temperatures, Hernandez, Nowack, and Mitrano tested the impact of different amounts and types of detergent used in washing. The use of detergent corresponded to a release of 0.1 mg fibers/g textile washed, while no detergent was associated with 0.025 mg fibers/g fibers. Despite this, the amount of detergent used did not generate significant differences in the results, nor did the type of detergent between liquid or powder (Hernandez, Nowack, & Mitrano, 2017). Alternatively, a study by De Falco *et al*., where the type and concentration of detergent varied, demonstrated that powdered detergents had higher rates of microfibers released relative to liquid detergents. The addition of detergent reduced the overall microfiber release as well (De Falco *et al*., 2017). Researchers attributed this to the fact that surfactants found in detergent generate foam, thus acting as a cushion and minimizing the rubbing and agitation of the clothes. The surfactant also adsorbs to the surface of the fibers, reducing friction between the latter and their subsequent damage and release (De Falco *et al*., 2017). Their study also concluded that depending on the washing conditions, a typical 5kg load of laundry can release as many as 6 million microfibers (De Falco *et al*., 2017).

In the second case, the types of synthetics being washed also have a part in the number of microfibers being released per article of clothing and per wash. A study by Napper and Thomas compared the release of microplastics from three different types of fabric: polyester-cotton blend, polyester, and acrylic. With the addition of no detergent and a load size of 6kg, the polyester cotton blend released the least amount of microfibers, with approximately 137 951 microfiber fragments released. This is compared to 496 030 particles released from the polyester wash cycle, and 728 789 from the acrylic wash cycle (Napper & Thompson, 2016). On the other hand, a study by Browne *et al*. which polyester blankets, fleeces, and shirts, found that all samples released more than 100 microfibers per liter of effluent, and more than 1900 microfibers could be released from just one garment during one washing cycle. Pirc *et al*. also investigated microfiber release, this time laundering 6 brand new fleece blankets, all of the same type, over multiple washing cycles. They determined that the first wash emitted significantly more microfibers than consequential washes, for all blankets (Pirc *et al*., 2016). The actual quantitative amount emitted in this first wash varied between the samples however, with some producing much more than others. This was attributed to varying initial conditions, at the time of purchase, and differences between the fibers of the blankets themselves. While comparing results with the washing of an old fleece blanket, researchers concluded that the amount of fiber release decreases with the number of wash cycles (Pirc *et al*., 2016). Finally, De Falco *et al*. evaluated the combined effect of material release for woven polyester, knitted polyester, and woven polypropylene, with varying washing conditions for time, temperature, mechanical action, and water hardness. They determined that woven polyester produced the highest microfiber emissions, which was true for different additions of detergents (De Facto *et al*., 2017). Later, softener was also added to the wash, which resulted in significantly lower microfiber emissions from the polyester. Overall, they concluded that all parameters examined (duration, temperature, mechanical action, and hardness), caused increases in the microfiber pollution of the garments (De Facto *et al*., 2017).

As it stands, the many discrepancies between the results and conclusions of the studies can be attributed to the material's types and number of times washed, as well as the conditions and inputs in the washing machine. Different models of machines also have different characteristics, varying in the amount of water used, the speed of the spin cycle, discharge rate, and water temperatures. There are no standard testing or sampling conditions when it comes to these parameters. Furthermore, the size of the mesh used for filtering out microfibers for analysis, as well as the filtration method change the amount and type of microfibers caught in the sample. As these methods varied, as did results from one study to another as well. To improve research methods and to create a more reliable knowledge base, such standards would have to be implemented in the testing for microfibers and the studies of the emissions from different textiles subjected to different conditions. Such studies are important to this project, as the type and quantity of fibers produced will affect the necessary parameters for a potential microfiber filter.

Despite the uncertainty surrounding the exact degradation rate of a synthetic textile, released microplastic fibers will flow through municipal drainage systems and into waterways without hindrance. This is due to the current lack of industry standards for washing machine and in wastewater treatment plants. In the case of the latter, of the three treatments possible – primary (physical treatment), secondary (microbiological treatment), and tertiary (chemical treatment) – none focus specifically on microfibers. Around 78 percent of the microfibers are still removed in some cases during primary treatment, with around 20 percent extracted during secondary treatment, but it is still possible to find microfibers in the effluent (Mason *et al*., 2016). In practice, secondary treatment is also relatively ineffective at removing microplastics, and therefore a tertiary, more expensive process must be employed (Mason *et al*., 2016).

Studies analyzing the amount of these pollutants released in wastewater treatment plant effluent report anywhere from 0.01 to 9.4 microfibers per litre of effluent, depending on the treatment process (Talvitie *et al*., 2015). Although this may not seem like a significantly smaller concentration to that of the wastewater inflow, treatment facilities process millions of liters of wastewater daily, and are thus releasing millions of microfibers into waterways daily. On a larger scale, when there are several wastewater treatment plants operating in this manner for any given area, it becomes an even larger problem (Mason *et al*., 2016). In fact, a 2017 study estimates that 0.6 to 1.7 million tons of microfibers end up in oceans every year (Boucher & Friot, 2017). Furthermore, marine wildlife research has demonstrated the consequences of microfiber affluence in different environments. In 2015, Chelsea Rochman *et al.* extracted anthropogenic debris from shellfish and fish along the coasts of Indonesia and the United States. This study confirmed that all debris found from the fish and shellfish in Indonesia showed traces of plastic (small pieces) while the debris in the United States consisted mostly of fibers from textiles (Rochman, 2015). This is evidence that current waste management systems in general are unable to recover these fibers, and that these pollutants have become ubiquitous with our waters.

The shear volume of these released fibers is creating a form of smog in the ocean such that light will not be able to penetrate as deep in the water, affecting aquatic life, water quality and ocean health (Salvador *et al*., 2017). Additionally, given the size and shape of microfibers, plankton and other marine organisms mistake the fibers for food and consume them. Ingestion of these synthetic materials take up space and weight inside the stomach without providing nutrients, which leads to malnutrition, inability to store enough fat for migration and reproduction, irritation of the digestive track, and often death (Salvador *et al*., 2017). There is also the added fact that, despite being biochemically inert on their own, once in the marine environment, microfibers act as sponges and adsorb surrounding pollutants and toxic substances (Boucher & Friot, 2017). Therefore, once ingested, the adsorbed toxins leach out into the organism's cells, which causes a range of health concerns depending on the pollutants (Salvador *et al*., 2017). The contaminants bioaccumulate within individual organism, but also in the food chain. As one climbs the trophic scale, the concentration of contaminants and their associated health effects magnify. (Salvador *et al*., 2017). In other words, the shear abundance of microfibers and their ability to adsorb toxins lead to physical and chemical pollution both in water and on land.

Not only are microfibers entering the environment from the wastewater treatment facility effluent, but also from the sludge produced during the primary, sedimentation treatment (Bayo *et al*., 2016). The sludge is generally any solids that are removed from the wastewater and will thus include microfibers. Other than some composting processes, there is generally no extra treatment done on the sludge (Bayo *et al*., 2016). As microplastics are not biodegradable, they will remain throughout this process, being incorporated into the treated sludge. This poses another method of chemical leaching into the environment; through land application from composting. Many sludge's are then received by farmers, looking to enhance the organic matter of their soil, for which the high organic matter and nutrient rich sludge is good. Any microfibers incorporated in the sludge will therefore also be applied to the land, making them available for leaching into water sources and available to soil organisms, as well as larger organisms (Bayo *et al*., 2016). Studies looking at the presence of microplastics in fields have determined that they maintain their size and shape, even after long soil retention periods (Salvador *et al*., 2017) Therefore, even what microplastics are removed from treated wastewater, they are still returned to the environment, posing a threat to its health and safety.

Unfortunately, the outlined narrative of microfiber pollution and its associated environmental concerns will only be amplified going forward. Firstly, there is no sign of synthetic fibers being used less in the clothing industry. In fact, the cultural attachment to fast fashion around the world has inevitably encouraged the use of man-made synthetics, as it is versatile, inexpensive, and easy to blend with other materials (Bain, 2015). Clothes typical of fast fashion are also not made to last, such that they release more microplastic fibers (Salvador *et al*., 2017). Therefore, as clothing consumption habits increase to meet ever-changing trends, as will the associated pollution. Secondly, most research involving microplastic pollution has only been conducted within the past decade, such that this is a fairly new field of study and that there is a limited bank of information available. With a lack of scientific knowledge comes a lack of public awareness around the issue and of solutions being offered, especially as the problem is still trying to be understood. Thirdly, as with many environmental concerns, climate change invites a complex, unknown set of variables that interact in ways that can be difficult to model, even with the most robust of scientific background information. For instance, it is unclear of how a warming of ocean temperatures would affect microplastics and subsequently, marine ecosystems. It is thus difficult to find mitigation approaches for problems that remain multifaceted. Finally, as much as built-in filters were inherent in washing machines leading into 1983, thereafter they were abruptly taken out without any uproar (José Luis Gutierrez-Garcia, personal communication, November 25, 2017). Currently, there are no regulations for filtering discharged pollutants from industrial and household machines, or in wastewater treatment plants, such that these synthetics have a clear path to water bodies and marine ecosystems. Essentially, with the continuous increase of synthetic fiber use, the lack of information about microfiber pollution, the uncertainty brought along by climate change, and the lack of policies against these pollutants, globally perpetuated microfiber pollution is only set to rise.

Despite current trends, it is important to note that there are efforts to counter this global issue. In Canada, examples of organizations include UpGyres and TerraCycle. UpGyres, founded in British Columbia in 2012, is a not-for-profit organization behind the *Stop Plastic Smo*g project. This project aims to stop microfiber discharge into marine ecosystems by creating and supporting technologies that will capture them (UpGyres, 2014). In addition to these goals, they have collaborated with TerraCycle, a US-based private company that aims to recycle the typically unrecyclable. TerraCycle has created a plastic recycling program, whereby users can purchase "Zero Waste Boxes", which collect and repurpose various plastic waste, such as microfibers (TerraCycle, 2017). With UpGyres, they are being upcycled into new products, such as other textiles, pillow stuffing, composite construction materials, 3D printing filament, etc. (UpGyres, 2014). Patagonia is another business, this time on the retail side, focused on initiatives that include making customers aware of microplastic fiber pollution and investing in research and development of solutions (Patagonia, 2017). Although these initiatives are much needed in addressing the problem, a design that is efficient, user-friendly and promotes a circular lifecycle is also needed.

1.1 Vision Statement

Given the research, microplastic fiber pollution is abundant, imminent, transboundary and being perpetuated, such that measures need to be taken to address it. There are a number of approaches applicable from pre-production of clothes to after microfibers reach waterways. Asking clothing manufacturers and companies to opt for natural fibers rather than synthetic ones, or to invest more into the quality of materials to reduce microfiber release during washing are unlikely options because of the lower cost and widespread use of synthetics. Converting solely to natural fibers also brings about other environmental concerns. Working with washing machine companies to implement filters in their appliances is another method of restricting the output of pollutants into drainage systems; yet most brands have removed their filters without talks of bringing them back. Other areas where microfibers can be targeted are in wastewater treatment plants, where a tertiary system could be adapted to deal with this problem.

That being said, within the scope of this project, it is deemed more feasible to address these pollutants within households, aiming to capture and upcycle the released microfibers at the drainage pipes of washing machines. A general lack of discussion of this global problem in society adds another aspect to the project of raising awareness. In other words, the team's vision statement is to address microfiber pollution produced from synthetic textile washing by (1) educating the public about the issue, and (2) developing a filter that catches these microfibers and allows them to feasibly be cycled back into the economy.

1.2 Methodology

To achieve these goals, a data analysis of standing solutions for this problem (discussed in section 2.0 of the report), technologies allowing for the separation of microfibers from water, and standards involving washing machines and household drainage is conducted using online databases. Professionals in various fields are also contacted to help shape design ideas. Of the current professors and staff at McGill University, Dr. Jan F. Adamowski, Dr. Marie-Josee Dumont, Dr. Ronald Gehr, Dr. Valérie Orsat, Shahin Eskandari, and Scott Manktelow were consulted for their various fields of expertise. A Montreal plumber by the name of Karl-Eric Boucher was contacted to gain a better understanding of the washing machine plumbing and associated standards. For the filter component, five filter manufacturers and distributors in and around the Montreal area - including H2Flow Equipment Inc., General Electric, and Texel Technical Materials Inc. - were contacted in order to learn more about the various products currently available.

Aside from water flow and filtration considerations, the team is also designing for retrieval of microplastic in order for it to be upcycled. For this reason, José-Luis Gutierrez-Garcia, Co-Founder and Project Director of UpGyres was emailed, initially to ask about the requirements for recycling and reusing these pollutants. Through multiple correspondences, he also has shared much of his research on microfiber collection and discussed the cooperation of homeowners, laundromats and small hotel chains, and lack of cooperation from larger hotels chains and appliance brands. For the purposes of this paper, given the considerations and constraints he has shared with the team, UpGyres will be considered as a potential client. This organization will ensure the recycling and upcycling of the product and thus ensure the circular economy of microfiber materials.

Given that the designed system would be made for individuals to use in their household, their acceptance and engagement of the product and the corresponding work involved is necessary. Consequently, a survey was created to test respondent's knowledge on this issue and to evaluate the marketability of a household solution. It was shared on each team member's social media Facebook profile, asking people to answer *and* share the link in order to minimize biases and get as many individuals of all ages to respond. Appendix A, fig. A1 to A8, illustrates each question in a figure with corresponding answer distribution. The goal was ultimately to gain perspective on the respondents' knowledge on the issues and evaluate their willingness to participate in the collection and proper disposal – which can be done through UpGyres for instance – of microfiber lint.

The survey also served as a tool to raise awareness of microfiber pollution, which works toward the team's vision statement. In fact, of the 71 respondents, 87.14 percent had never heard of this problem and many comments expressed shock and interest towards it (see Appendix A, fig. A8). This confirmed the notion that that this information is not common knowledge and reinforced the need for the information to be shared. Furthermore, results demonstrated that, of the individuals who wanted to participate in the collection of microfibers, 48.15 percent would be willing to bring this collected waste once a month to a central location for recycling and upcycling (see Appendix A, fig. A7). This near majority vote was an unexpected result, but one that will be taken into account for the design of the filtration system. The survey also confirmed the hypothesis that not all individuals would be willing to put in additional work and invest money into a device. Therefore, our other target client is more environmentally-inclined individuals or businesses that understand the widespread issue of microfiber and would want to do their part in limiting their pollution.

Finally, to then concede the collected information from data analysis, professionals and stakeholders, weekly meetings were organized. During these sessions, the team also brainstormed design ideas and planned for the advancement of the project. Therefore, the combination of research, conversations with various professionals, and brainstorming sessions helped build an understanding of the microfibers, washing machines and filters; establish a set of constraints that would have to be managed in the design; form design prototypes; and ultimate allow for the final design to be created.

