Hotshot Drain Water Heat Recovery System

ME 450
21 April 2009

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ABSTRACT
A significant portion of a typical household's energy bill comes from hot water heating. Among the processes within a home that use hot water, the shower consumes the majority of this energy. The Hotshot aims to reduce the shower's energy demand by capturing heat from the outgoing grey water and transferring it to the showers incoming cold water stream, thus reducing the demand on the water heater. This will reduce both the cost of using the shower and ultimately reduce a family's carbon footprint. The system uses a gravity fed plate heat exchanger (PHE) that is typically installed in the basements. Drain water from the shower is run through the heat exchanger and then is diverted back to the home's primary drain. The system is to be designed and tested with an emphasis on maintenance, cost efficiency, and installation. A product that meets these design requirements with documentation will be attractive to a large number of consumers, and in turn, will create a successful business.

EXECUTIVE SUMMARY

The average American family spends nearly $300 a month on energy bills. This, combined with a trend towards reducing carbon footprint, have people rethinking many of their daily habits in an effort to save energy and money. Within the home, the shower accounts for a significant portion (25%) of total energy expenditures and is the greatest source of water heating cost. This has led Mr. Jack Griffith, founder of Infrared-Energy Analysis, to invent the Hotshot. Mr. Griffith and his company perform residential energy audits and believe the Hotshot will help customers further reduce their energy bills.

Mr. Griffith has developed a prototype Hotshot whose primary component is an AIC LB31-30 flat plate heat exchanger (PHE). The PHE transfers heat from the shower's grey water to the shower's incoming cold water stream, reducing the amount of hot water, and energy, required to shower. Mr. Griffith has requested that we address a number of issues surrounding the prototype including clogging of the filter and heat exchanger and quantifying the benefits of the system.

Since we are approaching this from an entrepreneurial stand point, we had to determine if the Hotshot provided a sound base for a business investment. This included quantifying the savings possible from the system and determining what kind of families would subsequently benefit from it within a five year period. We determined that the cost savings possible from the Hotshot depend on a number of factors including: the number of showers taken per day, the duration of those showers, the type of water heater used, and the average cold water temperature. A Monte Carlo simulation was preformed as a way to combine all of these variables and produce a distribution curve showing the savings of households across the country. Our results showed that the mean savings for families with natural gas is approximately $71 per year, while the mean savings for families with electric water heaters is approximately $160.

Through decomposing the Hotshot's functions, we find that it must perform a number of tasks beyond the obvious transfer of energy. Our work on the Hotshot can be divided into four parts: the filter, attachment of the filter, a bypass system and the heat exchanger. We have developed a design that meets a set of engineering specifications for each sub function. Physical characteristics of the Hotshot have been chosen based on our parameter analysis; however, certain design parameters must be tested for.

To validate the engineering specifications we performed several tests on the heat exchanger. We decided to test the AIC LB31-40, which we found maximized transfer area with respect to cost. This PHE is one level larger than the current Hotshot prototype. We varied the temperature and flow rate at all the PHE ports and determined the effectiveness. Effectiveness was shown to correlate well with reference data and varied from 10% to 80% depending on showering conditions. Despite this range, we have shown the Hotshot is still cost effective for many households, specifically large families in colder climates. We were able to create a savings calculator from this data that will serve as a valuable marketing tool. We also found that the current PHE does not affect pressure at the shower head. We recommend that more testing be conducted for higher performing, more restrictive PHE's.

We also performed several tests on the filter to validate engineering specifications. We found that no filter had a negative impact on showering performance. We therefore recommend the finest filter be used to prolong PHE life. Life cycle testing should be completed for the filter to verity the specified maintenance interval.

Once our tests data was complied we addressed the environmental impact of the Hotshot. We found that the Hotshot is a sustainable technology as it offsets more energy than it is required to produce and maintain. Based on our testing and analysis we feel that the Hotshot has the potential to be a successful product. Some remaining challenges include further testing, marketing, mass production and distribution

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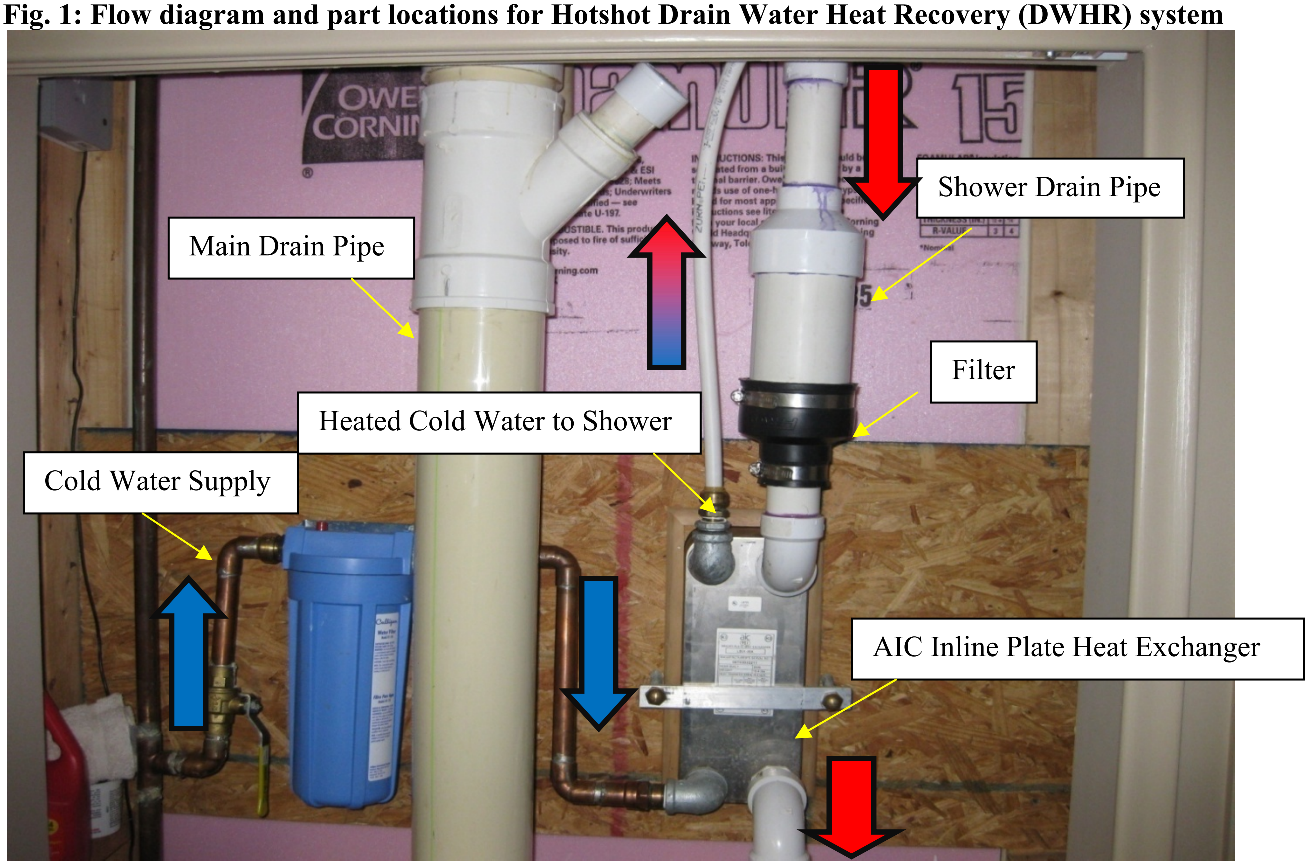
PROBLEM DESCRIPTION AND STATE OF PROTOTYPE

Rising energy costs and increasing environmental awareness has led consumers to demand energy saving products. One potential area for energy savings exists in the heating of residential water, specifically the heating of shower water. The average household in the entire United States spends \$170 (standard deviation \$90) a month on energy costs, 60% of which goes to space heating, 25% of which goes to water heating and the rest goes to other uses such as cooking and lighting [4]. Mr. Jack Griffith, founder of Infrared-Energy Analysis, LLC., provides in-home energy appraisals and is acutely aware of a shower's energy consumption. Thus, he has spent the last two years researching and developing a product he calls 'The Hotshot' shown in Fig. 1. The Hotshot is intended to reduce the required natural gas or electricity used to heat water for a shower. The Hotshot reclaims heat from drain water through a flat plate heat exchanger (PHE) to pre-heat the incoming cold water. The idea is that less hot water will be required for a comfortable shower, which reduces the consumers' energy bill and environmental impact. However, Mr. Griffith has encountered a problem with debris from the shower collecting in the filter and fouling the heat exchanger. Thus, Mr. Griffith has requested that we design a filter to prevent the blockage and make recommendations to improve the efficacy of the Hotshot. Mr. Griffith has also requested that we quantify the potential energy savings.

Fig. 1: Flow diagram and part locations for Hotshot Drain Water Heat Recovery (DWHR) system



BENCHMARKING

We investigated several competitive Drain Water Heat Reclamation (DWHR) models as reference for our design process. We also investigated the various types of heater exchangers and filters available to ensure our product operated as efficiently as possible.

Competitive DWHR Systems
Competing products were examined to compare against the Hotshot. The concept of DWHR is a relatively new idea and has been around for since the 1980s (US patent number 4,304,292). Common DWHR systems can be divided into two categories, copper coil and flat plate.

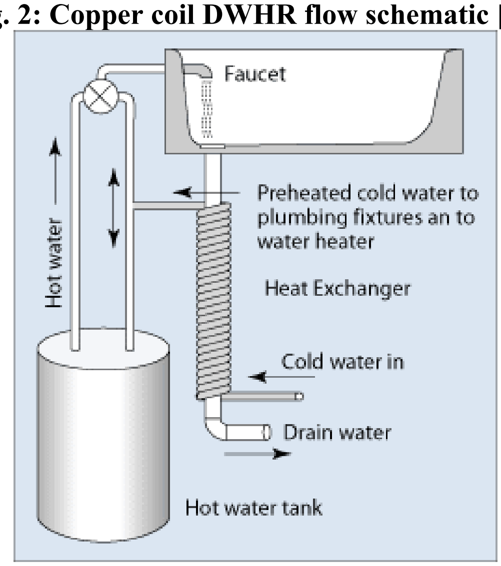
Copper coil DWHR systems: The first type of DWHR is the most common and consists of copper water lines wrapped around a main drain pipe. This system is used by GFX, the Power-Pipe, and the ReTherm. Each of these products extracts heat from shower drain water to preheat incoming cold water before entering the homes water heater as shown if Fig. 2. The efficiencies of each of these products were determined in a series of tests run by the Canadian Centre for Housing Technology [5]. The results for the tests are summarized in Table 1 below for competing 60 inch products.

Table 1: Competitive 60" copper coil DWHR efficiency and price

Model	Efficiency	Price
Power Pipe R3-60	55%	$830
GFX	48%	$634
ReTherm SC-60	43%	$715

One of the advantages of this type of DWHR is that it simply replaces a section of a home's main drain pipe and requires no more additional maintenance than a normal drain pipe. A drawback to this type of heat exchanger is that it is not as efficient as others (See Heat Exchanger Benchmarks). Copper Coil Heat exchangers must be quite long in order to maximize efficiency (models range from 30 inches to 60 inches). Additionally, each of these products reroutes water to a storage tank and are not compatible with tank-less water heaters.

Fig. 2: Copper coil DWHR flow schematic [28]



Flat plate DWHR systems: The EcoDrain is a product that has recently been introduced in Canada and is not available in the United States. EcoDrain representatives quoted us by email the cost of the unit at $500 for their horizontally orientated model. This model allows for installation directly below the shower, as it is connected directly to the shower drain and preheats the incoming cold water line similar to the Hotshot. EcoDrain claims to reduce water heater use by 25%-40% although there are no independent studies available to confirm this claim. EcoDrain uses a non-stick coating and larger plate spacing than conventional PHEs to avoid fouling. Larger plate spacing, however, is less efficient for heat transfer.

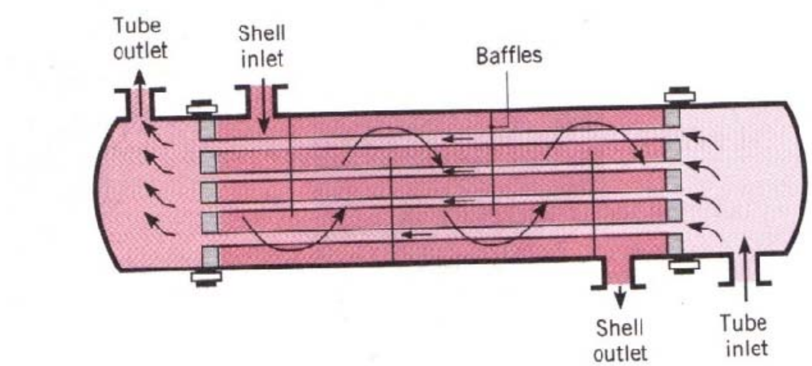
Another drawback of this product is that it needs to be installed below the shower, which makes it difficult to be retrofitted to existing homes.

Heat Exchanger Benchmarks

A wide variety of heat exchangers are available on the market. We focused on three types deemed suitable for the Hotshots: Shell and Tube Heat Exchangers (STHE), Plate Heat Exchangers (PHE) and Spiral Plate Heat Exchangers (SPHE). The relative benefits of each type of heat exchanger are discussed by Mr. T. Kuppan in the Heat Exchanger Design Handbook [15]. Through his analysis we were able to determine that the PHE was best suited for our application.

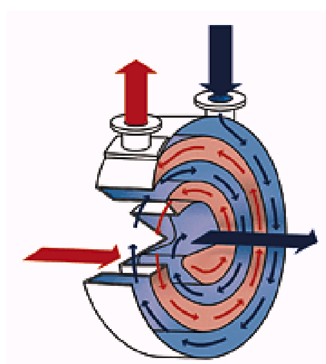
Shell and tube heat exchanger (STHE): STHE typically consist of concentric tubes in which fluid flows as shown in Fig. 3 below. The GFX and ReTherm DHWR units are essentially STHEs. According to Kuppan, STHE are typically used for high pressure applications (exceeding 30 bars). Since residential showering is not characterized as a high pressure operation, a STHE may not be the optimal heat exchanger or our application. Kuppan also states that fouling in PHE occurs at 10-25% the frequency of STHE and that PHE has a heat transfer ratio 3-5 times that of STHE.

Fig. 3: Flow schematic for a typical STHE [29]



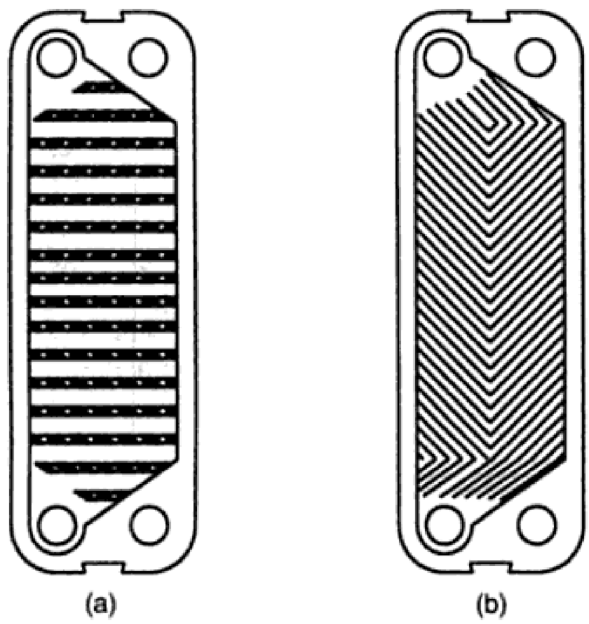
Spiral plate heat exchangers (SPHE): Spiral Plat Heat Exchangers transfer heat as shown in Fig. 4 below. To date, there are no known DWHR units that employ a SPHE. SPHE are used in applications where fouling is a major concern. According to Kuppan, the arrangement of the plates creates a scrubbing action which prevents the buildup of debris. The anti-fouling properties of a SPHE are desirable for DWHR because of the shower debris tends to accumulate in the heat exchanger. However, Kuppan also states that SPHE tend to fatigue when there is a high degree of thermal cycling. Common shower usage may pose a problem for SPHE .