2.0 Existing Technologies

As described by S. Khandani (2005), the method of analyzing existing solutions to the problem and subsequently breaking them down to concentrate on their flaws and weaknesses in the design process is called synthesis. Generally, the process will begin broad and will continue in more and more detail such that the overall form or type of the solution is chosen first while configuration and arrangement are chosen in detail as the process furthers. Although the synthesis steps are not all required for this design, many were followed when analyzing existing solutions. These include identifying constraints, preferable materials and geometries, possible failures and combining the designs to optimize a final technology that combines such findings (Samuel & Weir, 1999). In order to do so, the team focused its synthesis on four existing technologies. These include the *Lint LUV-R, Filtrol 160, GuppyFriend* and *Cora Ball.* A brief summary of each technology follows in Table 1 as well as their corresponding pictures in Appendix B.

2.1 Lint LUV-R

The *Lint LUV-R* is a compact stainless-steel filter that can be mounted on a wall or cabinet. Its import (right hand side pipe) can then be connected to the washing machine discharge hose while its out port is connected to the drain pipe that leads to the septic tank (left hand side pipe). This filter has been designed specifically to prevent septic system failures due to clogging by collecting lint and other synthetic solids that are released during a washing cycle. The filter requires cleaning approximately every three weeks for the average household of four and can catch microfibers up to 1500 μm (Lint LUV-R, 2017).

2.2 Filtrol 160

The *Filtrol 160* is another design that has been developed for septic tanks. Like the *Lint LUV-R,* it is also wall mounted. However, rather than using a rigid filter, the *Filtrol 160* uses a reusable bag filter that needs to be hand washed every one to three weeks, or every ten to fifteen laundry cycles. This filter can catch microfibers up to 160 μm. The *Filtrol 160* also has an innovative safety factor such that if the filter is full there is an overflow device that allows a filter bypass for the discharge water. Similar to the *Lint LUV-R,* the *Filtrol 160* must also be connected to the machine drain pipe and homeowner's septic outlet pipe (Filtrol, 2017).

2.3 GuppyFriend

Unlike the previous two technologies, the *GuppyFriend* has been designed specifically for microfiber pollution. This bag, made 100% of polyamide is the first of its kind. It captures 99% of released microfibers during a wash cycle. Essentially, the clothes are places in this bag and washed. The bag reduces friction which reduces the amount of fibers released. All microfibers are then trapped in the bag where they can then be picked out by the user. Although this bag is very efficient at catching microfibers, it is currently only sold in one size (50x70 cm) and can only be filled halfway. For example, the bag can only fit two fleece jackets making it inefficient for large laundry loads. Although the bag is completely recyclable, it is still relatively new on the market and its lifecycle is still unknown (GuppyFriend, 2017).

2.4 Cora Ball

Like the *GuppyFriend,* the *Cora Ball* has also been created specifically to catch microfibers released from textiles. This innovative ball is placed in the washing machine with the dirty clothes. As the machine cycles, water flows through the ball, trapping fibers in the coral-like structure of the ball. Designed to mimic the filtering capability of ocean corals, the *Cora Ball* is made of 100% recycled plastics which also makes the ball recyclable. However, the small surface ratio of ball to water means one ball can only catch up to 35% of released microfibers per load of laundry. It is therefore recommended to use 2 to 3 *Cora Ball*'s per wash. However, further research is required to measure the effectiveness of using multiple balls. Additionally, due to the balls orientation, it is not recommended to be used with any lace, tassels, crocheted sections or frayed threads as these can get caught in the ball and damage the ball or the clothing (Cora Ball, 2017)

2.5 Summary of Existing Solutions

Table 1 consolidates the information from all existing solutions in order to facilitate comparison between products. In general, there are two types of solutions, those that go inside the washing machine drum, and those that attach to the drainage pipe. Each come with their own set of benefits and challenges; it becomes a question of designing a solution that is both efficient and user-friendly. With this in mind, design considerations will be assessed in the next section.

Table 1: Summary of Existing Technologies

(Lint LUV-R, 2017; Filtrol, 2017; GuppyFriend, 2017; Cora Ball, 2017)

Product	Medium	Function	Filter Description	Time Until Cleaning	Additional Information
Lint LUV-R ($140CAD)	Exterior Wall-mount Connected to drainage hose	System filters discharge from wash cycle	Stainless steel filter attached to system Catches microfibers up to 1500 µm	Every 3 weeks (for average household of four)	For septic systems
Filtrol 160 ($140USD)	Exterior Wall-mount Connected to drainage hose	System filters discharge from wash cycle	Reusable bag filter attached to system Catches microfibers up to 160 µm	Every 1 to 3 weeks, or every 10 to 15 loads	For septic systems Patented device Overflow safety factor
GuppyFriend ($37CAD)	Inside washing machine	Bag engulfs clothes, preventing microfibers from escaping the bag, and reducing friction (such to minimise fiber-release)	100% polyamide material Catches microfibers up to 50 µm 99% efficiency	Every 2 to 3 loads	Designed specifically for microfiber capture Does not fit a lot of clothes
Cora Ball ($20USD)	Inside washing machine	Balls designed to trap floating microfibers in a washing machine during cycle	100% recycled and recyclable plastic 35% efficiency	When visible	Designed specifically for microfiber capture Patent under review Recommended to use 2 to 3 per load

3.0 Design Considerations

Having identified the problem and existing solutions, design considerations can be determined for creating a set of criteria. These criteria, while also being essential to the design process, can be used to create a distinguishable measure for judging the most appropriate solution (Khandani, 2005). In order to do so, general considerations are addressed through their varying degrees of importance and applicability to the defined design problem. Creating this list of priorities was done in terms of broad values the team wished to address followed by more specific considerations for these values. The four general categories that were chosen include; social, environment, economic, and technical. These considerations were chosen based off their relevance to the microplastic fiber information and problem definition. In addition, these values were believed to be the most general and universally applicable to most engineering design projects. As mentioned above, these values gave forth to more specific concerns which will be further explained and discussed.

3.1 Social Considerations

As with most products that are directed towards a commercialized market, social awareness and proper adoption from its users is a crucial part to the success of the product. Although microplastic fiber pollution has had increasing attention in some scientific and engineering related studies, its presence is still vastly unknown amongst the general population. In order to better understand the view of microplastic fiber pollution and possible solutions, the team designed a survey that addressed stakeholders, such as washing machine users, to gain insight in their knowledge of microfiber pollution and their willingness to take part in a solution. As part of our design considerations, it was assumed that any majority answer that was received from the conducted survey would represent the overall thoughts of the targeted population. The design should take into account these social values as they represent the usability of the product once it is installed. For example, the design should consider user-friendliness involved in the installation, accessibility and cleaning of the device. Collectively, these considerations should promote a design that allows the user to easily install it and remove the collected lint in a manner that is both straightforward and not too frequent. There might also be certain stigmas associated with the collected microfibers as they might be seen as dirty and unappealing for the consumer to touch and remove. This further reinforces the need for easy removal of the lint.

In addition, the proposed solution should account for any user failure. For example, filters that are not cleaned as frequently as suggested should involve a safety factor in case of backflows and leaks. The design should address this possibility and assure users that in the event of a malfunction, there is a safeguard which has been put in place.

3.2 Environmental Considerations

In order to create a device that would mitigate the microplastic fiber release, it is imperative that the design actually catches these fibers. Efficiency is a crucial part of the design as this would ensure adequate removal of the microfibers from the discharge water. Additionally, as established in the vision statement, the team aims at promoting a circular lifecycle for the fibers. The design should thus promote proper removal and disposal of the microfibers. This would ensure fibers are not returned to the environment and, therefore, the design would promote a beneficial decrease of microfibers in the waterways, which will limit the physical and chemical effects on marine ecosystems and wildlife.

Additionally, the device should be designed to promote sustainable practices. This should involve both the manufacturing of the device as well as the aforementioned disposal and removal. For example, a device which cannot sustain frequent use without decreasing efficiency or simply breaking would lead to frequent changing, and thus increase waste. Likewise, a design that loses efficiency after a few uses would diminish environmental benefits through increased microfiber pollution. Improper removal would also decrease cyclic efforts and would not adhere to the given vision statement. For this reason, it is important to focus just as much on the collection of fibers as the disposal through proper channels or organizations such as UpGyres.

3.3 Economic Considerations

Social considerations are also taken into account in the economic side of the design as it is important to consider that any design that mitigates this problem may not necessarily offer any economic incentive for the consumer. Traditionally, if a product must be purchased but offers only environmental benefits, its success is limited as it interests a very small population of environmentally-friendly customers. It would therefore limit the designs appeal if the consumer cannot receive any incentive back, or if initial price and installation costs were too high. It is also important that the device does not incur frequent replacement costs, as previously mentioned.

As with any engineering project, implementing a design that is inexpensive to produce and run is essential. The design should not include materials that are difficult and expensive to acquire as this would further increase costs for both the manufacturers and consumers. Looking for standard material sizes and avoiding customized components will also work towards minimizing costs.

3.4 Technical Considerations

As with any engineering design, all technical components must be carefully analyzed. As the device is targeted for human use, its design should consider suitable ergonomic installation as it should encourage easy access for the user. Once again, if the device is placed in such a way that the user cannot remove the lint properly, any benefits from having the device are lost and can potentially cause the system to fail if there is a blockage.

In order to fully understand the limitations and parameters by which this project must abide, a holistic understanding of the context in which it will be used must be presented as well. This will generate the constraints to which any solution must adhere for a well engineered design. Firstly, the proposed solution should most importantly be adaptable to all washing machines, including front loading and top loading machines. In fact, not all washing machines have a standard discharge pipe and placement of such a pipe, as can be seen in Figure 1. It is therefore imperative that in order to have a successful design, it should be considered adaptable to all drain hoses or washing machine drums.

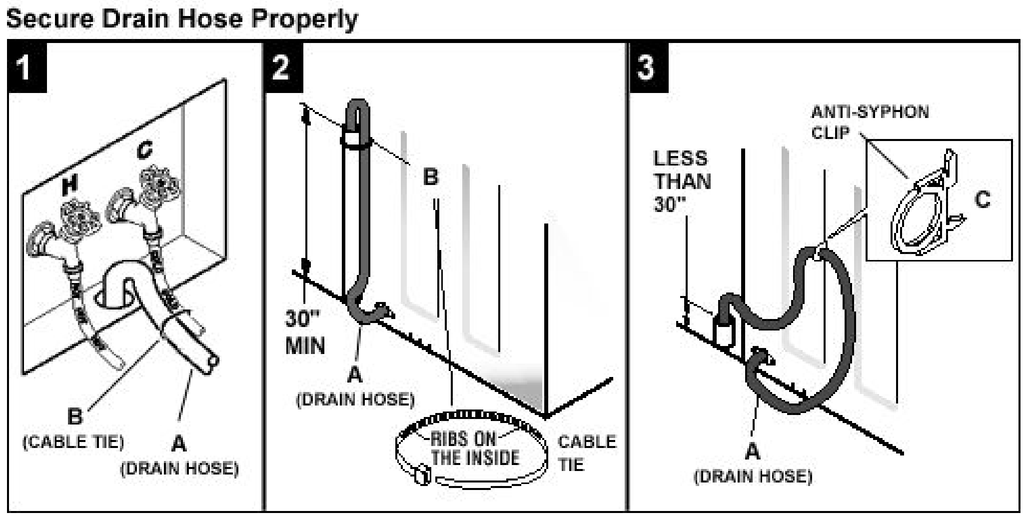

Figure 1: **Possible Drain Hose Orientations**

(image credit: http://www.geappliances.com/geac/askxprt/imgs/hose.gif)

3.5 Evaluation of Existing Solutions

Consolidating the existing solutions and evaluating them based on the social, environmental, economic and technical considerations discussed in this section is an efficient method of determining that in which works and does not work. This evaluation was made in Table 2 below. Socially, both the *Cora Ball* and *GuppyFriend* were the simplest design for users as they do not require any installation. However, the methods of collected the trapped fibers are tedious. Additionally, all four technologies do not offer any resources for the microfibers once they are collected. Users are simply encouraged to keep them in a jar until further notice or simply to dispose of them in the garbage. Although this may keep the fibers out of our waters, they are still not being dealt with in a circular manner. Therefore, as stated in our vision statement, this issue would need to be addressed in our chosen design.

Environmentally, the design must promote proper removal and disposal of the collected lint. Unfortunately, the existing technologies do not encourage that. Most designs use water to wash off the built-up microfibers which defeats the purpose of getting them out of our water treatments system. All four designs, as mentioned, require the user to pick out the lint which may be unappealing and time consuming to many. Unfortunately, as these designs are also very new on the market, it was difficult to find any testing that has been done which can confirm exactly how efficient the designs are for microfibers specifically. However, after the *GuppyFriend,* both mounted filters are the most efficient at removing both microfiber lint as well as any other build up such as hair.

Table 2: Evaluation of Existing Solutions Based on Design Considerations

Technology	Pros	Cons	Desired Components
Lint LUV-R	- Applicability - Self installation	- Efficiency for microplastics (up to 1500 μm) - No easy removal of lint build up - Expensive ($140)	- Easy connection to outlet and inlet pipe of machine
Filtrol 160	- Efficiency - Applicability - Designed for overflow	- No easy removal of lint build up - Expensive ($140)	- Outlet filter - Bag type capture system - Include method of dealing with back pressure
GuppyFriend	- Very efficient (up to 50 um) - Cheap ($20) - Applicability	- Reduced laundry loads - No easy removal of lint build up	- Bag like filter/material - Adaptability to any machine
Cora Ball	- Cheap ($20) - Easy to manufacture - Can be used in any machine	- No easy removal of lint build up - Efficiency (35%)	- 3D printing to reduce cost - Applicability

Economically, the existing solutions differ in their price range however, this is reflected in their abilities. For example, although the *GuppyFriend* and *Cora Ball* are inexpensive there is a trade off between their efficiencies. As mentioned, the *Cora Ball* can only capture 35% of fibers while the *GuppyFriend* offers a very limited amount of space for clothes. It might therefore be economically favorable to utilize the mounted filters for an average family of 4 as it would not require multiple loads of laundry or multiple filters.

Technically, both the *Cora Ball* and *GuppyFriend* require the least considerations as they are adaptable to any machine and ergonomically, are the easiest to use. Both the *Lint LUV-R* and *Filtro 160* however, must come with adaptable kits to account for different drain pipe sizes. Additionally, their installation requires a connection to the machine drain pipe which can cause further drainage head losses. It is therefore important to consider the orientation of the pipe into the filter as this orientation can cause backflow and leaks. That being said, with the external systems, there was more flexibility relative to the methods of filtration and of collection.

It is also worth mentioning that washing machines, specifically *GE* ones, used to have a lint filter manufactured in them. This "Fine Mesh" plastic lint filter would catch lint and debris that would accumulate at the bottom of the drum however, this was not specific for microplastics

(GE Appliances, n.d). Unfortunately, since these filters have been phased out, their pore size and material information is unavailable. That being said, any model manufactured after 2001 has had its filter removed due to more efficient pumps and larger holes under the agitator. This has resulted in better removal of water through the drainage system which pulls any lint and debris out of the pipes without causing blockages.