Fig. 4: Flow schematic for the Alfa Laval Thermal, Inc. SPHE [REF]



<u>Plate heat exchanger (PHE)</u>: A PHE is the current heat exchanger used in the Hotshot and the Ecodrain DWHR units. A PHE is more efficient than the STHE and is able to withstand thermal cycling unlike the SPHE. However, PHE cannot withstand large pressures and temperatures. The physical limits for common PHE gaskets are pressures exceeding 300 psi and temperatures exceeding 300 F [15]. The operation conditions for DWHR (80 psi, 120 F) are well below these limitations. However, the pressure and temperature constraints may be avoided if a PHE is brazed and therefore does not contain any gaskets. Brazed PHEs are typically more compact and less expensive than frame and plate (gasket) PHEs. PHEs come in a variety of corrugation types, the two most common are shown below in Fig. 5 where (*a*) is a washboard corrugation and (*b*) is a chevron or herringbone corrugation. Washboard PHE's are less prone to fouling and operate at lower temperatures. Chevron PHE's are typically more efficient but contribute to larger fluid head loss [15]. The plates also come in a variety of materials; some common materials are AISI 304 and AISI 316 stainless steel [16].

Fig. 5: Corrugation types for PHE [REF]



Filter Benchmarks

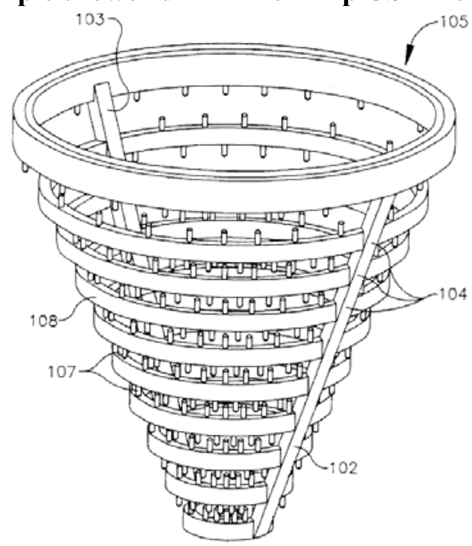
The fouling concerns previously discussed for heat exchangers may be addressed by filtering the incoming fluid. In our case, DWHR heat exchangers are clogged with hair and other shower debris. Listed below are several filters we have considered.

<u>Wire mesh filters</u>: Mesh filters come in a variety of materials, shapes and sizes. Human hair diameter ranges from 17 μm to 181 μm, so we are interested in filters on that order (No. 400 – No. 4) [17]. Mesh filters at this rating are generally inexpensive, ranging from $1.09 to $40.16 per square foot depending on material, where plastic filters and typically less expensive than metal filters [18]. Filters made of Nylon, Polypropylene (PP), Polyethylene (HDPE) and Polytetrafluoroethylene (PTFE) are resistant to rust and corrosion but may degrade in the presence of chemicals, such as Drano or Liquid Plumber, as discussed in the filter material selection section on p. 23. Metal filters like chemically etched stainless steel are also resistant to rust and corrosion but are much more expensive. Mesh filters may be cut in the variety of shapes or rolled into cylindrical tubes, where tubes typically have a higher debris capacity [19].

Liquid filter bags: Liquid filter bags are employed in a variety of industrial applications, most notably in distillation and wine fermentation. The capacity and efficiency of liquid filter bags is defined by ASTM F795-88. Capacity and efficiency are competitive processes, considering liquid flow is more restricted as debris accumulates. Filter bags rated to 10 microns have efficiencies ranging from 90% to 94%, meaning 90% of particles 10 microns in size would be blocked, and capacities ranging from 180 to 215 grams at 35 psid and 12 gpm [20]. Filter bags come in a variety of sizes, however, the smallest filter available from Filtration Systems or Purolator Facet, Inc. was 4" OD and 8" in length [21]. Liquid Filter Bags have a higher capacity than wire mesh filters and therefore need to be changed less frequently. However, a liquid filter bag's high capacity may affect heat exchanger and shower performance by restricting flow rate..

Shower drain traps: Typical drain traps fit over the existing shower drain to remove hair and other debris. Fig. 6 below shows a patented shower drain trap (US Patent 6487729) which as concentric rings and prongs to collect hair. Shower drain traps are inexpensive and are easy to change. However, these filters are not as efficient as wire mesh filters or liquid filter bags because they have much larger micron ratings. A shower drain trap could be used in series with another filter.

Fig. 6: Example shower drain filter trap US Patent 6487729



Backwash cleaning: Backwashing is a filter cleansing process commonly used in swimming pools and water softeners. As debris accumulates on a filter, water is forced through the opposite side to clean the filter. The debris is suspended in water and drained away leaving a clean filter. An advantage of a backwash system is that filters would never have to be changed. However, for DWHR systems a pump may be required to execute a backwash, which adds cost and complexity to the system. To automatically backwash a filter, sensors, actuators and integrated circuits would likely be required. A system could be manually backwashed which would require turning several valves in sequence.

Packaging

The Hotshot should be packaged into a self contained unit to facilitate the ease of installation. An outer housing with plumbing fixtures and mounting attachments would decrease installation time. The housing would also contain the main components of our design including the heat exchanger, filter and plumbing pipe. Several packaging benchmarks were explored, namely the outer housings for Tankless Water Heaters (TWH). TWHs have standard copper water connections ranging from ½" Male National Pipe Thread (NPT) to ¾" Male NPT [16]. TWHs are also designed to be sleek and come in a variety of sizes. A representative TWH, the Bosch Tankless Water Heater 1600P LP, had dimensions of 25.75" x 16.75" x 8.5" and weighed 37 lbs [16]. The Hotshot packaging design would be limited by the heat exchanger (17 lbs and 12" length for current AIC LP31-30 PHE) and filter design (4"-8" OD standard waste drain pipe) [22]. Typical TWHs are fastened directly to housing support studs. Common TWHs cabinets are made of aluminum; however PVC or other plastics may also perform satisfactorily [16].

COST ANALYSIS

There are a number of factors that determine how much savings a family can expect with the Hotshot installed in their home. Obviously, the number of people in the home and the duration of their showers are primary factors. However, there are a number of less obvious considerations that affect savings. For example, the type of hot water heater has a large effect. Natural gas heaters are drastically less expensive than their electric counter parts [7]. Furthermore, the Hotshot will be most efficient in cold climate areas, where the incoming cold water can be substantially lower temperature than other parts of the country.

In order to combine all of these unknowns, and determine the percentage of households that would benefit from installing the Hotshot, we ran a Monte Carlo simulation to produce a distribution (Fig. 7). The simulation included the averages and standard deviations of the various residential water usage statistics from sources DOE and REUW, and randomized them through five thousand trials [1] [8]. The simulation used energy prices that were national averages, rather than region specific. Data concerning the averages and standard deviations of variables such as shower length, shower flow rate, and population data were amassed from a number of sources and can be found in Appendix B.

Fig. 7: Annual savings from Hotshot with natural gas and electric water heaters

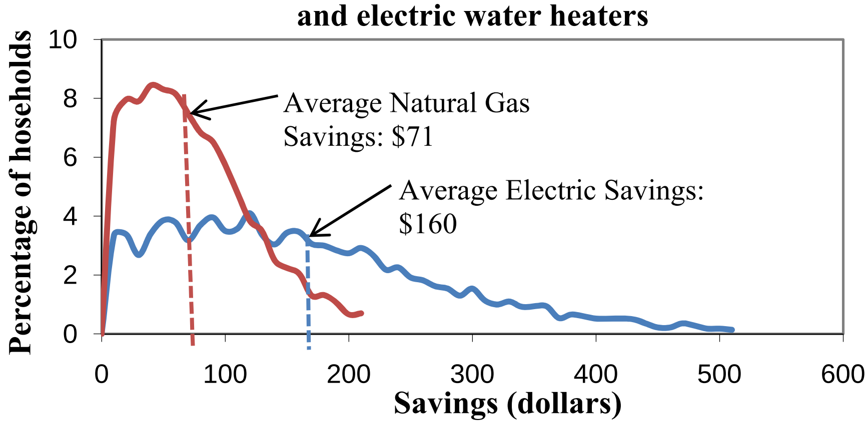


Fig. 7 represents the distribution of savings for homes with either natural gas or electric water heaters. The mean savings for families with natural gas is approximately $71 per year, while the mean savings for families with electric water heaters is approximately $160.

Based on the opinion of Jack Griffith, as well as the claims of competitors, we aim for the Hotshot to pay for itself in energy savings within five years for the majority of our customers. A $500 price point is competitive with the rival products on the market and corresponds with Jack Griffith's price estimate. Adding to the cost of the unit, we must account for the installation fees of hiring a plumber. This adds $75-$113 of labor costs [11]. Considering that we aim for the unit to be paid back in five years the future value of this initial investment must be considered. We assumed a 5% interest rate. In order to have paid off the cost of the Hotshot within five years a family must save at least $146 dollars per year. While only about 10% of homes with natural gas water heaters achieve this savings, over 50% of homes with electric heaters achieve a savings of $146 or greater.

DEMOGRAPHICS

From the cost analysis of the Hotshot it is apparent that there are a large number of people that could profit from the Hotshot after five years. According to Roberts [3], 10% of the population would be interested in purchasing a product with a five-year payback period and therefore are potential Hotshot buyers. In this section we will define the demographics associated with these consumers. A typical Hotshot consumer would own his or her homes and are settled in his or her current location. People who rent or may relocate in the near future lack the long term financial incentive to make such an investment. The home would have a basement to ensure there is access to the drain pipe, and it would be located in a cold climate where consumers are more aware of their heating costs. The Hotshot will be marketed to families because they consumer more water and energy. Beyond drawing customers that are trying to save money, we also aim to market the product towards environmentally conscious consumers. Consumers who value the Hotshot's ability to reduce their carbon footprint may make regardless of the payback period. According to green marketing studies, middle income families tend to be the most environmentally conscious consumers. The range of income corresponding to the most disproportionate amount of environmentally conscious people is between $45,000 and $75,000, which corresponds to 25% of the US population [3]. Similarly, the age range of 35 – 60 also corresponds to a disproportionate amount of environmentally conscious people, making up 40% of the US population [3]. Typical Hotshot customers would fall into these age and income ranges.

PROJECT REQUIREMENTS AND ENGINEERING SPECIFICATIONS

Engineering specifications were developed based on the customer needs outlined by our marketing research and benchmarking. Information for several benchmarks is shown below in Table 2; these values are referenced to ensure that the Hotshot can capture a piece of the market.

Table 2: Manufacturer Claims of Competing DWHR Products [2][5][6][9][10]

Product	Type of Heat Exchanger	Highest Model Efficiency (%)	Cost ($)	Savings ($/Year)	Payback Period (Years)	Expected Lifetime (Years)
ReTherm	Copper Coil	43	413-623+Install	150	4	40+
GFX	Copper Coil	48	417-570+Install	85-220	3-5	N/A
Power - Pipe	Flat Plate	55	461-1,231+Install	90-250	2-5	N/A
EcoDrain	Copper Coil	N/A	~$500+Install	50-300	2-10	30+

Installation Specifications

In order for the Hotshot system to be considered easy to install it must meet several design requirements. The first of these requirements is that a single plumber or someone with general plumbing knowledge would be able to install the Hotshot without any additional training. In addition, the Hotshot should not require the use of specialty tools or equipment that would not be available to a plumber. To ensure that the Hotshot meets these requirements, only standard connections should be used for the inlet and outlet pipes which should be clearly labeled. The Hotshot should not be too large or heavy to be lifted by the installer, for this reason the final design must weigh less than 51lbs and be no more than 3' x 2' x 1'. The weight was selected based on the requirements specified by the NIOSH guidelines for one person lifting [23]. The size was estimated from what we deemed a comparable product which is also installed by plumbers; a tank-less water heater [24]. In order to make the Hotshot installation a one man job brackets should be built in to the housing which will allow the enclosure to be supported while lines are connected. These brackets should be placed 16 inches apart to accommodate the most common spacing of interior wall studs which would be used during mounting [24]. Finally, the Hotshot should be retro-fit able in houses with easy access to shower drain pipes. The recommendations came from our sponsor, Jack Griffith, who has worked in real estate for several years.

Maintenance Specifications

The most important design requirements to facilitate maintenance are that the system requires no power (passive), and that the system will continue to function if clogged. Mr. Griffith has observed that the prototype installed in his home frequent backs up (every 2-3 weeks). Thus, Mr. Griffith has requested a new filter design that will eliminate the clogging problem and will only require biannual cleaning. Access to the filter should not require the use of any tools. The entire system must also be resistant to debris such as sand, harsh chemicals such as Drano, hard water, and freezing water. The Hotshot should be expected to last several decades, or equivalent to the life of a shower. Lastly, the Hotshot system should remain unharmed if a mechanical pipe clearing is performed.

Performance Specifications

The addition of the Hotshot should not have any perceivable effect on shower performance. The head loss through the heat exchanger should be less than 5 psi, which is comparable to competitive DHWR units [5]. Standard plumbing code dictates a 2.5 gpm volume flow rate for showers; however, low flow shower heads have flow rates near 2.0 gpm [5]. The shower volume flow rate should not be less than 2.0 gpm. Similarly, the drainage flow rate should also be no less than 2.5 gpm in order to prevent the accumulation of water in the tub and the perception of a drain clog for all homes. We also anticipate that the Hotshot will give rise to a transient temperature response. As the Hotshot progressively heats the incoming cold water, the resulting temperature experienced by the consumer could become dangerously high if the shower temperature valves are not adjusted. This is important for small children and the elderly who at a greater risk of scalding at temperatures exceeding 120°F [5]. Mr. Griffith claims that the Hotshot reaches a steady state condition in nearly one minute, we will seek to verify this settling time through our testing. Furthermore, all of the individual components of the Hotshot should handle the previously described ranges for temperature, pressure and flow rate. A summary of all the engineering specifications for the Hotshot is shown in Table 3 on p. 14.

Table 3: Summary of Engineering Specifications for the Hotshot

Specification	Requirement	Conflict
Product Cost	$500	Payback, Cost, Size, Weight
Payback Period	5 years	Product Cost
Filter Cleanings	2/year	Cost
Head Loss	5psi	Flow Rate
Flow Rate	2.5 gpm	Filter
Temperature Limit	120°F	Payback Period
Size Limit	3'x 2' x 1'	Cost
Weight Limit	51 lbs	Cost

CONCEPT GENERATION AND SELECTION

We found that the Hotshot can be broken down into two primary functions, filtration and heat transfer. From our benchmarking analysis we have decided to purchase a PHE, hence we are not designing components associated with heat transfer. We will justify our choice of PHE in the Parameter Analysis Section. However, the filtration aspect of the Hotshot is designable and can be broken into the following sub-functions: filter type, filter attachment and flow by-pass. Several designs were proposed for each sub-function and scored against the design requirements.

Filter Type

The Hotshot's current filter, a simple grate, does not perform satisfactorily. The filter clogs after a couple of weeks and fails to keep debris out of the heat exchanger. The majority of our group brainstorming went into developing inexpensive, robust, replaceable filters.

Planar filters: We knew that we had to create a filter with a greater capacity to collect drain debris. The current grate filter has a small surface area. Once this surface area is covered, the filter fails to pass water and the drain will back up into the shower. With this in mind, we considered the ways to increase the capacity of debris before the filter became impassable. The first, and simplest, idea was to just make a larger grate. While this did increase capacity, it would have to be very large to satisfy our objective of bi-annual cleaning. Along similar lines, it was proposed that we use filters that are in parallel; when one filter clogged the water could flow through side mounted filters (Appendix C.1). However, this appeared to suffer from the same problems as the larger grate: it would be too large. Furthermore, it was not clear that a parallel configuration of filters was better than one large filter of comparable size.

Considering size constraints, a filter made up of many small grates in series was proposed. As shown in Appendix C.1, where the water would travel through progressively finer grates. This would allow large debris to be trapped by the upper grates and small debris would be caught by the lower sections. This system is compact and does add capacity. However, the series filter would be difficult to clean and to service since the middle sections are not exposed.

Conical filters: All of the filters described above become clogged once their flat surface area has been covered with debris. We concluded that the best filter design should be able to fill a *volume* with materials. There are a number of water filters available for home and commercial use that are cylindrical in shape. The water enters along the axis of the cylinder and is forced through the walls of the filter to the outside. Debris is collected within the center of the filter. These systems have a large debris capacity in a compact size and can have excellent filtering properties. Unfortunately, these filters are expensive and would cut into the price savings of the Hotshot. Designs that use the concept of filling a volume of space with debris rather than a flat surface area can be found in Appendix C.2.

Maintenance free filters: Our team investigated a number of filtering systems that could be completely maintenance free. These filters would involve a self cleaning feature, or possibly a backwash system to flush material off the filter. Self cleaning filters often use parallel flow to continually sweep debris off the filter and down a separate drain.

Backwashing filters are often found on larger, more complicated systems that pass large quantities of fluid. Many swimming pools use a backwashing system to flush dirt off the filter. We considered creating a system for the Hotshot that used the cold water pipe to force water the opposite way through the filter and run any dirt out the bypass pipe (Appendix C.3). This would require a number of valves and a filter designed to be backwashed. While the backwashing system could produce a near maintenance free Hotshot, we felt that it added unwarranted complexity and cost to the passive Hotshot design.