Although there exist different designs, identifying a solution that can successfully address all considerations lead to step three of the engineering design process. Based on the considerations, synthesis process, and vision statement, the design aspects were then brainstormed and evaluated. To begin this process, the team settled on a list of criteria the design should encompass. This included a device that was applicable to many different types of machines, such that it was accessible to all consumers. This will also increase the potential for it to be up scaled, to the industry level, with fewer adjustments necessary. This is important to the team as it increases the extent to which the technology can make an impact, maximizing the number of situations and potential for preventing microfiber pollution. In considering this, the team decided a filter on the outlet of the machine would be the most appropriate. It can then be adapted to all different models, meeting the previous criteria.

For reasons of accessibility and efficiency, it will also be designed for the end of washing machine discharge hose, such that the consumer can easily remove the filter so it can be cleaned and it provides more freedom of designing the most efficient system. The filter must be designed in a way that is simple and encouraging for consumers to clean. This includes ideas such as a flat surface, such that it can be left to dry, or a bag that can be turned inside out and brushed with a fine tooth comb. Such a design would increase the user accessibility and experience with the filter as well as addressing the safety of the user. The idea of using a bag to filter out the microplastic, similar to the *GuppyFriend* and *Filtrol 160*, is ideal as well. As discussed, it is more efficient at collecting the waste than some other methods, as well as relatively inexpensive, and easily adaptable to different filtering scenarios. As mentioned above, the *GuppyFriend* is more efficient at catching the microplastics but less efficient for washing, as it can only be loaded half full, and may pose problems in different types of washing machines.

The ability to apply the same principles but at the drain outflow, is a consideration for the design. The *Filtrol 160* includes a method of dealing with back pressure, or overflow of water, such that it would not flow back into the machine and cause damage. Such an aspect is important for the design as it increases safety, as well as decreasing the potential for the occurrence of adverse circumstances. Finally, although the *Cora Ball* is not as efficient as desired, the aspect of reducing cost by 3D printing materials would be advantageous. Therefore, the team will keep this in mind while designing aspects other than the filtering material, for the device.

4.0 Prototyping

4.1 Assumptions and Parameters

After revising the appropriate considerations for such a design, possible prototypes for a washing machine filter device were brainstormed. Each system is designed to be connected to the end of the washing machine discharge hose. Since there are no standards for the size of a washing machine discharge hose, the attachment of this hose to the filtering device will have to be available in sizes ranging from inside diameters of ¾ in. to 1 ¼ in. (or 0.01905 m to 0.03175 m) applicable to all four prototypes. Furthermore, there are currently no standards for washing machines regulating how much water they use, their discharge rates, or their discharge frequencies. The age of the machine can also significantly affect these characteristics, as older washing machines generally use more water, with the newer machines being more efficient and often developed with a faster discharge frequency. While older machines may have a discharge rate of around 12 gallons/minute (or 0.757 L/s), current models have rates somewhere between 17 and 22 gallons/minute (or 1.07 L/s and 1.39 L/s) (General Appliances, n.d.). For the purposes of this design, a maximum discharge rate will be considered to be 25 gallons/minute, as this accounts for newer models of washing machines as well as older models, including a safety factor.

Discharge occurs in 'spurts' of water, with not all being discharged at once, but in segments. As such, it will be assumed in this report that the discharge will occur in 5 second intervals, with 30 seconds between discharge segment. When considering the discharge from the machine, the height of the hose must be at least 30 inches (or 0.762 m) from the base of the washing machine, and no more than 8 feet (or 2.44 m) in height (General Appliances, n.d.). With this in mind, compact washing machines can only pump the discharge to a maximum of 5 feet (or 1.52 m) (General Appliances, n.d.). Furthermore, for each additional foot of drain pipe height, the discharge flow rate will be reduced by approximately 1 gallon/min (General Appliances, n.d.) which is approximately 0.0631 L/s. Therefore, in the case of an external filtering device, it will be suggested that it is placed at 1 foot (or 0.305 m) above the top of washing machine, or at the height of the household discharge pipe. This will ensure it is accessible to the user for cleaning, placed either behind the washing machine, or on a wall beside the washing machine, if it is not accessible behind (such as the case in stackable washing machines).

There are no standards for the size of the discharge hose either, both from the washing machine and for the household drainage pipe. They generally vary between ¾ in. and 1 ¼ in. (or 0.01905 m to 0.03175 m) in outside diameter (General Appliances, n.d.). Additionally, the household plumbing system generally has a minimum inside diameter of 1 ¼ in. or 0.03175 m. The length of the discharge hose from the machine must extend no more than 7" (or 0.1778 m) into the household drainage pipe (General Appliances, n.d.). These considerations were taken into account when developing the prototypes.

With washing machines running cycles at different temperatures of water, the filtering material must be able to withstand heat as well. Generally, when using the hot cycle on a washing machine, inflow water will be received at a maximum water temperature of 60℃. This will be considered as the maximum temperature for the filtering material.

The head loss within the pipe was then calculated, in order to determine the effect of the fluid flowing through the pipe, based on the friction. Do do this, several assumptions were made. This includes: (1) design for the smallest pipe diameter of ¾" or 0.01905 m, (2) design for a discharge rate of 25 gallons/min or 1.577 L/s, (3) the discharge is only water, (4) the washing machine has three possible cycles, cold (15℃), warm (30℃), or hot (60℃), (5) there is no temperature change in the water during the washing cycle, and (6) the discharge hose comes out of the washing machine at a height of 0.1 m from the floor, while the household discharge drain pipe is at a height of 1.5 m from the floor.

Aside from washing machine assumptions, it is assumed that the filter size does not have to be as small as the size of the fibers themselves, as they are much longer than they are wide. In this manner, even if their width is smaller than that of the filter, if they do not have the correct angle and the pressure is not substantial; they will not escape from the filter pores. As well, it is assumed that each filter will have the capacity to hold approximately fifteen loads of laundry, meaning the filter will not have to be cleaned after every wash.

As mentioned, the team also sent out a survey to gain insight on user participation. With this, it is assumed that in purchasing the product, the consumer will be willing to clean the filter, and will do so at a frequency of about once per month, depending on the design and how often the machine is used. In addition to this, it is assumed that for a wall-mounted design, the consumer has sufficient wall space in proximity to the washing machine to install the filter; either behind the washing machine, or beside the washing machine, at an appropriate height. Following this, it will be assumed that the device is to be used in a domestic environment, for the discharge of one washing machine. The ability of scaling the device up to a more industrial size (for washing machines in dormitories, large apartments, laundromats, etc.) will be seen as an asset.

To begin analyzing the engineering parameters associated with the design, the velocity of the system was determined. For each cycle condition, several properties had to be determined. This includes the kinematic viscosity, Reynolds number, and friction factor. The values for the kinematic viscosity, at each possible operating temperature, were taken from the textbook, *Engineering Fluid Mechanics,* by Crowe *et al.* (2009). The calculations for these can be seen in

Appendix C, with values summarized in Table 3 below. The head loss was then calculated for each cycle, where the velocity of the system was $v = 5.533\ m/s$.

Table 3: Calculated Values of Kinematic Viscosity, Reynolds Number, and Friction Factor for Different Cycle Temperatures

Cycle Temperatures	**Kinematic viscosity,** $\upsilon\ [m^2/s]$	**Reynolds Number,** *Re*	**Friction Factor,** *f*
Cold @ 15℃	1.14×10^{-6}	92 459.34	6.922×10^{-4}
Warm @ 30℃	0.800×10^{-6}	131 754.56	4.858×10^{-4}
Hot @ 60℃	0.474×10^{-6}	222 370.57	2.878×10^{-4}

Following this, the hydrostatic pressure was calculated to determine the pressure exerted by water in the pipe. To do so, the specific gravity was also required. The determination of both the specific gravity and the hydrostatic pressure is included in Appendix C. The density of water for each operating temperature condition was taken from the textbook *Engineering Fluid Mechanics,* by Crowe *et al*. (2009). The summary of these calculations can be seen in Table 4.

Table 4: Calculated Values of Hydrostatic Pressure and Specific Gravity for Different Cycle Temperatures

Cycle Temperatures	**Specific Gravity,** γ **[N/m³]**	**Hydrostatic Pressure,** p **[Pa]**
Cold @ 15℃	9800.19	− 13720.266
Warm @ 30℃	9770.76	− 13679.064
Hot @ 60℃	9447.03	− 13225.842

These calculations will be important during this design process, in determining the appropriate size of the filter, device, pipe configuration and avoiding head loss and backflow. Once these flow characteristics were determined, attention was turned to the filter material. Measuring the flow rate through the filter material, under standard pressure, was important in determining the maximum flow rate of the filter. This test was completed twice, and the time was averaged, to ascertain a volumetric flow rate through the filter. The resulting flow rate through the filter was determined to be 0.131 L/s or 0.0346 gallons/s. This flow rate was for a filter surface area of 2 in.² or 0.00129 m². From this, the flux, or flow per unit area of filter, was calculated, to be 26.85 gallons/s/m² or 101.55 L/s/m². These calculations are shown below.

Test 1:

$$Q_1 = \frac{2L}{15.5s} = 0.129\ L/s$$

OR

$$Q_1 = \frac{0.528\ gallon}{15.5s} = 0.03409\ gallon/s$$

Test 2:

$$Q_2 = \frac{2L}{15s} = 0.133\ L/s$$

OR

$$Q_2 = \frac{0.528\ gallon}{15s} = 0.03522\ gallon/s$$

Average flow rate:

$$Q_{avg} = \frac{Q_1+Q_2}{2}$$

$$Q_{avg} = \frac{(0.129+0.133)L/s}{2}$$

$$Q_{avg} = 0.131\ L/s$$

OR

$$Q_{avg} = \frac{Q_1+Q_2}{2}$$

$$Q_{avg} = \frac{(0.03409+0.03522)gallons/s}{2}$$

$$Q_{avg} = 0.03465\ gallons/s$$

Flux (flow rate per area of filter) was calculated using equation 3:

(1) $u = \frac{Q}{A}$

Where,

u = flux [L/s/m²] or [gallons/s/m²]

Q = flow rate [L/s] or [gallons/s]

A = area of filter surface [m²]

$$u = \frac{0.131\ L/s}{0.00129\ m^2}$$

$$u = 101.55\ L/s/m^2$$

OR

$$u = \frac{0.03465\ gallons/s}{0.00129\ m^2}$$

$$u = 26.858\ gallons/s/m^2$$

As was discussed earlier, this filtration device is to be designed for a worst case scenario, which includes a flow rate through the filter of 25 gpm. This is the same as 0.4167 gallons/s or 1.577 L/s. Using this, required flow capacity of the filter, and the actual flow through the filter, the necessary area was required. In other words, this is the area required to accomodate the worst case scenario of flow through the filtration device, calculated through equation 2. This will be used in determining the appropriate size of the filtration device.

(2) $Area\ required = \frac{Q_{max}}{u}$

Where,

Q_{max} = maximum flow rate through filter [gallons/s]

u = flux [gallons/s/m²]

$$Area\ required = \frac{0.4167\ gallons/s}{26.858\ gallons/s/m^2}$$

$$Area\ required = 0.0155\ m^2$$

After the required filter surface area was obtained, the dimensions of the filter surfaces within the device were calculated. This was done assuming the primary filtration stage had a diameter of 4 in, or a radius of 0.0508 m, and the secondary stage had a width of 5 in or 0.127 m. These were the technical considerations going into the third part of the engineering design cycle: brainstorming possible solutions.

Following the development of a design, the team returned to the technical parameters to validate some design choices. For practical purposes, these considerations are included in the preceding part of the report. To fully understand the calculations, it is useful to understand the exact mechanism of the filtration design, which is described in Section 5.0 of this report. For now, all that will be explain is that the primary filter is cylindrical in shape, meaning its surface area, A, is defined by the equation A = $2*\pi*r*l$ (where r is the radius of the filter and l is the length of the filter membrane) and the secondary filter will be assumed to be rectangular in shape such that its surface area is defined by A = w*l (where w is the width of the filter and l is the length of the filter material. Based on the exact method of filtration, including the technology chosen and an explanation of the primary and secondary filtration stages (which will be explained in Section 5.0), the length of filter required with respect to the flow rate was calculated for different flow scenarios. It will be assumed that the two filtration stages are of equal filter length, meaning the length included in the calculation of the surface area should be l/2. Thus, given these parameters, the required length of filter surface is calculated below using Equation 3.

$$(3)\ \ Area\ Required = 2\pi r\frac{l}{2} + w\frac{l}{2}$$

Where,

r = radius of primary (cylindrical) filter [m]

l = required length of filter material [m]

w = width of secondary (hammock) filter [m]

$$0.0155\ m^2 = 2\pi(0.0508)\frac{l}{2} + (0.127)\frac{l}{2}$$

$$0.0155\ m^2 = 2\pi r\frac{l}{2} + w\frac{l}{2}$$

$$0.0155\ m^2 = \frac{l}{2}(2\pi(0.0508) + 0.127)$$

$$\frac{l}{2} = \frac{0.0155}{2\pi(0.0508)+0.127}$$

$$\frac{l}{2} = 0.03478\ m$$

$$l = 0.06956\ m$$

Therefore, each filtration stage will need a filter length of 0.0348 m, or 3.5 cm, for a total filtration length of 6.96 cm. Following this, the team wanted to again design for the worst. This included a flow rate reduced by half due to a buildup of filter cake. This will ensure there is still sufficient filter surface area even if the user forgets to clean the filter for a long period of time. This calculation is shown below.

$$Q_{half} = \frac{(0.03465\ gallons/s)}{2}$$

$$Q_{half} = 0.017325\ gallons/s$$

Flux, using equation 1 from above:

$$u = \frac{Q}{A}$$

$$u = \frac{0.017325 \ gallons/s}{0.00129 \ m^2}$$

$$u = 13.430 \ gallons/s/m^2$$

Area required, using equation 2 from above:

$$Area\ required = \frac{Q_{max}}{u}$$

$$Area\ required = \frac{0.4167 \ gallons/s}{13.430 \ gallons/s/m^2}$$

$$Area\ required = 0.03103 \ m^2$$

Length of filter material required, using equation 3 from above:

$$Area\ Required = 2\pi r \frac{l}{2} + w \frac{l}{2}$$

$$0.03103 \ m^2 = 2\pi r \frac{l}{2} + w \frac{l}{2}$$

$$0.03103 \ m^2 = 2\pi(0.0508)\frac{l}{2} + (0.127)\frac{l}{2}$$

$$0.03103 \ m^2 = \frac{l}{2}(2\pi(0.0508) + 0.127)$$

$$\frac{l}{2} = \frac{0.03103}{2\pi(0.0508)+0.127}$$

$$\frac{l}{2} = 0.06954 \ m$$

$$l = 0.1391 \ m$$

Therefore, to manage a filter material flow rate reduced by half due to filter cake requires a total filtration length of approximately 14 cm, meaning each filtration stage should be at least 7 cm long. Following this, the required area and length of filter material required were calculated for a worst case scenario: the primary filtration stage, where the flow is tangential, not working properly, and only filtering at 50% of the surface area. This uses the original flow rate of the material, the associated flux and required area.

Length of filter material required, using equation 3 from above:

$$Area\ Required = (0.50)(2\pi r \frac{l}{2}) + w \frac{l}{2}$$

$$0.0155 \ m^2 = 2\pi r \frac{l}{2} + w \frac{l}{2}$$

$$0.0155\ m^2 = (0.50)(2\pi(0.0508)\tfrac{l}{2}) + (0.127)\tfrac{l}{2}$$

$$0.0155\ m^2 = \tfrac{l}{2}(\pi(0.0508) + 0.127)$$

$$\frac{l}{2} = \frac{0.03103}{\pi(0.0508)+0.127}$$

$$\frac{l}{2} = 0.1083\ m$$

$$l = 0.2165\ m$$

Therefore, if the primary filtration stage worked at half capacity - 50% of the filter surface area - the filtration device would require a length of 21.65 cm. While keeping these values in mind, the team decided on various lengths for the prototype. To begin, it was important to build the device at a longer length than necessary to ensure it adequately filtered the water and functioned properly. For this reason, the team decided to start with an initial total filter length of 22 cm or about 9 in. Keeping these values in mind, it is possible to shorten and redesign the device based on performance.

Using the flow rate of the material that was determined above, both the average flow rate and the reduced flow rate, the associated velocities through the material can also be ascertained. This is correlated to the flow through the outlet of the device, after passing through the filter material. The area of this outlet is based on a pipe diameter of 1 in. (or 0.0254 m). These are calculated using Equation 4 below, and will further be used in determining the pressure drop through the device. It is important to note that the flow rate must first be changed from a volume unit of L (or gallons) to m^3.

(4) $v = \frac{Q}{A}$

Where,

v = velocity [m/s]

Q = flow rate [m^3/s]

A = area of outlet pipe [m^2]

Flow rate:

$$Q_{avg} = 0.131\ L/s * (1m^3/1000L)$$

$$Q_{avg} = 0.000131\ m^3/s$$

Velocity, using equation 4:

$$v = \frac{Q}{A}$$

$$v = \frac{0.000131\ m^3/s}{\pi(0.0127)^2\ m^2}$$

$$v = 0.2585\ m/s$$

The inlet velocity was previously stated as being 5.333 m/s. This, along with the determined outlet velocity, will aid in determining the pressure at the inlet and outlet of the drain hose, the pressure drop, and the back pressure. The pressures will be determined using Bernoulli's equation, Equation (5), as seen below.

$$(5)\ \frac{P_1}{\gamma} + \frac{v_1^2}{2g} + z_1 = \frac{P_2}{\gamma} + \frac{v_2^2}{2g} + z_2$$

where,

P_1 = Pressure at inlet from discharge hose [Pa or N/m^2]

γ = specific gravity of fluid; water [N/m^3]

v_1 = velocity at inlet to discharge hose [m/s]

z_1 = height of inlet to device [m]

P_2 = Pressure at outlet of discharge hose [Pa or N/m^2]

v_2 = velocity at outlet of discharge hose [m/s]

z_2 = height of outlet to device [m]

Pressure difference during cold cycle @ 10℃:

$$\frac{P_1}{\gamma} + \frac{v_1^2}{2g} + z_1 = \frac{P_2}{\gamma} + \frac{v_2^2}{2g} + z_2$$

$$\frac{P_1}{9800.19\ kg/m^2} + \frac{(5.333\ m/s)^2}{2(9.81\ m/s^2)} + 0 = \frac{P_2}{9800.19\ kg/m^2} + \frac{(0.2585\ m/s)^2}{2(9.81\ m/s^2)} + 0.0508m$$

$$P_1 - P_2\left(\frac{1}{9800.19\ kg/m^2}\right) = \frac{(0.2585\ m/s)^2}{2(9.81\ m/s^2)} + 0.0508m - \frac{(5.333\ m/s)^2}{2(9.81\ m/s^2)} - 0$$

$$P_1 - P_2 = \left(\frac{0.2585 - 5.333)m^2/s^2}{2(9.81\ m/s^2)} + 0.0508m\right)(9800.19kg/m^2)$$

$$P_1 - P_2 = -2036.86\ Pa$$

$$P_2 - P_1 = 2036.86\ Pa$$

Pressure difference during warm cycle @ 30℃:

$$\frac{P_1}{\gamma} + \frac{v_1^2}{2g} + z_1 = \frac{P_2}{\gamma} + \frac{v_2^2}{2g} + z_2$$

$$\frac{P_1}{9770.76\ kg/m^2} + \frac{(5.333\ m/s)^2}{2(9.81\ m/s^2)} + 0 = \frac{P_2}{9770.76\ kg/m^2} + \frac{(0.2585\ m/s)^2}{2(9.81\ m/s^2)} + 0.0508m$$

$$P_1 - P_2(\frac{1}{9770.76\ kg/m^2}) = \frac{(0.2585\ m/s)^2}{2(9.81\ m/s^2)} + 0.0508m - \frac{(5.333\ m/s)^2}{2(9.81\ m/s^2)} - 0$$

$$P_1 - P_2 = (\frac{(0.2585 - 5.333)m^2/s^2}{2(9.81\ m/s^2)} + 0.0508m)(9770.76\ kg/m^2)$$

$$P_1 - P_2 = -2030.75\ Pa$$

$$P_2 - P_1 = 2030.75\ Pa$$

Pressure difference during hot cycle @ 60℃:

$$\frac{P_1}{\gamma} + \frac{v_1^2}{2g} + z_1 = \frac{P_2}{\gamma} + \frac{v_2^2}{2g} + z_2$$

$$\frac{P_1}{9447.03\ kg/m^2} + \frac{(5.333\ m/s)^2}{2(9.81\ m/s^2)} + 0 = \frac{P_2}{9447.03\ kg/m^2} + \frac{(0.2585\ m/s)^2}{2(9.81\ m/s^2)} + 0.0508m$$

$$P_1 - P_2(\frac{1}{9447.03\ kg/m^2}) = \frac{(0.2585\ m/s)^2}{2(9.81\ m/s^2)} + 0.0508m - \frac{(5.333\ m/s)^2}{2(9.81\ m/s^2)} - 0$$

$$P_1 - P_2 = (\frac{(0.2585 - 5.333)m^2/s^2}{2(9.81\ m/s^2)} + 0.0508m)(9447.03\ kg/m^2)$$

$$P_1 - P_2 = -1963.46\ Pa$$

$$P_2 - P_1 = 1963.46\ Pa$$

Finally, the filter permeability was determined. This is an important parameter as it takes into account the existence of a filter cake on the material. A filter cake is residual waste left on the filter that impedes the flow through the membrane. In the case of this design, filter cake would occur when the user failed to clean the filter and microfibers and other debris built up on the surface. To examine this, Darcy's Law was used, in equation 6 below. To do so, the cake thickness is required. Again, it was assumed to be 1cm, a worst case, if the user had not cleaned it after several washes. Darcy's law also requires the fluid viscosity, water in this design, which was taken at the three assumed washing cycle temperatures: 15℃, 30℃, and 60℃.

(6) $\frac{Q}{A} = \frac{k}{\mu} \frac{\Delta p}{L}$

Where,

Q = filter flow rate [m³/s]

A = area of the cake cross section [m²]

k = permeability [m²]

μ = fluid viscosity [Pa*s]

Δp = pressure drop across the cake [Pa]

L = thickness of filter cake [m]

The permeability during the cold cycle at 15℃, with a fluid viscosity of 1.14×10^{-3} Pa*s:

$$\frac{Q}{A} = \frac{k}{\mu}\frac{\Delta p}{L}$$

$$k = \frac{Q}{A}\frac{L}{\Delta P}\mu$$

$$k = \frac{0.000131\ m^3/s}{0.0155 m^2}\frac{0.01 m}{2036.86\ Pa}(1.14 x\ 10^{-3}\ Pa \cdot s)$$

$$k = 4.730 \times 10^{-11}\ m^2$$

The permeability during the cold cycle at 30℃ with a fluid viscosity of 7.97×10^{-4} Pa*s:

$$\frac{Q}{A} = \frac{k}{\mu}\frac{\Delta p}{L}$$

$$k = \frac{Q}{A}\frac{L}{\Delta P}\mu$$

$$k = \frac{0.000131\ m^3/s}{0.0155 m^2}\frac{0.01 m}{2030.75\ Pa}(7.97\ x\ 10^{-4} Pa \cdot s)$$

$$k = 3.317 \times 10^{-11}\ m^2$$

The permeability during the cold cycle at 60℃ with a fluid viscosity of 4.66×10^{-4} Pa*s:

$$\frac{Q}{A} = \frac{k}{\mu}\frac{\Delta p}{L}$$

$$k = \frac{Q}{A}\frac{L}{\Delta P}\mu$$

$$k = \frac{0.000131\ m^3/s}{0.0155 m^2}\frac{0.01 m}{1963.46\ Pa}(4.66\ x\ 10^{-4} Pa \cdot s)$$

$$k = 2.006 \times 10^{-11}\ m^2$$

The results of this study show that the cold cycle at 15℃ has the largest permeability while the hot cycle at 60℃ has the lowest permeability. The minimal difference between these values means that changes in the permeability of the material will not be of great concern to the functioning of the device. Despite this, it is important to consider this parameter, as well as all other discussed, while designing an appropriate filtration device for microfibers.

4.2 Conceptualization of Design

Given the existing technologies, the extracted design considerations, and the established parameters and assumptions, consolidating this information to conceptualize design possibilities is now possible. After significant discussion among team members, certain prototypes were assembled to meet a range of considerations, with the first prototype being a sock filter. This simple design would connect to the head of the washing machine drainage pipe and predominantly consist of a bag filter, made of nylon, with a small sieve size in order to efficiently capture microfibers. Bag filters have an increased surface area for maximizing flow through the filer and an in-pipe system removes the need for an exterior enclosure that can take space and not be as esthetic. This design is simple, and therefore more cost efficient, making it available to a larger consumer base. As well, it is easily adaptable to all types of washing machines, with the only necessary adjustment being the size of the discharge hose, as there is no standard for this. It is more of a connection to the existing washing machine, than its own separate device, meaning it would be easy for the washing machine industry to take it on as an addition to their machines, removing the additional cost to the consumer. If the industry had a filter at the output of the discharge, it would not only reduce the pressure through the filter, making it more efficient for collecting microplastics, but also solve some of the issues they had with washing machine filters before, such as: cleaning the filter (it would be in a more user accessible position), and easier to replace and repair. Although it does improve on the initial problem with having filters in washing machines, it is not as visible as a separate device attached to the wall, and therefore might follow the 'out of sight out of mind principle' in which the consumer forgets to clean the filter as often. Furthermore, there is little room for the water to go if there is build-up of pollutants on the filter blocking the discharge flow. More safety considerations would thus have to be implemented.

Another potential design prototype was the multistage filtration device, whereby the system would be cylindrical in shape, mounted onto the wall vertically, in a position accessible to the consumer, the discharge hose from the washing machine, and the household plumbing system. The washing machine discharge hose will connect to the top of the container, the filter cylinder will extend vertically downwards, and a second discharge hose, from the bottom of the device into the household plumbing system, will be supplied with the purchase of the apparatus. In total, the filter would consist of three different filtering layers, each of different sieve size, to allow for some separation of the waste, within the device. A larger size filter at the top would catch some of the large particles in the wastewater, such as particles of mud or dirt; the middle filter would catch items such as hair; and the smallest, end filter would catch the microfibers. It is understood from this design that some these microfibers would get caught up in the other layers, but it is assumed that the majority would pass through to the bottom filter, where they could be easily collected. The microfibers within this bottom filter layer would also be much purer, which makes it ultimately easier for upcycling. With this in mind, it could pose a problem for the remaining two layers – if the intention is to recycle the fibers caught in the finest filter, consumers may be less careful with the waste from the other two layers, throwing them in garbage, or disposing of them inappropriately, as they may still contain trapped microfibers. The other issues with this device include the flow rate of water from the discharge hose. With three different filtering layers, it minimizes the total filtering surface area of each layer, thus slowing flow rates and would pose a larger risk to the overflow of the device, or even cause back pressure into the washing machine. The device would have to be designed larger to avoid this, which not everyone will have the same amount of space required for installation. As well, multiple filtering layers makes it more difficult to clean, as each layer would have to be removed, cleaned, and replaced. Finally, more materials and complex designs mean more costly the device.

The third prototype developed to solve the issue of microplastic pollution from domestic washing machines is an angled filter within a tank. The filter would be held in a rectangular plastic tank with a funnelled bottom. For this, the discharge hose from the washing machine would enter through the top if the tank. The funnelled bottom would lead to the discharge pipe, which would be supplied, into the household plumbing system. The funnelled bottom also allows for efficient passage of water into the discharge pipe, after filtration. This system will be stable on the wall, such that it can't be removed by the user, and therefore it is important that it is accessible to them so cleaning the filter will be easy. This prototype relies on a concept already familiar with consumers: the dryer lint filter, which will be placed perpendicular to the axis created by the inlet and outlet hoses. In this manner, they should be comfortable cleaning it and removing the lint. Although, the rigid support, mounted on the wall, may mean it is less accessible to the consumer, especially if they suffer from a mobility issue. There is also a potential for error in mishandling of the filter by the consumer, if they do not place it back in the filter as it should be. Another consideration is the flow through the filter; while trying to minimize the size of the apparatus while maximizing the surface area, a flat filter would have a smaller surface area and therefore a lower total flow rate capability, meaning it may impede flow rate more than another method, such as a bag filter. The flat design may also have an uneven distribution of pressure from the discharge. The area directly under the discharge hose would be subjected to most of the flow, and therefore higher pressures, potentially making it less efficient.

The design of the fourth prototype encompasses many different aspects to create as user-friendly a product as possible. It is cylindrical in shape, which can be mounted on the wall with easy access to the drain pipe and the household plumbing system. The discharge hose from the washing machine will be connected to the lid. The lid will be threaded onto the rest of the cylinder, with a quarter turn locking system. This makes it easy to remove when the filter has to be cleaned. Inside the top of the lid will be three fan blades, positioned as those from an air fan. In this manner, the water from the washing machine discharge will fall onto the fan, rotating it, and dispersing the water within the filter. In the main cylinder, a filter bag will be situated to receive the water from the fan. This fan will distribute the water over the filter, reducing the pressure in one individual area. This will make it more efficient, as a too high pressure can cause the microplastics to be pushed through the filter pores. Its place at the top of the cylinder makes it easily accessible for cleaning, as once the canister is opened it will be positioned for easy removal. Again, this discharge hose will be included with the filter, so the consumers are not responsible for obtaining it. It will be connected to the bottom of the filter via another pipe adaptor, in a similar manner to the one for the discharge hose on the top. At this outlet, beneath the filter, there will be a sensor measuring the velocity of the flow leaving the filter and entering the discharge pipe. This sensor will be connected to an LED light attached to the container. As such, if this flow is reduced beyond a certain velocity, the LED light will be turned on, signalling the consumer that the filter must be cleaned. This is an easy, convenient way to remind the user that the filter must be cleaned. The advantages of this prototype include the user accessibility. It was designed with the idea of creating a system that was more receptive to the demand placed on the consumer, and ease the cleaning process. That being said, these added features will increase the cost of the filter relative to other options.