Liquid bag filters: It was noted that washing machines have filtering needs similar to the Hotshot, as the drain water contains a large quantity of lint (similar to hair running down the drain). There are a number of washing machine filters that are made of a fine nylon mesh as shown in Fig. 8. The nylon mesh is durable and the bag shape provides the ability to fill a large quantity of material and still pass water. The bag filters can be bought off the shelf in a variety of sizes, ranging from 4” to 20” in diameter and 1-1000 micron rating [26]. The cost of the bag filters depends on the size and micron rating but is in the range of only a few dollars each at single quantity prices (See Appendix E). The bag filter is fairly inexpensive and it can be thrown out and replaced when it becomes full. This eliminates any need for the Hotshot user to have to clean potentially unsafe and foul material from the filter. The main constraint in using the bag filter is developing a means of attaching it and making the filter easily accessible (see Filter Attachments).

Fig. 8: Nylon bag filters come in a variety of sizes, materials and micron ratings

Filter Selection: Our team selected the filter bag as our filter for the alpha design based on our scoring matrix shown in Table 4 on p. 16. The table summarizes the advantages and disadvantages of all the filters considered relative to the Hotshot’s current grate filter, where the values are 1 for much worse, 2 for worse, 3 for the same, 4 for better and 5 for much better. The bag filters is exceptional because it is inexpensive, comes in a variety of sizes and micron ratings, has a large capacity for debris, and is disposable.

Table 4: The nylon mesh bag will be developed as the Hotshot filter

Selection Criteria	Filter Concepts					
	A Larger Grate	B Parallel Filter	C Series Filter	D Cylinder Filter	E Backwash Filter	F Bag Filter
Debris Capacity	4	4	4	5	5	5
Filtering Ability	3	4	4	5	4	5
Ease of Cleaning	3	2	1	2	5	5
Ease of Replacing	3	3	1	3	3	5
Ease of Manufacturing	2	2	2	2	1	4
Projected Cost	2	2	2	1	1	2
Net Score	17	17	14	18	19	26
Rank	4	4	5	3	2	1
Continue this Design?	**No**	**No**	**No**	**No**	**No**	**Develop**

Filter Attachment

Considering that we had chosen the bag filter we had to brainstorm ways to attach it to the Hotshot system. Unlike conventional filters, such as a metal grate or a solid cylindrical filter, the bag filter offers little mechanical interface to mount it to the Hotshot. Considering the engineering specification we created designs that were easy to disassemble, water tight and did not require tools.

The first component we examined was how to fix the bag filter to the incoming drain pipe. One simple solution involved sliding the bag filter over the end of the pipe and fixing it in place with zip ties. This was quickly discarded, however, because we were not convinced that the bag would stay in place and we felt it was not a professional solution. To improve on this design we considered putting a ridge on the bottom edge of the drain pipe and fixing the bag filter with a hose clamp (Appendix C.6). The ridge would provide a boundary to keep the clamp and filter from sliding off.

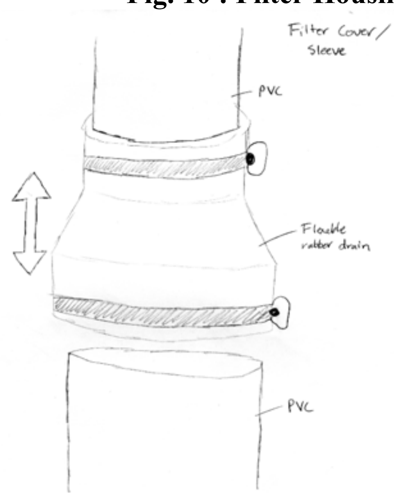
We noted that the filter bags we ordered have a rigid plastic ring around the mouth of the bag that holds the bag open. We sketched a design that uses a tapered and threaded end cap to hold the filter in place as seen in Fig. 9. The bag filter is placed through the end cap until the mouth meets the taper. The end cap is then threaded onto the end of the drain pipe, clamping the filter into place. This design was simple, had few parts, created a solid connection, and would be user friendly. We also felt that the end cap design would convey a professional appearance. Table 5 summarizes our conclusions about the attachment method of the bag filter.

Table 5: The tapered end cap is the best method of securing the bag filter

Selection Criteria	Filter Attachment Concepts		
	A Zip Ties	B Hose Clamp	C Tapered End Cap
Clamping Force	1	2	3
Ease of Use	2	2	3
Filter Access	3	3	2
Professionalism	1	2	3
Net Score	7	9	11
Rank	3	2	1
Continue this Design?	**No**	**No**	**Develop**

Fig. 9: Filter Attachment

Fig. 10 : Filter Housing



<u>Filter housing:</u> The filter bag works differently than many other types of filters in that it is flexible and fluid can pass through it from all directions. We need to enclose it in some way that fluid does not leak, but can still be accessed for replacement. Jack Griffith's prototype Hotshot has a flexible rubber sleeve that is held in place with clamps. To clean the filter he can loosen the clamps and slide the sleeve out of the way. This can be illustrated in Fig. 10 below. We find the rubber sleeve to be a good method of enclosing the filter.

Rather than use hose clamps with flathead screws around the sleeve we would like to instead employ a more robust fastener. In addition, we have specified that accessing the filter should not require any tools. While browsing the hardware store, we came across large hose clamps with wing nuts on them rather than a screw head. Grainger has a quick release clamp as shown in Fig. 11, p. 18. A quick release clamp like this is very easy to use and should be able to hold the sleeve in place.

Fig. 11: A quick release clamp is an easy way to hold the filter sleeve in place

http://www.grainger.com/Grainger/items/2TA51

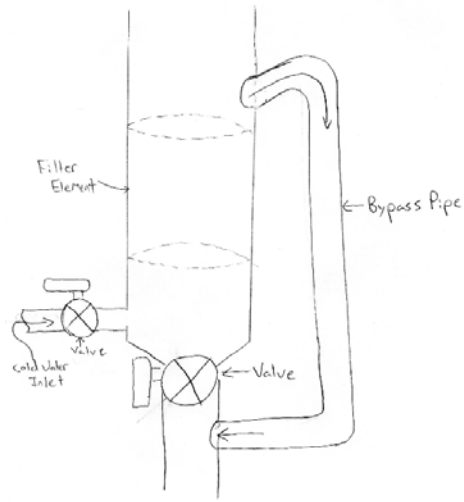
Filter Bypass

Our engineering specifications require that the Hotshot not interfere with normal operation of the shower. The filter, regardless of its size and design, will inevitably fill with debris. When this happens the drain water will back up into the shower, bringing with it unwanted bacteria and filth. In order to maintain normal shower operation even when the filter has clogged we determined that a filter and heat exchanger bypass pipe should be implemented.

The bypass pipe is a simple concept. It places a secondary parallel path for the water to flow in the event that the filter becomes clogged. The bypass will divert drain water around the entire Hotshot system and back to the home's main drain. Initially, we sketched putting a pipe running diagonally downward from the shower's drain pipe located slightly above the filter. We determined, however, that this configuration will cause water to run down the bypass even when the filter is not clogged, reducing the performance of the Hotshot.

To avoid unwanted water from running down the bypass we considered placing a valve at the bypass pipe. This valve would open once the water pressure reached a predetermined threshold. This idea was discarded once we realized we could achieve the same function in a simpler and cheaper way. If we use a bypass shaped like a conventional plumbing 'trap' (Fig. 12) it would require that the water back up to a certain height before it would run through the bypass. This design eliminates unwanted water from entering the bypass. We plan to conduct an experiment to find the optimal height that the bypass should be located (see Test 2, p. 27).

Fig. 12: A trap shaped bypass keeps unwanted water from flowing away from the heat exchanger



ALPHA DESIGN

The alpha design incorporates all of the major functions from our team's concept generation and selection. A mesh bag filter was chosen for its low cost, good filtering capabilities, and large capacity for debris. However, attaching a flexible filter to a rigid pipe posed an interesting design hurtle. The primary consideration in designing the filter assembly was ease of maintenance; we had to figure out a way to make the nylon bag quickly removable yet solidly mounted. To achieve this we incorporated a tapered and threaded end cap that would trap the mouth of the filter to the incoming drain pipe. The bag filter would be enclosed in a flexible rubber sleeve that connected and sealed it to the lower drain pipe. The following CAD drawings illustrate the filter assembly.