When systems are overly simplified or overly complicated, the user-friendliness of the device pays the price. Each prototype has its own unique features that lead to advantages and disadvantages. While the sock filter is too simplistic and has less safety factors incorporated, the multilayer system eases upcycling by separating larger contaminants from the discharge, allowing for microfibers to be collected on the last smallest sieved filter. Cleaning for the latter system would however be more complicated, unlike the sock filter. The third, funnel prototype has the user's interest in mind with its design, but questions of reduced flow rate and frequency of filter cleaning arise, which are better accommodated in the fourth fan-LED design. Yet, this prototype is set to be one of the more costly options. Therefore, the recurring concerns through the conceptualization of the final design are the convenience of infrequent microfiber collection from filters, the cost of the device, and the flow rate through the system. Safety factors will need to be implemented to ensure that backflow does not occur in the pipes, which would potentially cause flooding and deem the product unfunctional. The system would also have to be designed to promote filtration efficiency to thus avoid issues of slowed flow rates and back logging of discharge. For this reason, further brainstorming and discussion with mentioned professionals led the team to design a fifth and final prototype, which will be discussed in Section 5.0.

5.0 Final Design

5.1 Crossflow Configuration

The above mentioned technologies present both positive and negative aspects. Yet, combining these technologies would still lack further innovative technology and would not solve all the requirements. For this reason, the team combined the design parameters with a relatively new wastewater treatment technology: crossflow configuration filtration, to develop our design, *Fib-Less!*. Although this technology was not designed specifically with microplastics in mind, it is very appropriate to this application, as will be discussed further. Applying a mitigating method to microfiber pollution on a wastewater treatment scale is expensive, highly technical, and therefore difficult. Thus, the solution was to scale down the technology (while adding a few additional components) to a domestic level. This resulted in a design that uses crossflow filtration, otherwise known as tangential flow filtration.

Crossflow filtration is an ideal means for both microfiltration and nanofiltration. Using a membrane filtration cylinder, contaminated water is passed through at a certain pressure and speed. This causes clean permeate to expel out the membrane pores due to transmembrane pressure. It then leaves the tube where it can be collected, or in this case, further filtered. As some clean water leaves, some will continue through the tube (Li *et al*., 2008). This slurry now has a higher concentration of contaminants as it leaves the tube. An example of this process can be seen in Figure 2.

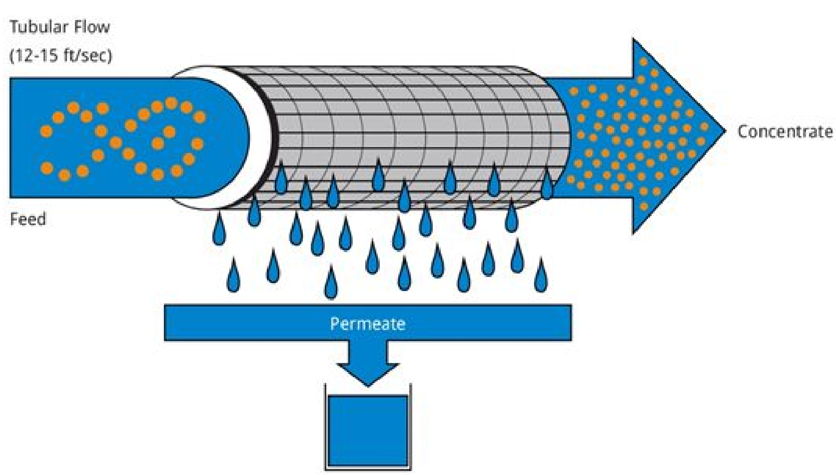

Figure 2: Schematic of Crossflow Filtration

(image credit: http://www.porexfiltration.com/learning-center/technology/tmf-industrial-wasterwater/)

Unlike traditional filtration that uses perpendicular flow, tangential flow results in less backup on the filter surface area, or filter cake (Li, *et al*. 2008 & Wiesmann, *et al*. 2007). The tangential flow also creates less pressure on the filter membrane, maximizing its efficiency. High pressure of the water flowing into the filter membrane in a perpendicular flow configuration will cause the fibers to be pushed out of the mesh. Therefore, having a tangential flow system will minimize this effect without significantly impacting the pressure. This, along with the shape of microfibers, being much longer than their width, means a filter with a larger mesh size than the width of the microfibers is permitted. However, the efficiency of the crossflow filtration is dependent on how well its membrane can perform surface filtration on the suspended contaminants (Vogel, 1997). Therefore, an appropriate filter material is essential for success of the design. Finally, when discharge passes through the filter configured in crossflow, the initial recovery is generally no higher than 20 percent (Vogel, 1997), such that further filtration is required. With these considerations and the technology in mind, the fifth and final prototype was conceived.

5.2 Enclosure Components

The design is composed of a cylindrical plastic enclosure, divided into two compartments, mounted horizontally on the wall (see Figure 3 below). The washing machine drainage hose is attached at one end, and the outlet is connected at the opposite end, on the bottom of the device. In the first compartment of the enclosure, the crossflow filter runs parallel to the discharge pipe (from the washing machine) and the discharge flow. This is in cylindrical form, with the discharge flowing into the center and the permeate (mostly water) being expelled through the surface. At the inlet, the filter will be connected to the end of the device.

Opposite this, the cylinder filter will end in an eccentric coupling. An eccentric coupling is essentially an off-set funnel, or cone that serves two purposes in this application. Firstly, it impedes the flow of the discharge water through the device slightly, ensuring the permeate is pushed through the tangential filter surface. This was an important adaptation to make to the technology, as we are scaling it down from the wastewater treatment size (and there are size requirements in a domestic setting), there is less filter time and area to work with. The second function of the eccentric coupling is to direct the water into the secondary filtration stage. Furthermore, it is important that the coupling is offset and not centered, as a traditional funnel is, because it adds an additional safety factor. In the worst-case scenario of water back-flowing through the device into the machine, it must rise that much more to pass back through the coupling and into the primary stage of the device. In other words, the flow from a traditional funnel is impeded by a solid space which is half the difference between the entrance and exit diameters in size. In the case of an eccentric coupling, this impedance is the size of the whole difference between the inflow and outflow diameters, meaning it is offset by the trajectory of the flow that much more. This piece was made through 3D printing for the purposes of the prototype. Thus far, moving through the design, the feed from the washing machine discharge will enter the system, navigate through the crossflow configuration and be directed into the secondary filtration stage by means of an eccentric coupling. While the permeate, or filtered water, is expelled outwards through the tangential filter, the concentrate will enter the second compartment through the cone-like nozzle.

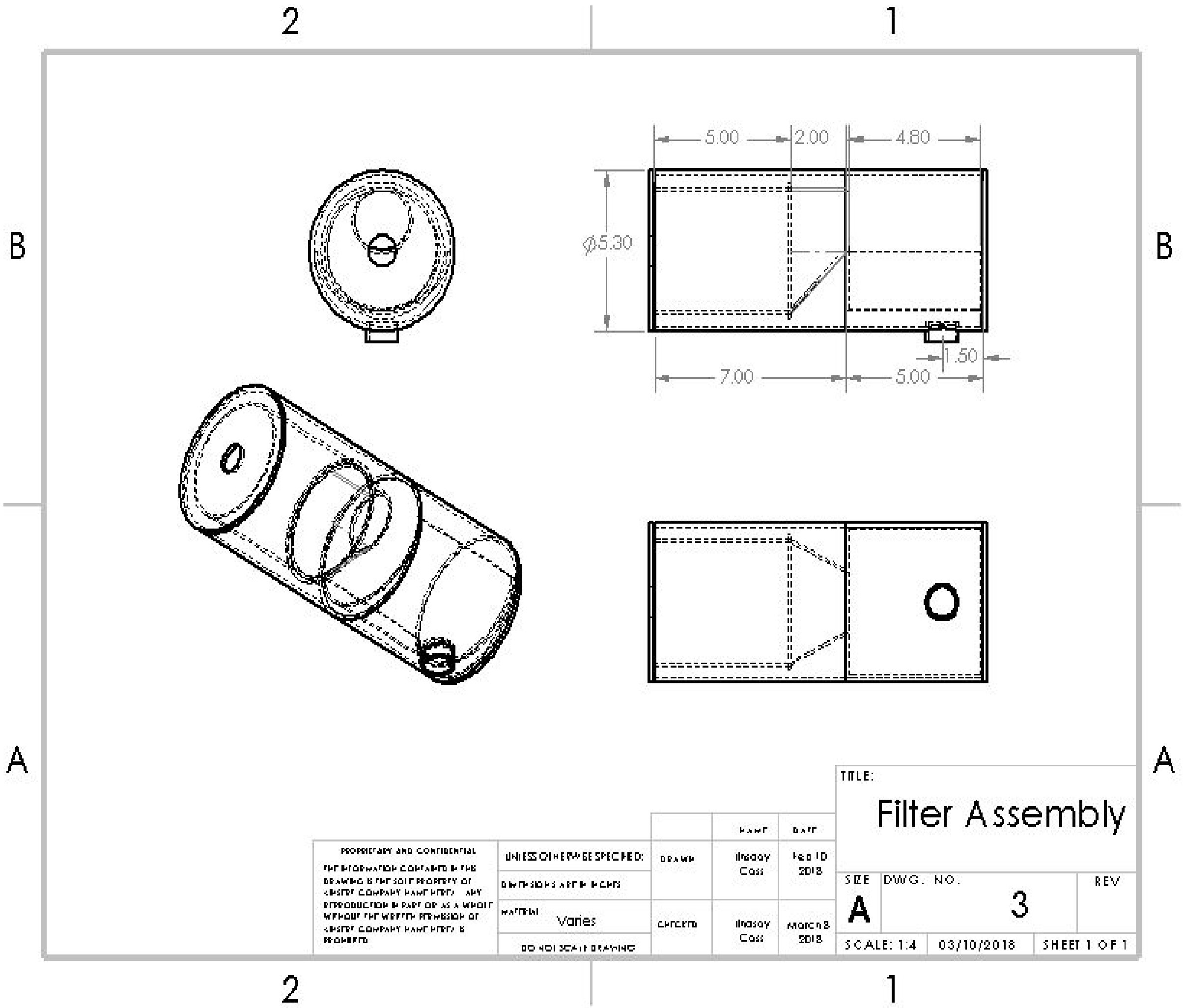

Figure 3: Components of the Final Design

In order to filter and retain the rest of the microfibers entering the second compartment, another filtration unit is necessary. This secondary filtration stage will filter fibers coming from the concentrate stream and is where the majority of the waste will be retained. To filter this concentrate, the same filter material will be used as in the primary filtration stage. This filter membrane will be configured as a hammock, such that it is elevated off the bottom of the device. This creates a channel, leaving the drainage port free from obstruction and is important to ensure that all the water filtered in the primary stage can leave through the discharge as well. The hammock will be suspended through a support system, 3D printed. On the far end, it will be connected to the end of the device, and the other end will be a round, 3D printed shape, with a hole where the end of the eccentric coupling will sit. Again, this will not be perfectly circular to ensure it is not resting on the bottom of the device and the channel is still present. The two supporting ends of the hammock filter will be connected via two rods, such that they are separated the appropriate length of the filter membrane. The sides of the filter can then be suspended over these supports and they can be sealed with silicon. This will prevent any water from passing around the support, unfiltered.

In having the majority of the fibers enter the second compartment, the team can ensure that the user must only access the one filter where they can easily clean the microfibers and upcycle them. As the survey results indicated (see Appendix A, Figure A7), individuals would likely clean their filter once a month. Their ease of cleaning and access to the filter is also an important consideration. According to Dr. Gehr, a civil engineering professor at McGill University and expert in wastewater treatment, crossflow filters are 'self-cleaning' due to the flow of discharge through the device. This means that the crossflow filter will not require frequent cleaning or replacement, which reinforces the user-friendliness and value of this design. The key to this is to regulate the transmembrane pressure and the crossflow rate to ensure the efficiency of the system. This will prevent fouling and will allow the fibers to enter the second compartment in an effective manner (Schwartz & Seeley, 2003). With this in mind, the two ends of the device will be threaded, allowing the consumer to easily access both sides of the filtration device. On the inlet end, the tangential filter is connected, and therefore when it is unthreaded, the filter surface will be removed, allowing easy access. Although this filter will not need to be cleaned or replaced, as discussed, the consumer will be able to check it to ensure it is working properly and efficiently. On the other end, the secondary filter will again be connected to the end of the device. This is much more important as this is the filter surface which will collect the lint and need to be cleaned. Therefore, the user will again be able to unthread the end, conjointly removing this filter membrane. It provides a very easy mechanism for them to then clean the filter, before threading it into place again.

Once the microfibers are captured, clean water from both the first and second compartments can then both be funneled to the drain pipe, connected to the end of the device (under the secondary filter). Here, the enclosure will have a slight 'lip', such that a pipe adapter is not needed and the discharge hose can be attached directly to this protrusion. This will ensure that all water drains from the interior of the filtration device, where it can leave the household plumbing system and be brought to a treatment plant without the burden of microplastic fibers entering neighboring waterways and affecting the ecosystem.

5.3 Selected Materials

Currently, the filter membrane chosen for this system is a nylon filter - for durability - of 200 μm in pore size. Nylon is able to withstand varying temperatures as established by the different washing machine cycles. As well, it is long lasting meaning it will withstand many washes, reducing the need for replacement. The 200 μm pore size is small enough that it will effectively collect microfibers, while still allowing a sufficient flow rate through the membrane. This is important as it prevents back pressure into the washing machine discharge hose. Although there are possible microfibers smaller than 200 μm in size, the filter will still be efficient. The unbalanced size of the fibers, having a much smaller diameter than length, means that they will be trapped by pore sizes smaller than that of their diameters. Only under exact positioning or increased pressure will they pass through. The placement of the filter membrane tangential to the flow will ensure that the pressure against the filter surface is not exceedingly high, such that the fibers are not pushed through. An appropriate filter membrane is essential to the proper functioning of this device.

Following the determination of the filter material, the team decided on an acrylic exterior casing for the device. The acrylic is important as it is again durable and resistant to different temperatures, as well as being transparent. This allows the user to see inside the filtration device, as it is being used, to ensure everything is functioning properly, but also to see when the secondary filter surface may need to be cleaned. If the user can see inside the device and the filter appears dirty, it serves as a direct reminder that it should be cleaned. Ensuring proper use and care also increases the longevity of the device while making sure it is working as efficiently as possible A rendering of the device, as it would look like after being produced is shown in Figure 4 below.

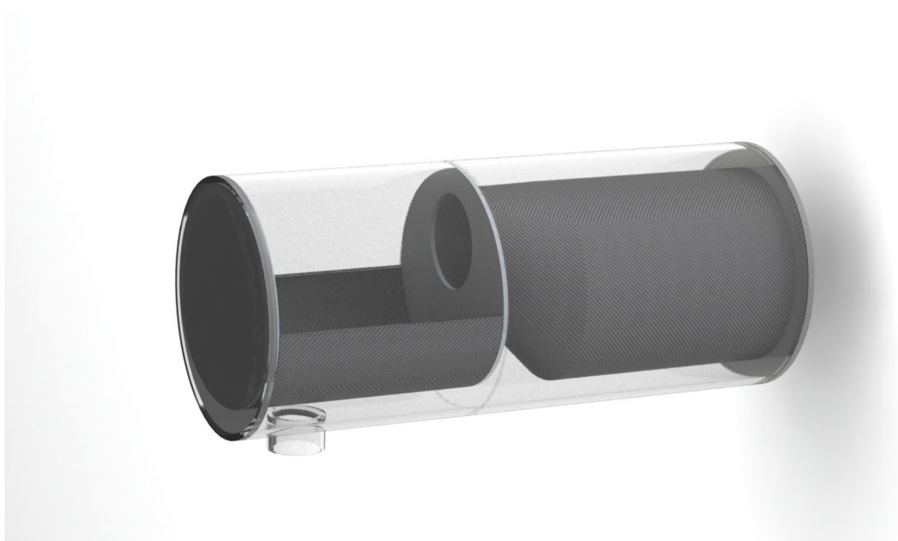

Figure 4: Rendered Image of the Final Design and Product *Fib-Less!*

As was mentioned in Section 5.2, several of the interior parts for the device were 3D printed. Although this was sufficient and convenient for the building of a prototype, in scaling up the design, this would be more tedious, time consuming, and expensive than necessary. Such parts could be made from molded plastic in a commercialized setting to increase the efficiency of the production process. Additionally, for the purposes of the prototype, acrylic was not accessible or affordable, partly due to the necessary timeline, with regards to the various competitions the design was entered in. Therefore, to allow the device to be built and tested in enough time for both the Quebec and Canadian Engineering Competitions, cheaper, more accessible PVC and ABS were chosen for the exterior housing. Again, in making a consumer product, this enclosure would be made from an acrylic material. Finally, an appropriate polyester filter material was not obtainable and therefore a 200 µm felt filtration material was used in its place. Although this may have some effect on the flow rate, it can be somewhat accounted for in the modelling. Additionally, the main disparity between the two materials is the durability, for which polyester is much more durable. The nature of the prototype meant it was intended for short term testing and use, and therefore the durability of the material was of less concern. For a consumer product, which would be built to be used for a long period of time in the consumers home, the polyester filter material would be used.

Although the prototype is currently made of plastic, as that is what is presently economically feasible, as new technologies and more sustainable options emerge, such as biopolymers, the design will adapt to encompass those. This will be done to increase the environmental feasibility and sustainability of the design.

One example of such a material development is the use of a graphene filter membrane (instead of the polyester). This is a new material and as such it has not been incorporated into the design yet. The uses, and most importantly the cost, are still being developed. As more information about this device becomes available, the team will consider it as a replacement for the current polyester filter. It seems a promising technology though, as graphene filters have been reported to filter large quantities of water quickly. Graphene is "an atomically thin carbon-based two-dimensional material," (Seo *et al.*, 2018) used for microfiltration. The properties of the material are advantageous, including good mechanical strength, thermal and chemical stability, hydrophobicity, and uniform, thin thickness. The current application is for desalination of water although it is known to purify water, allow little through other than water (Seo *et al.*, 2018). Generally, the material allows water to flow through while blocking any large pollutants and its mild hydrophobic tendencies allow faster water filtration than common polymer membranes (Peters, 2018). Tests thus far have been on a very small scale, so the abilities and applications of the material in scaling it up remain to be seen (Seo *et al.*, 2018). Usually these graphene filter materials are oil based, but a more sustainable option to this is Graphair, a graphene filter membrane made from soybean oil. Made by the Commonwealth Scientific and Industrial Research Office (CSIRO) in Australia, tests have shown the filtration rate through Graphair can be halved in time and minimal clogging of the pores occurs. It is also able to be produced at a much cheaper cost than traditional graphene filters (Peters, 2018). The team hopes to follow this research in the future as it is scaled up and marketed as a possible filtration material.

5.4 Appenditures and Fastenings

The final aspect of the design involved working out the small working parts of the device. This included the inlet and outlet ports, the wall mount, and the discharge hose. Again, the user accessibility was important in this aspect of the design, making sure the user could easily execute the required steps on their own.

With this in mind, the outlet hose of the washing machine must be connected to the filtering device in a manner easy enough for the user to do while remaining secure and minimizing the possibility of failure. Such failure includes an attachment unable to withstand the pressure of the fluid flowing through the pipe and into the filter. For this purpose, a pipe adaptor will be used, which will be attached to the end of the cylindrical enclosure. This will be pre-installed for the user, when they buy the device. Due to the variance in the size of discharge hoses from washing machines, they will therefore have to preselect the pipe adapter size, upon purchase of the filtration device. Then, they must just slide the end of their washing machine discharge hose onto the end of the pipe adapter, and secure it with a pipe clamp. The pipe clamp will need to be tightened with a screwdriver to ensure it is adequately tight.

As was mentioned previously, to avoid the buildup of any excess water within the filtration device, the outlet port was extruded. This eliminates the need for a pipe adapter, as the new discharge hose may be attached directly to this extrusion. This connection will be done by the user, sliding the hose on top of the extrusion and connecting it with a second pipe clamp, in the same manner as the inlet. For added safety measures, there will also be a rubber seal placed on the outside of the extrusion, so the pipe rests on the seal rather than directly on the acrylic housing. The most complicated part for the user will be in determining the appropriate positioning and length of the discharge hose. The filtration device will supply a new discharge hose which the user may use to connect the outlet of the device to their household plumbing system, but the exact configuration of their system will determine the required length of the discharge hose. As most washing machine pumps are only powerful enough to pump the water at the desired flow rate, to a height of five feet or eight feet, depending on its size, adding a filtration device and additional drainage hose significantly decreases the pressure of the water and therefore the pump efficiency. For this reason, if the drainage hose is too long for the users configuration (washing machine to filtration device to household plumbing system), there will not be enough power to push the water through the final discharge hose and into the household plumbing system. This will cause water to sit in this tube. For this reason, the user will have to cut the supplied hose to an appropriate length given their washing machine configuration. Along with this, it is important to note that the discharge hose must not be inserted more than 7 inches into the household drainage pipe, for maximum efficiency.

6.0 Analysis

Following the consensus of a design, it was important that it was modelled, to determine appropriate dimensions and to optimize the design, as well as build a working prototype. Due to the constraints of funding and the deadlines of the various competitions the team had entered, the two were done at the same time. This was not ideal as it lead to a prototype which has slightly different dimensions than the optimized modelled design. The lack of funds have made it difficult to obtain the appropriate materials, of the desired size, to build the optimized design. A brief discussion of the modelling and testing process is reviewed below.

6.1 Testing

The first testing of the device that had to be completed was with respect to the filter material. This was important to determine not only if the filter allowed sufficient flow, but to determine the flow rate through the filter material. This measurement was discussed previously, in Section 4.1 Assumptions and Parameters. A small portion of the filter was taken, with an area of 2 in^2 (or 12.9 cm^2) and a 2 L volume of water was measured. The flow through this piece of filter was then measured, to determine its maximum flow rate. Then, the filter itself, with a large filter surface area, of 90 in^2 (or 580.6 cm^2) was tested on the outflow of the washing machine; the filter was assembled in a bag formation, the discharge hose was placed in the opening. A washing cycle was completed, testing the flow of water through the filter in this setting. Different drain hose discharge heights were experimented with, being 0 m, 1 m, and 1.5 m. Although the filter was capable of filtering discharge at all heights, the discharge was significantly faster at a 0 m height. Following this, once it was concluded that the filter allowed adequate flow and would not cause back pressure, the primary filtration stage could be tested. This included the tangential filter surface and the eccentric coupling. Testing just this first filtration stage was important because it is the area which will generate the most pressure on the flowing water. Ensuring the water flow rate is still enough to prevent back pressure was important before continuing with the design. The results of this were successful; the water continued to flow out the discharge port and any generation of pressure on the flowing water was not significant enough to cause it to flow back into the machine. Finally, the whole device could be tested, including both the primary and secondary filtration mechanisms.

The testing for the purposes of this prototype was done continuously on one washing machine. Although it does pose as a form of validation for the design, it is important to continue testing. As was mentioned previously, in Section 4.1, there are no standards dictating washing machines, their design or the conditions of operation. Any device designed for a washing machine must therefore be designed for all different models and ages of machines. Although this can be somewhat accounted for in the modelling of the design, it is important to continue testing on as many different machines as possible to ensure the adaptability of the filtration device to different washing machine pumps, flow rates, and flow conditions.

6.2 Modelling

In order to complete the design cycle, modelling and simulating the filter was an important step following the testing process. As the testing validated the functionality of the design, the modelling would ensure optimized dimensions of the filter components such as its diameter and length. Modelling was performed using COMSOL Multiphysics 5.3. Due to the complexity and lack of prior knowledge of the software, the filter was modelled in a simplified manner. Upon speaking to Shahin Eskandari, a Ph.D student in the department of Bioresource Engineering, it was decided that the model would be completed in 2D axisymmetric model rather than 3D due to the complexity the 3D model would have required. 2D axisymmetric models consist of creating a 2D geometry that is symmetrically replicated in all directions around the central axis. Due to this type of model, it was not possible to draw an eccentric coupling as is would not make the geometry radially symmetric. Therefore, another simplification includes adding a centered coupling rather than an eccentric one.

Assumptions also included modelling only for a cold water cycle and the fluid passing through the filter consists of only water. Furthermore, the option for adding the physics of a turbulent flow was not possible with the COMSOL package offered at Macdonald Campus. Laminar flow was thus the physics used in completing the model. The materials used were user-defined, whereby the first consists of the fluid material and the second, the porous matrix representing the filter material. In characterizing the fluid crossing through the porous matrix, the Forchheimer drag was taken into account to ensure the model be as realistic as possible. The Brinkman equation is incorporated in these physics and works to describe the matrix as being porous.

Preliminary results, which can be seen in Figure 5, show that the velocity travels through the model as expected. Flow through the crossflow filter is uniform and shows no direct spots of increased velocity, except at the corners directly as the water exist the inlet and enters the cross-flow chamber. As the water enters the coupling, the velocity increases which will successfully allow if to enter the second filtration chamber where the remaining filtration can occur.

Additionally, the cross-flow chamber length was varied using a parameter sweep, whereby the model was tested between 12 and 20 cm long. Results also indicated that varying the length of the filter did not, in fact, change the velocity profile. This validated the mathematics performed above which shows that a filter length of 14 cm is sufficient for filtering in a worst case scenario. In other words, the primary filter can be as small as 14 cm and any larger would be for aesthetic and user-friendliness reasoning. In terms of determining the other dimensions, there were significant limitations, such that future modelling would be important to determine the remaining optimal dimensions.

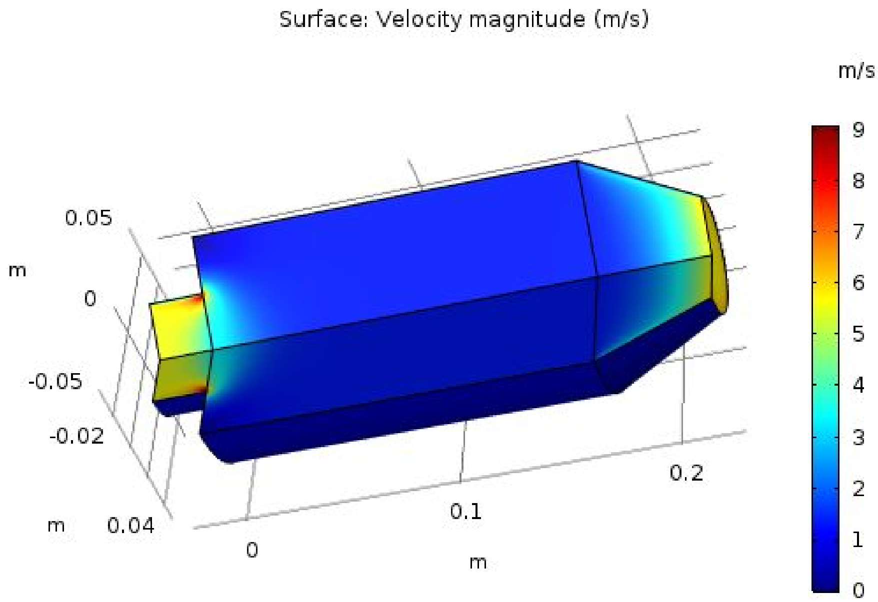

Figure 5: Velocity Profile Results of Simulation

7.0 Discussion

7.1 Economic Analysis

A thorough economic analysis was done on the production of this filtering device, including the assessment of costs with the intention of manufacturing it for a consumer market in the future. The economics of this undertaking are important, as the use of such a filter is currently an additional cost for the consumer. Therefore, there must be incentives to encourage the participation in this project. The production of the prototype was significantly less than that of a manufactured filter device due to the use of cheaper, more available materials. The prototype design cost \$71 to produce, while a prototype made of the same materials and dimensions would be around \$110. The highest cost from this will be the exterior housing as it must be adapted and molded for this specific application. By applying an economies of scale approach to the final cost, the unit price for the consumer should reflect the increased production and replicability in the manufacturing. Table 5 shows a comparison between the cost of the prototype and the cost of building a prototype of the marketed product.

Table 5: Overview of Expenses for Prototype and for Single *Fib-Less!*

	Prototype	**Product**
Housing	Free	$75
Pipe Adapters (x2)	$6	$6
Discharge Hose	Free	$5
Filter	$25	$4
Filter Housing	$6	$6
Threaded Adapters	$30	$10
Wall Mount	$4	$4
Total	**$71**	**$110**

As was mentioned, the significantly lower prototype cost relative to the product cost is due to the use of cheap and widely available materials. Applying a general economies of scale of 25% to the manufacturing cost of the product brings it down to approximately $80. This is highly possible as many of the products used in this design can be bought in bulk, directly from the manufacturer to reduce costs. Additionally, specific processes can be developed to create some of the components which are more unique to the design, such as the enclosure housing. This can include the use of molds for the exterior housing. Such developments will reduce costs as it limits material waste and other manufacturing steps, but will also reduce the necessary time. Although this cost analysis for the manufacturing of the filters does not include other costs, such as transportation, wages, and asset fees, the overall cost is relatively little, such that they may be accounted for and the consumer price of the device will still be competitive. Therefore a price for the product would be determined at a later date, once these factors could be more adequately assessed.

Although another device with this purpose does not exist, there are similar products, as explained in Section 2.0 Existing Technologies of this report. The cost of two such devices, the

Filtrol 160 and *Lint LUV-R* is $140 CAD, each. This is significantly higher than the predicted $80 manufacturing cost of this device, allowing for other, currently unknown costs within the market price. Overall, this project aims to minimize the costs necessary in order maximize the target market and to encourage users to participate. It can therefore be seen that there is still a window to add such charges where *Fib-Less!* can still remain competitive with the market average.