Fig. 13: Exploded view of the filter assembly

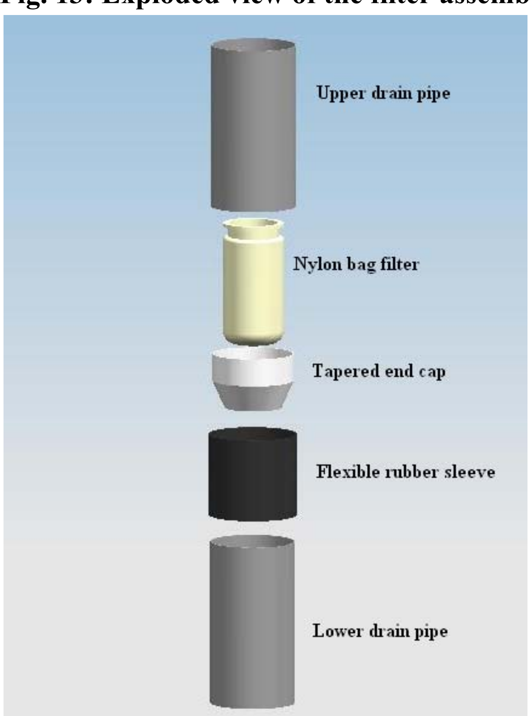
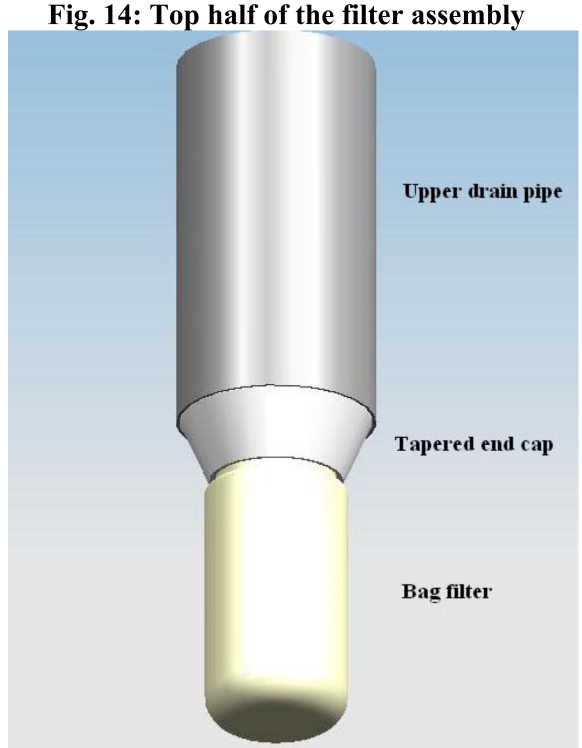


Fig. 14: Top half of the filter assembly



As can be seen from the exploded view (Fig. 13), the nylon bag filter slides into the tapered end cap. The mouth of the bag filter is a rigid plastic ring that interfaces against the taper, keeping it from being pulled through. The end cap and upper drain pipe are threaded to mate with one another. This is best illustrated in Fig.14, and the tight threaded seal will prevent any debris from getting through, even if a small amount of water leaks through due to back pressure.

The complete filter assembly is described in Fig. 15 on p. 20. As shown, a flexible rubber sleeve binds the top and bottom drain pipes, enclosing the filter and forming a water proof seal in the process. The sleeve can be moved up or down to access the filter. Quick release clamps (Figure 11, p. 18) hold the sleeve in place (not shown in CAD model).

As discussed in the concept generation, a filter and heat exchanger bypass is necessary to ensure that the shower will perform normally even if the filter has clogged. We determined that the best way to implement this was with a 'trap' shaped pipe located a certain distance above the filter assembly, as represented in Fig. 16. Should the filter become clogged the column of water would have to rise to the bypass level to be diverted.

ALPHA DESIGN PARAMETER ANALYSIS

According to our functional decomposition, there are two main functions of the Hotshot, filtration and heat transfer. In this section we will investigate how we selected the parameters for the PHE and filter to meet the specifications. Additionally, we will discuss the need for experimentation to assess the uncertainty associated with several Hotshot design parameters.

Fig. 15: Complete filter assembly

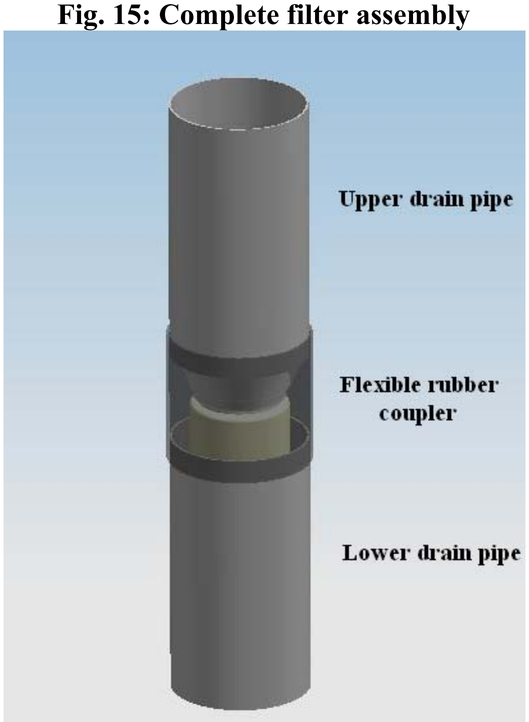
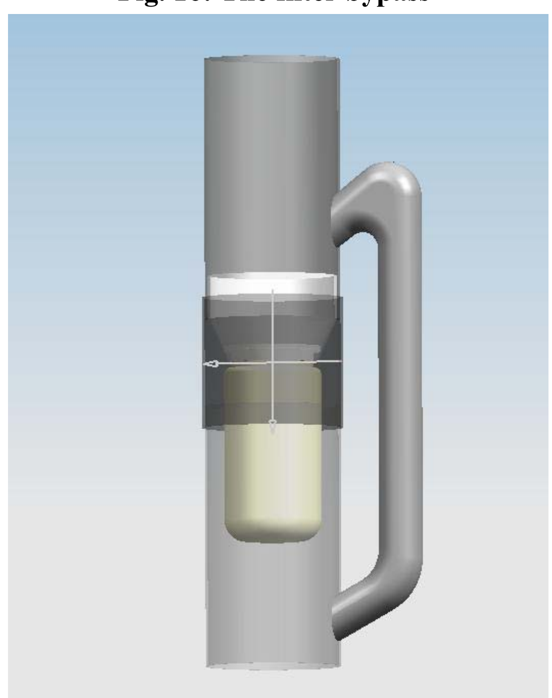


Fig. 16: The filter bypass



Heat Exchanger Parameters
From the previous benchmarking studies we have determined that PHEs are the most effective heat exchangers for our product. However, there are several parameters that may be selected to optimize heat exchanger performance with respect to cost. Reasons for selecting specific plate material, geometry and quantity are discussed in the following sections.

Pressure Drop: As discussed earlier, a common plate configuration for PHE plates are chevron configurations (See Fig. 5, pg 8). Chevron plates are manufactured in a variety of inclination angles, which is defined as the relative angle between plate crests and fluid flow. The current Hotshot heat exchanger, the AIC LB31-30 PHE, has chevron plates at 60° inclination (ΔP = 6.7 psi, Nu = 4.98).

Literature search and calculations: According to the literature, the inclination angle is the most important parameter in determining pressure loss and heat transfer [31, 32]. According to Martin, the friction factor can be approximated within ± 10% for single phase counter flow using the Eq. 2 shown below, where φ is the inclination angle and f is the friction factor:

$$\frac{1}{\sqrt{f}} = \frac{cos\varphi}{\sqrt{btan\varphi + csin\varphi + f_0/cos\varphi}} + \frac{1-cos\varphi}{\sqrt{af_1}} \quad \text{(Eq. 2)}$$

Constants f_0 and f_1 depend on Reynolds number and were calculated to be 7.75 and 2.27 respectively for the current PHE (AIC LB31). For our case, Reynolds number (*Re*) was determined to be 1,114 based on the density (ρ) and viscosity of water (80 psi and 60°F), the volume flow rate (2.5 gpm) and a hydraulic diameter (D_h, 180mm) as defined by Martin according to PHE parameters. Constants *a*, *b* and *c* were determined from Wang to be 3.8, 0.045 and 0.09 respectively. Head loss is related to the friction factor by Eq. 3 shown below where ΔP is the pressure drop across the heat exchanger, *u* is the velocity across the plate channel (0.16 m/s) and L_P is vertical length between PHE ports (444 mm):

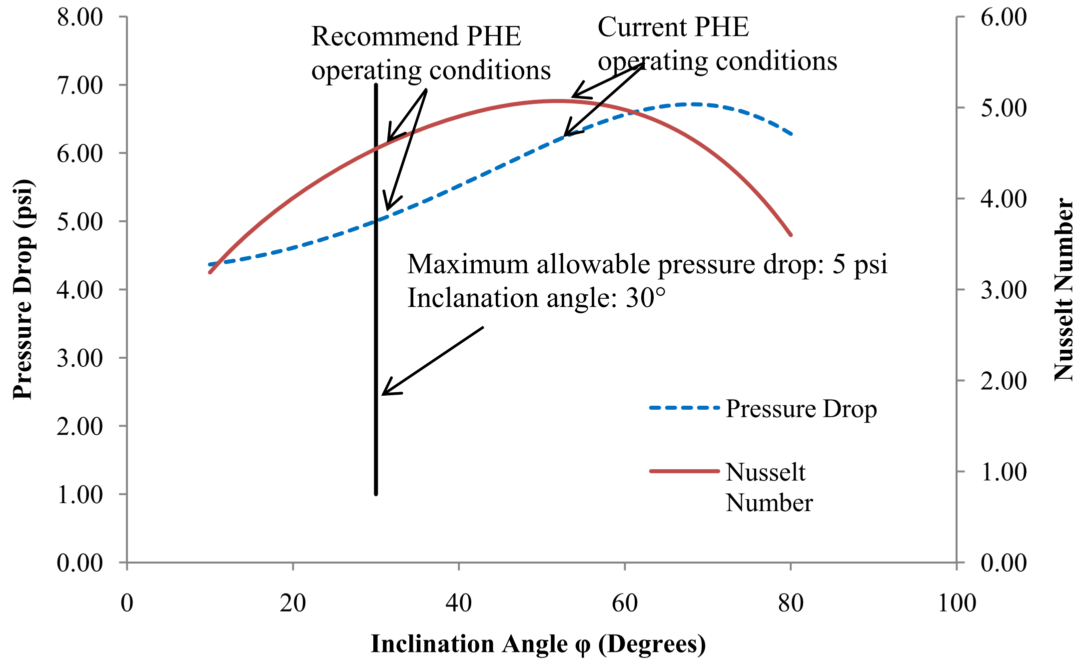
$$f = \frac{2\Delta P D_h}{\rho u^2 L_p} \quad \text{(Eq. 3)}$$

The average Nusselt Number (*Nu*), a measure of convective heat transfer across a surface, also depends on inclination angle as given below in Eq. 4 The Prandlt Number (*Pr*) for water is approximately 7 and the ratio (*d/L*) is defined as the hydraulic diameter (D_h) divided by *sin(2φ).*

$$Nu = 0.40377 f Re^2 \left(\mathrm{Pr}\, d/L\right)^{1/3} \quad \text{(Eq. 4)}$$

Optimization and conclusions: The Nusselt Number and pressure drop were calculated for inclination angles ranging from 10° to 80°, the valid range for the equations. The resulting values are plotted below in Fig. 18 on p. 23. According to our benchmarks of other DWHR systems, we require that the pressure drop across the heat exchanger not exceed 5 psi. This specification ensures that shower performance is not significantly affected by the presence of the Hotshot. From Fig. 18, a 5 psi pressure drop corresponds to 30° inclination. Heat exchanger effectiveness is maximized at the largest value of Nu (5.07 at 52° inclination); however, this inclination corresponds to a pressure exceeding our specifications (6.7 psi at 52° inclination). There appears to be a trade-off between heat exchanger effectiveness, as characterized by Nu, and pressure loss. The ratio of Nu to pressure drop is maximized at a 32° inclination (ΔP = 5.1 psi, Nu = 4.63). At this inclination the pressure drop exceeds the specification by a significantly small amount (2%), therefore we have specified PHE plates have an inclination angle of 30°.

Fig 18: Pressure drops is minimized and PHE effectiveness is maximized simultaneously at φ = 32°



<u>Heat Transfer:</u> For maximum performance, the Hotshot should extract large amounts of heat from the shower grey water and transfer it cold water headed to the shower. The heat transferred from the grey water to the cold water offsets the heat energy required by the water tank and is the source of the consumer cost savings. Hence, large heat transfer rates (q) correspond to large consumer cost savings. For this to occur we would like to maximize the heat transfer rate which is a function of thermal resistance (1/U), plate area (A), and log mean temperature difference (ΔTlm) by Newton's Law of Cooling (Eq. 5):

$$q = UA\Delta T_{lm} \quad \text{(Eq. 5)}$$

From Eq. 5, we can see that there are several ways to increase heat transfer, namely we can increase the effective transfer area and decrease thermal resistance. Ideally, we would increase the temperature differential; however this is a parameter set by the Hotshot's environment and cannot be manipulated in design.

Plate Area: Effective heat transfer area for PHE can be increased two ways, through increased plate area and the addition of more plates. However, cost tends to increase with effective heat area and considering budgetary constraints, and the desired Hotshot marketing price of $500, we sought to maximize transfer area with respect to price. Price and transfer area data were gathered for 58 PHEs from the suppliers Mc-Master Carr, Grainger and AIC Alliance. Please note that the listed prices correspond to a single PHE, additional savings are expected for volume purchases if the Hotshot prototype proceeds to mass production. The PHE data is shown in Appendix F.

Several PHEs were identified as candidate models because of their low cost to area ratios and low total cost (less than $500). The current Hotshot prototype currently works with the AIC LB31-30 which as an effective transfer area of 10.20 sq. ft at a price of $37.84/sq.ft. Our team is plans to test the AIC LB31-40 (13.60 sq.ft at $34.41/sq.ft).

Thermal Resistance: Thermal resistance will, by definition, obstruct the flow of heat. For our product we would like small thermal resistances to maximize heat transfer and energy savings. Thermal resistance can be shown to depend on the convective heat transfer coefficient (*h*), the plate conduction coefficient (*k*), thickness (*L*) and a fouling factor (R_f) as shown in Eq. 6 where subscripts hot and cold fluid flows are denoted by *h* and *c* respectively.

$$\frac{1}{U} = R_{fc} + \frac{1}{h_c} + \frac{L}{k} + \frac{1}{h_h} + R_{fh} \quad \text{(Eq. 6)}$$

Plate Conduction Resistance: The thermal resistance through the plate is typically very small compared to other resistance contributions because the plates are thin and have relatively large conduction coefficients. For the AISI 316 Stainless Steel used in AIC PHE plates, conduction coefficients equal 13.4 W/mK and plate thickness range from 2 mm to 5 mm (L/k = 0.00015 – 0.00037 m^2K/W) [35,36]. There are several more expensive PHE models ($2500 and greater in Appendix F) that utilize Nickel plates instead of stainless steel for its large conduction coefficient (90.7 W/mK).

Plate Convection Resistance: Large values for convection coefficients are required for small thermal resistance and large heat transfer. Much work has been done to quantify convection coefficients for PHEs. J.H. Lin of National Taiwan University performed experiments for single phase fluid flow over PHE plates with various corrugation angles and bend radii. The correlation of his dimensionless data is shown below in Eq. 7 [37]. From this analysis, Dr. Lin concludes that Reynolds Number and corrugation angle have the greatest effect on average Nusselt Number. Descriptions for the dimensionless Pi groups are shown on p. 23 in Table 6 [37]. Measurements for convection coefficients often contain large amounts of error. Dr. Lin claims Eq. 7 is valid within ±30% for the Re range specified in Table 6. A detailed description of each Pi group can be found in Appendix G

$$Nu = 10^{-2.79}\Pi_2^{0.912}\Pi_3^{0.334}\Pi_4^{-0.282}\Pi_5^{0.198}\Pi_6^{0.104}\Pi_7^{0.010} \quad \text{(Eq. 7)}$$

Table 6: Dimensionless Pi Groups for correlation [37]

Dimensionless ∏ groups

Groups	Definition	Effect	Range
Π_1	$h_x D_h/k$	Local Nusselt number	–
Π_2	$\rho V D_h/\mu$	Reynolds number	300–7000
Π_3	R/D_h	Geometry	1.21–3.25
Π_4	x/D_h	Location	1–14.5
Π_5	β	Geometry	$\pi/12$–$\pi/4$
Π_6	$\rho^2 D_h^2 k \Delta\theta/\mu^3$	Temperature difference	1.328E+11–10.507E+11
Π_7	$\mu c_p/k$	Prandtl number	0.703–0.706
Π_8	$h_m D_h/k$	Average Nusselt number	–

Using Eq. 7, we obtained estimates for both hot and cold convective coefficients to be 88.66 W/m^2K and 49.23 W/m^2K respectively for LB31 plates with 30° corrugation angle. The fluid properties were referenced from Incorpera [26] and details are shown in Appendix H. The hot and cold thermal resistances are 0.01 m^2K/W and 0.02 m^2K/W respectively. Note that these values are approximately 100 times larger than the plate convective resistance values. Since Nu strongly depends on Re, hydraulic diameter (D_h, defined in Appendix F) is a key design parameter. However, as shown in Appendix F, there is little variation in D_h among PHEs. The hydraulic diameter for the selected heat exchanger is 7.06. The largest available hydraulic diameter is 13.23 at a PHE cost exceeding $2,000.