The device will be available through both retailers and through an online store, maximizing its influence. Primary market plans would have it available online only in order to judge, and hopefully gain, public interest. As well, after the initial fixed cost of the filter device for the consumer, there will be very few variable costs. The cross flow configuration means that the predominant filter surface does not clarify the majority of the contaminated water (this will be filtered through the collection chamber). In addition to this, it is 'self-cleaning' as this filter will be cleaned with new washing cycle, and cycle of water discharge. The collection chamber also becomes more efficient with an initial collected concentration of material. As such, the filter membrane should not need to be replaced. This will reduce costs from other designs, which require regular replacement of the filter as they become less efficient with an increase in collected material.

In order to increase the accessibility of the product and incentivize consumers to invest in the product, further development may be done. On a domestic scale, some governments offer tax credits or subsidies for environmentally-friendly initiative in households. For instance, in Quebec, implementing this device may qualify for a tax credit under section C: *Water Conservation and Quality* of the RénoVert or "GreenReno" program for recognized renovation work in dwellings (Revenue Quebec, 2018). Although this is an initiative the customer would have to take on themselves, it will alleviate some of the economic responsibility. On the business scale, the project could work towards an association with the LEED accreditation system, whereby a business owner would receive LEED credits for utilizing a washing machine filter in their building, when applicable. This is especially relevant for business' such as hotels, laundromats, and university residences, where laundry is a prominent procedure. In discussing the future applicability of such a program with the founder of UpGyres, Jose Luis Guitierrez-Garcia, he discussed the difficulty he had with hotel chains in accepting this problem. Therefore, having an incentive for them is important to ensure they are willing participants in the project.

As mentioned previously, in Section 1.0 of this report, it used to be standard for washing machines to have filters. Despite not being appropriate for filtering out microfibers from the wastewater, this shows that the concept is capable of being implemented within the industry. In further discussions with Jose Luis Guitierrez-Garcia though, the industry has showed no interest in researching this problem further or realizing a solution. Despite this, the project seeks to gain industry acknowledgement and support in the future, with the intention of eventually engaging their participation. As the problem becomes more familiar and further research into the problem is completed, it will be more difficult for the industry to remain disengaged. Ensuring their involvement will also seek to minimize the cost on the consumer.

Sustainability with regards to the environment and the economy requires the environmental impact of projects and policies to be assessed and included in an economic analysis. This can be difficult, especially in terms of a project such as this, as it is hard to valorize the environmental impact of this design. The effect of the microfiber pollution, although it can be seen now, may have a stronger impact in the next generations, meaning its true economic cost is not as significant today as it will be in the future. The same issues occur when trying to valorize the impact of removing washing machines as a source of plastic pollution. In current economic analysis, the provisioning services of the environment are not considered. Although this can be difficult to do, ensuring clean oceans is very beneficial to society. It leads to higher biodiversity, a better fishing industry, healthier atmosphere, temperature regulation, as well as many other recreation benefits. These are all important qualities of life and values within society. With continuing and increased plastic pollution, including that from washing machines, these services will become more and more affected, less healthy, and therefore less able to provide for society's needs and desires. In a United Nations Environment Programme (UNEP & GRID-Ardenal, 2016) report on valuing plastic, it is estimated that plastic pollution in the marine environment from a consumer source, costs a total of $8 billion per year. From this, plastic pollution from textiles and accessories costs a total of $333 million dollars, a cost placed directly on societies across the world (UNEP & GRID-Ardenal, 2016). This not only impacts economies but also, of course the environment. As this is a cost on societies, both from the plastic pollution as well as from the impacts it has on the environment and human activities related to the environment, including it in an economic analysis will help to close the gap and ensure this waste is disposed of properly. It makes it economically beneficial for society to handle and dispose of their waste responsibly because there is a direct economic impact to such behaviour.

Additionally, UNEP reports on the market and industry failure of plastic as a product, which directs plastic as a waste product directly into the environment. The cost of plastic for the consumer is so cheap it does not reflect the cost of recycling and disposing of the product. This therefore becomes a cost placed on society. Again, it advocates the need for including the cost of plastic pollution and disposal in an economic analysis. This is associated with the life cycle cost of plastic, covering both its initial cost and its final cost, in disposal or recycling (UNEP & GRID-Ardenal, 2016). In turn, this promotes the proper disposal of plastic, increasing its recyclability as recycling costs can be included in the initial cost of plastic. As well, it can include the environmental cost of plastic, reducing the economic impact of plastic pollution.

Bringing this back to the design project, these ideas will be kept in mind while analyzing the filtration device. The project aims to work towards a future of economic stability with regards to the environment as this ensures not only the environment's health but also our health. It is believed that this is a shift in perception society must make to ensure environmental sustainability as well as a balanced economic cost for the future. Although costs associated with plastic are minimal right now and any change in that would cause drastic changes in society, continuing with this will only increase the economic deficit of the future. Having such a device for microfiber pollution may be an additional cost right now, but it reduces future costs in trying to clean up the oceans and decreases economic losses associated with the ocean's decreased provisioning services in the future. Based on this, the project will also seek to promote such initiatives towards sustainability.

7.2 Scalability of Design

Although testing is a crucial and large part of the design, producing such a technology is simple, yet effective. As we discussed in the Section 5.0, the filtration unit requires nothing more than a casing, a filter and its support as well as some piping. In addition to this, the cost for production is estimated at $80, well below the price of other similar devices on the market. Producing such a device on a large scale is not complicated. Its simple design will allow it to be easily produced on an manufacturing scale-point. As well, unlike other, more complicated installations (*Filtrol 160, Lint LUV-R)*, this device is both easy to install and user friendly and unlike simple designs (*Cora Ball, GuppyFriend)*, this filter is efficient. This makes it a good alternative to other current apparatus' available. However, further testing of the device in order to optimize the transmembrane pressure and crossflow rate will require extensive research. Therefore, development of the product while it is on the market is also possible.

Once tested and optimized however, this device can be introduced to households and ideally to industries. Its applicability and flexibility will allow it to be adapted by many environments. Like any other product, its success is highly driven by its market demand. From the sample survey results, it can be seen that there is an interest (See Appendix A, Figure A4 & A5) for a product like this on the market however, its success is also hindered by a lack of knowledge about this issue. As knowledge on the issue increases, the demand for such a product should increase as well, making this an ideal technology that can be scaled up to address this demand.

7.3 Competition Comments

Attending both the Quebec and Canadian Engineering Competitions (QEC and CEC, respectively), left the team with lots of advice with regards to the project and design. Primarily, the judges at QEC suggested the testing and modelling of the device be continued. With more time to work on the design following the competition, the team did continue the testing and modelling. Additionally, they suggested researching the patentability of the project. The team has since contacted many people within the patenting industry, both at McGill and at companies. It was decided that a provisional patent was most appropriate for the design and project at this point in time. To do so, the patenting officer Kitt Sinden from Aird McBurney was contacted as he was supportive of our student status and generous in his work. The team also spoke with David Nguyen, the Technology Transfer Manager for McGill University who assessed our patent potential and put the team in contact with McGill's affiliated patent lawyers, Norton Rose Fulbright Law Firm. The associated documents of the design, including a description of the design, a copy of the team's poster and drawings of the filtration device were collected to be filed under a provisional patent.

At the CEC, the judges were very interested in our business model and potential to become a start-up. They gave us an idea of where to begin our project - by contacting high polluters such as apartment buildings and university residences, as well as starting communicating within the fashion industry. It was recommended that we attend Fashion Week and Eco fashion week to generate awareness about the problem and interest in our design. With Eco Fashion week being in Vancouver, from March 31-April 2, unfortunately this was not possible. The intention is to keep this in mind going into the future; for next year but also for potential stakeholders that should be involved in this design. This is important as it also feeds into developing a sustainable economy. Involving the fashion industry to raise awareness for this problem, such that the stream of pollution can be included in the costs of the textiles is important to ensure widespread adoption of a solution. Overall, these comments were worthwhile as the team had not thought about start-up potential and the associated considerations yet. In fact, the judges had also suggested finding think-tank and project starting companies that specialize in projects started by women. These comments may be used in the future to develop a more specific initial target market.

8.0 Conclusion

Like any engineering design, the process that leads to its inception is both challenging and rewarding. As stated in our vision statement, the team set out to create a design that can successfully mitigate microplastic pollution. In order to do so, the chosen design should catch these microfibers as they are released from textiles and promote their recycling by means of easy removal and collection. The use of this filtration system, in combination with the company UpGyres, will successfully allow the collection of the microfibers and their recycling, in order to fully address this issue in a sustainable fashion. Furthermore, educating the public was another part of the vision statement and will continue to be considered. The survey was a first step in achieving this goal; competing in the Quebec Engineering Competition for Innovative Design in January of 2018 and the Canadian Engineering Competition in March 2018 is another means by which the team can spread the message about the serious pollution caused by microfibers from washing synthetic clothes.

In order to gain a complete understanding of the requirements and capabilities of our chosen design, it will be necessary to complete more steps in the design process such as testing the model through COMSOL to optimize the dimensions of the final design for more representative inputs (i.e less assumptions and using larger multiphysics packages in COMSOL). Soon after, the team will work towards building the resultant prototype in order to test and evaluate its efficiency, and to develop the best possible product. Taking into account all the information acquired as well as keeping an open line of communication with the mentors and resources involved in this project will be a key aspect of accomplishing the vision statement.

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Appendix A

Survey Results

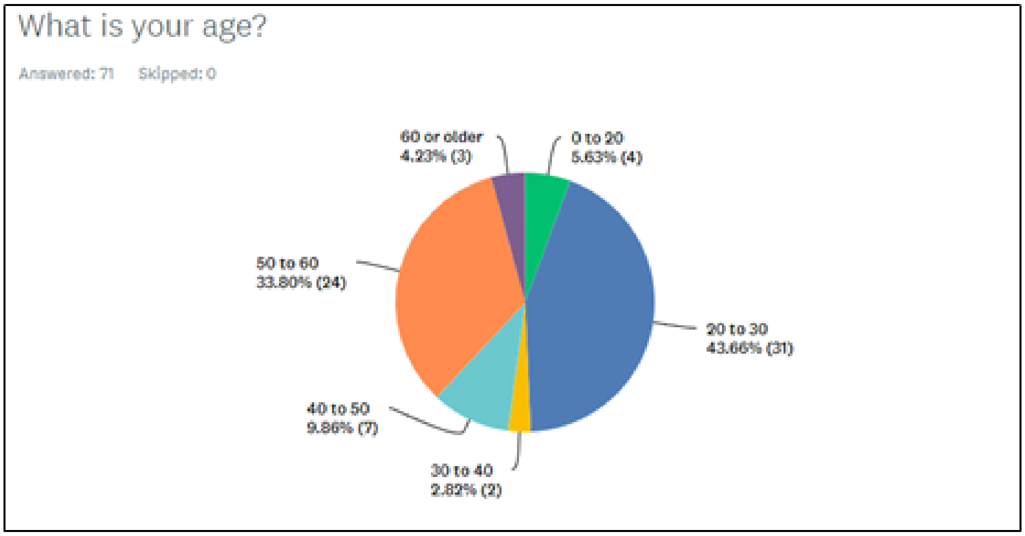

Figure A1: Question 1 Results

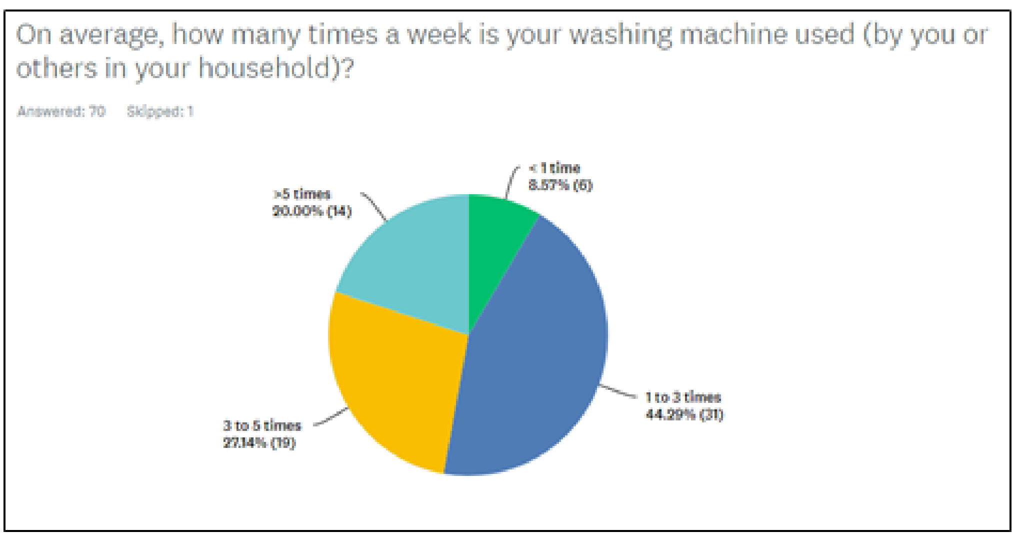

Figure A2: Question 2 Results

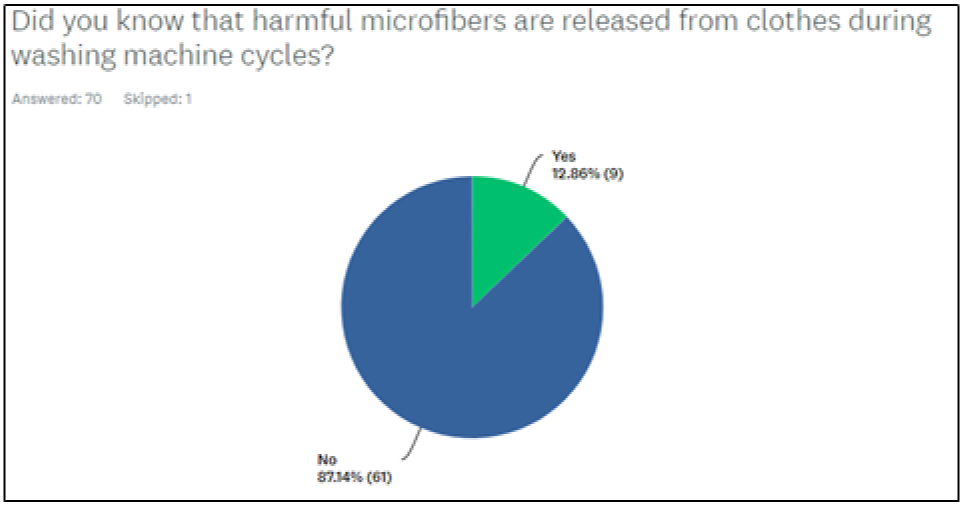

Figure A3: Question 3 Results

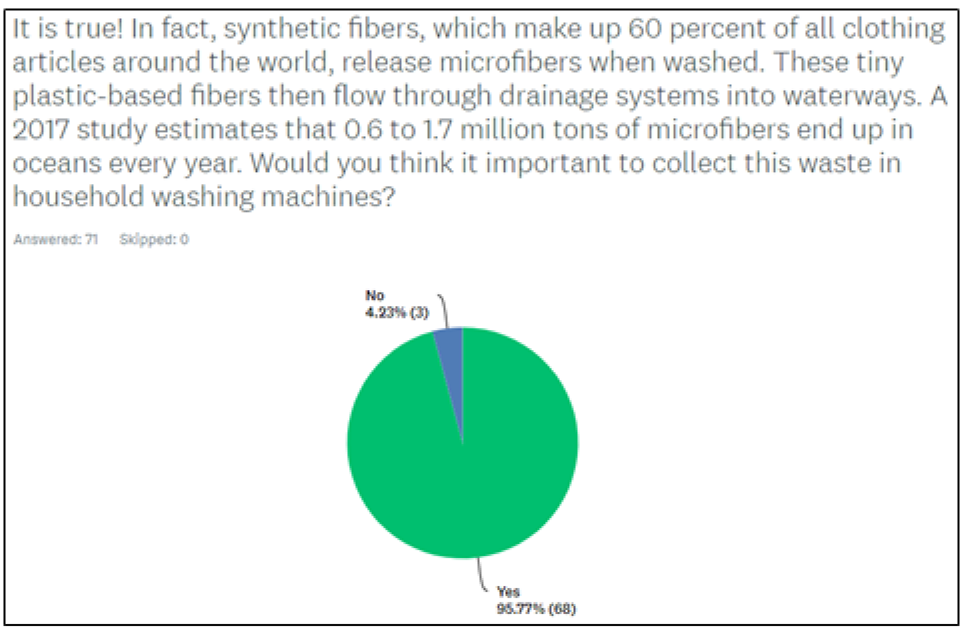

Figure A4: Question 4 Results

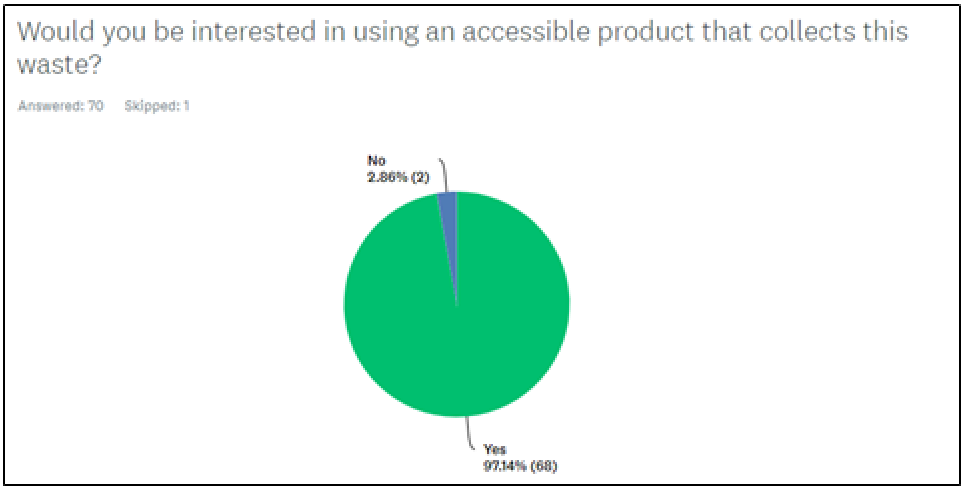

Figure A5: Question 5 Results

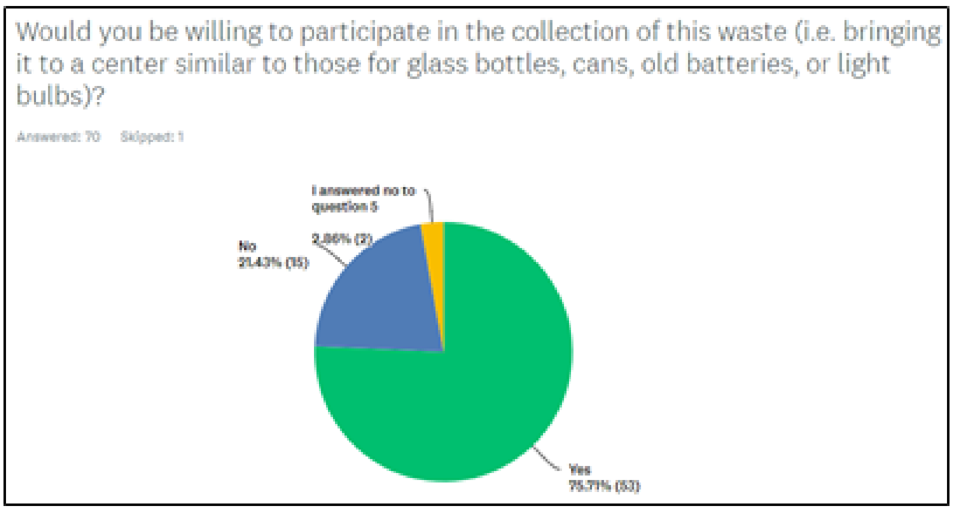

Figure A6: Question 6 Results

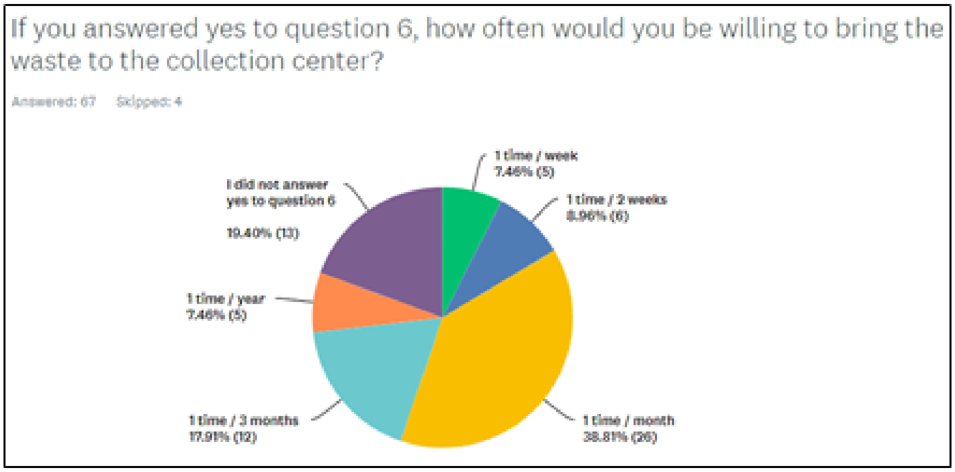

Figure A7: Question 7 Results

Do you have any remarks on this issue?

Answered: 35 Skipped: 36

- "This information should be made more public"
- "Thanks for raising my awareness. Creating it actually. I had no idea this was an issue."
- "This sounds like a very important issue and of course I would like to be part of the solution but I can't help but wonder if there isn't a better way than having to drive to a special facility to dispose of the fibres."
- "Microfibre waste is very important. I'm more interested as a consumer in how the manufacturers are going to solve the problem, not pass the cost of solving the problem down to the end product consumer."
- "how does this not slow the cycle down due the increased filter at the output which is normally high flow. What happens if the filter clogs?"
- "Does the amount of microfibers released vary depending on the temperature of the water? (Warm VS Cold cycle)"
- "99% of people will not go to bring the plastic to collection centers, it is too time consuming. Find another way. cool."

Figure A8: Sample Answers for Question 8

Appendix B

Existing Technologies

Figure B1: *Lint LUV-R* filter after installation

(credit: http://www.environmentalenhancements.com)

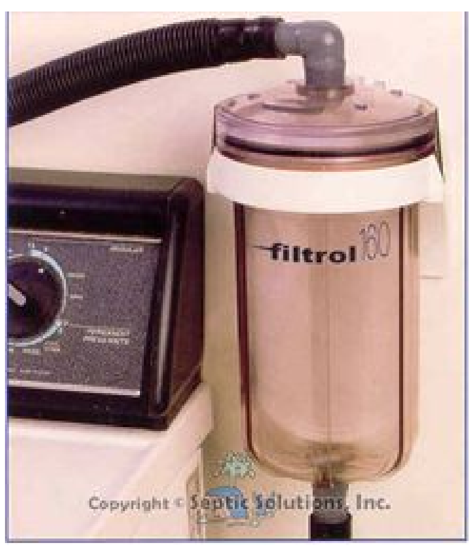

Figure B2: *Filtrol 160* after installation **(credit: http://www.septicsolutions.net/store/Images/Filtrol160/Filtrol160_LG.jpg)**

Figure B3: The *GuppyFriend* washing bag

(credit:https://guppyfriend.langbrett.com/wp-content/uploads/2017/09/LANGBRETT_STOP-MICRO-WASTE_GuppyFriend_Inhalt_offen.jpg)

Figure B4: The *Cora Ball* **(credit: http://rozaliaproject.org/wp-content/uploads/2017/03/for-Kickstarter-imagery.002.jpeg)**

Appendix C

Supporting Calculations

The specific gravity was calculated using equation (1), below. The density of water was taken from the Engineering Fluid Mechanics Textbook, by Crowe *et al*. (2009), for each cycle temperature, being 999 kg/m³ at 15℃, 996 kg/m³ at 30℃, and 983 kg/m³ at 60℃.

(1) $\gamma = \rho g$

where,

γ = specific gravity [N/㎥]

ρ = density of water [kg/㎥]

g = gravity [m/ s^2]

Cold cycle, @ 15℃

$$\gamma = \rho g$$

$$\gamma = (999\ kg/㎥)(9.81\ m/s^2)$$

$$\gamma = 9800.19\ N/m^3$$

Warm cycle, @ 30℃

$$\gamma = \rho g$$

$$\gamma = (996\ kg/㎥)(9.81\ m/s^2)$$

$$\gamma = 9770.76\ N/m^3$$

Hot cycle, @ 60℃

$$\gamma = \rho g$$

$$\gamma = (963\ kg/㎥)(9.81\ m/s^2)$$

$$\gamma = 9447.03\ N/m^3$$

In order to calculate the velocity of the system, the cross sectional area of the pipe had to be known. This was calculated using a diameter of ¾ in. or 0.01905 m. This calculation follows, using the equation (2) for area

(2) $A = \frac{\pi}{4}D^2$

where,

A = area [m^2]

D = diameter [m]

$$A = \frac{\pi}{4}D^2$$

$$A = \frac{\pi}{4}(0.01905m)^2$$

$$A = 2.850 \times 10^{-4}m^2$$

The inlet velocity of the system was calculated using the area and flow from the washing machine, which is 1.577 L/s. The equation used to compute this is shown below, equation (3), and the associated calculation follows.

(3) $V = \frac{Q}{A}$

where,

V = velocity [m/s]

Q = flow rate [m^3/s]

A = area [m^2]

$$V = \frac{Q}{A}$$

$$V = \frac{0.001577m^3/s}{2.850\times10^{-4}m^2}$$

$$V = 5.533m/s$$

The kinematic viscosity of water was taken at the three temperatures of the different cycles, in order to calculate the Reynolds number. These values were taken from the Engineering Fluid Mechanics textbook, by Crowe *et al*. (2009), and are as follows:

Cold cycle, @ 15℃ $\upsilon = 1.14 \times 10^{-6}\ m^2/s$

Warm cycle, @ 30℃ $\upsilon = 0.800 \times 10^{-6}m^2/s$

Hot cycle, @ 60℃ $\upsilon = 0.474 \times 10^{-6}m^2/s$

The Reynolds number was calculated using the found kinematic viscosities, the calculated velocity, and the pipe diameter of ¾ in. or 0.01905 m. The equation used for this calculation equation (4) below, and the associated calculations follow.

$$(4)\ Re = \frac{VD}{\upsilon}$$

where,

Re = Reynolds number

V = velocity [m/s]

D = diameter [m]

υ = kinematic viscosity [m²/s]

Cold cycle, @ 15℃

$$Re = \frac{VD}{\upsilon}$$

$$Re = \frac{(5.533m/s)(0.01905m)}{1.14\times10^{-6}m^2/s}$$

$$Re = 92\ 459.34$$

Warm cycle, @ 30℃

$$Re = \frac{VD}{\upsilon}$$

$$Re = \frac{(5.533m/s)(0.01905m)}{0.800\times10^{-6}m^2/s}$$

$$Re = 131\ 754.56$$

Hot cycle, @ 60℃

$$Re = \frac{VD}{\upsilon}$$

$$Re = \frac{(5.533m/s)(0.01905m)}{0.474\times10^{-6}m^2/s}$$

$$Re = 222\ 370.57$$

Once the Reynolds number was known, the friction factor could be determined. This was computed according to equation (5) below. The friction factor was computed for the water at each of the 3 different washing cycle temperatures.

$$(5)\ f = \frac{64}{Re}$$

where,

f = friction factor

Cold cycle, @ 15℃

$$f = \frac{64}{Re}$$

$$f = \frac{64}{92459.34}$$

$$f = 6.922 \times 10^{-4}$$

Warm cycle, @ 30℃

$$f = \frac{64}{Re}$$

$$f = \frac{64}{131754.56}$$

$$f = 4.858 \times 10^{-4}$$

Hot cycle, @ 60℃

$$f = \frac{64}{Re}$$

$$f = \frac{64}{222370.57}$$

$$f = 2.878 \times 10^{-4}$$

Using this information calculated above, and equation 6 below, the head loss was calculated, as shown below:

$$(6)\ h_f = f\frac{L}{D}\frac{v^2}{2g}$$

Where,

h_f = pipe head loss [m]

f = friction factor

L = length of pipe [m]

D = diameter of pipe [m]

v = velocity [m/s]

g = force due to gravity [m/s²]

Cold cycle, @ 15℃

$$h_f = f\frac{L}{D}\frac{v^2}{2g}$$

$$h_f = (6.922 \times 10^{-4})\frac{1.5m}{0.01905m}\frac{(5.533m/s)^2}{2(9.81m/s^2)}$$

$$h_f = 0.0850m$$

Warm cycle, @ 30℃

$$h_f = f\frac{L}{D}\frac{v^2}{2g}$$

$$h_f = (4.858 \times 10^{-4})\frac{1.5m}{0.01905m}\frac{(5.533m/s)^2}{2(9.81m/s^2)}$$

$$h_f = 0.0597m$$

Hot cycle, @ 60℃

$$h_f = f\frac{L}{D}\frac{v^2}{2g}$$

$$h_f = (2.878 \times 10^{-4})\frac{1.5m}{0.01905m}\frac{(5.533m/s)^2}{2(9.81m/s^2)}$$

$$h_f = 0.0354m$$

For now, the hydrostatic pressure was calculated to determine the pressure exerted by water in the pipe. To do so, equation 7, as seen below, was used. This calculation follows, based on the three different specific gravities, as the density of the water varies with the three different cycle temperatures.

$$(7)\ p = -\gamma\Delta z$$

where,

$p =$ Hydrostatic pressure [Pa or N/ m^2]

γ = specific gravity [N/m²]

$\Delta z =$ change in elevation of the discharge hose [m]

Cold cycle 10℃

$$p = -\gamma\Delta z$$

$$p = -(9800.19\ kg/m^2)(1.5m - 0.1m)$$

$$p = -13720.266\ Pa$$

Warm cycle 30℃

$$p = -\gamma \Delta z$$

$$p = -(9770.76\ kg/m^2)(1.5m - 0.1m)$$

$$p = -13679.064\ Pa$$

Hot cycle 60℃

$$p = -\gamma \Delta z$$

$$p = -(9447.03\ kg/m^2)(1.5m - 0.1m)$$

$$p = -13225.842\ Pa$$