*Fouling Factor***:** Finally, fouling also contributes to the thermal resistance. Fouling occurs when a debris film coats PHE plates. The film develops over time and can degrade PHE performance. Since the Hotshot is intended to last for decades and our selection of PHE may not be disassembled for cleaning, it is important to limit fouling. According to Incorpera, fouling factors range from 0.0001 to 0.0009 m^2K/W for domestic water. For our application soap, shampoo and other shower liquids may enter the PHE and contribute to fouling. Little research exists on this topic and our team plans to test the effect of fouling on PHE performance.

Log Mean Temperature Difference: Log mean temperature difference is defined based on the inlet and outlet temperature differences shown below in Eq. 8 [26]. For a counter flow heat exchanger, ΔT1 is the difference between the hot inlet temperature and the cold outlet temperature, and ΔT2 is the difference between the hot outlet temperature and the cold inlet temperature.

$$\Delta T_{lm} = \frac{\Delta T_2 - \Delta T_1}{\ln(\Delta T_2 / \Delta T_1)} \quad \text{(Eq. 8)}$$

Cold outlet temperature and hot outlet temperature are both unknown. The relationship between these temperatures is determined by the PHE effectiveness. However, AIC has informed us that this information is proprietary so additional independent testing will be required. According to a spec sheet provided by AIC, the LB31-30 will produce cold water outlet temperature of 86°F given a 41°F input in Appendix D. We plan to independently evaluate PHEs performance for a range of temperatures

FILTER PARAMETERS

Similarly to the PHE parameters, we have also evaluated filter parameters. The following sections discuss decisions for filter size, material, micron rating and temperature considerations. We will also comment on the uncertainty for each parameter and the need for testing.

Filter Length: Filter bags typically come in two diameters, 4 inches and 8 inches, and a variety of lengths. We have chosen to use a 4 inch diameter filter because they are less expensive and easier to mate with standard PVC pipe and connections. Previously we specified that our filter should only need to be cleaned every 6 months; thus, we need to determine the length of the filter bag. Assuming the properties listed in Table 7 from *Chemical and Physical Behavior of Human Hair* and US Census data we can estimate the length of a filter for bi-annual cleaning ranges between 0.01 and 10.5 inches. These numbers were determined by calculating the volume of hair lost by a family of three in six months. The large ranges for hair loss per day, hair length, hair diameter contribute to this large range. We have chosen to conduct tests on a filter 8 inches in length.

Table 7: Range of Hair Loss [39]

Hair Loss Properties	Minimum	Maximum
Hair Loss Per Day (Strands per Day)	50	100
Average Hair Diameter (μm)	17	181
Hair Length (in)	0	72

Filter Material Selection: Filter bags are made with many different kinds of materials; the most common are polyester, polypropylene and nylon. Each of these materials has different properties which must be taken into account when choosing a filter. For this application it is important that the material used is resistant to the different chemicals which may make their way down a shower drain. A table of how well the different materials resist a variety of common chemicals based on manufacturer specifications is shown below.

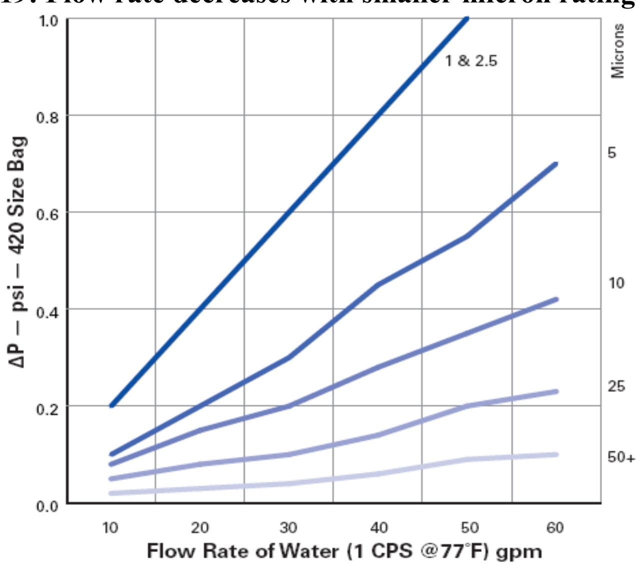
Table 8: Manufacturer ratings for material resistance to various chemicals [24]

Material	Water	Organic Solvent	Petroleum Oils	Alkalies	Organic Acids	Mineral Acids
Polyester	Excellent	Excellent	Excellent	Good	Good	Good
Polypropylene	Excellent	Good	Fair	Excellent	Excellent	Good
Nylon	Good	Excellent	Excellent	Good	Fair	Poor

Polyester felt is the least expensive of the material choices and is available in micron ratings as low as 1 micron. It is also the most resistant to chemical damage of the three materials. The polypropylene is also resistant to most chemicals with the exception of oils. Also this material is more expensive than the polyester felt. Despite not having the best resistance to chemicals the nylon is more durable and is the only filter which the manufacturer recommends for reuse. The nylon mesh is also ideal for higher micron ratings than the other filter materials, all the way up to 1000 microns. This is the most expensive material of the three however all are relatively inexpensive. It was also found that the main component in drain cleaner Drano, sodium hydroxide, is an alkali and should not have a significant effect on any of these materials over their 6-month use period.

Filter Micron Rating: When choosing the correct filter one of the most important attributes is the micron rating, which determines the minimum size of debris that will be allowed to pass through. It is important to know that the micron ratings from the manufacturer for many filter bags is a nominal rating with no specific efficiency in retaining particles and some are absolute rated to be 90% efficient, so it may be necessary to choose a lower micron rating to achieve the desired filtration [25]. The main cause of clogging in the current Hotshot prototype installed in Jack's home is hair. Once hair builds up in an area, soap and other sediment can build up along with it causing a blockage in water flow. However, there is very little literature available on the filtration of hair. Using the diameter of hair as a guide for selecting the micron rating may not be ideal as hair will likely tangle and collect without passing through a larger micron rating. It is important to choose a micron rating that is not too small as the flow rate through the filter is dependant this rating. Fig. 19 on p.25 is from the manufacturer of polypropylene filter bags and shows that the smaller the micron rating is the lower the flow rate in gallons per minute will be.

Fig. 19: Flow rate decreases with smaller micron rating [25]



Unfortunately, the flow rate is also dependant on several other factors such as the surface area of the filter bag, the pressure, and how much sediment has previously built up in the filter. For this reason we will need test a variety of filters to determine if they will provide the greatest amount of sediment filtration while still ensuring that the flow rate remains above the 2.5 gpm specification needed to prevent backups from occurring. The test that will be completed to determine the appropriate micron rating is described in the future plans section on testing.

Pipe material: The most common materials used for plumbing are copper and PVC. In order to determine which material we will use for our tubing, we need to consider cost, manufacturability and thermal insulation. After completing price comparisons on McMaster-Carr, we determined that PVC would be cheaper in the sizes for our pipes, but can increase drastically with thickness [28]. From our previous experience we also know that PVC can be more easily manufactured for our end-cap than copper. In addition, we compared the thermal conductivities of PVC, 0.19 W/m-K, and copper, 400 W/m-K. From this, along with a brief heat transfer analysis, we determined that a copper pipe would lose larger amounts of heat than PVC. For these reasons we have selected to use PVC for our pipes in order to minimize product cost and effectiveness, therefore saving our customers the most money.

Temperature limits of materials: One of the material properties that need to be considered during selection is the upper temperature limits of the material. We do not have to worry about burns from contact to elements during servicing as all temperatures will be below the temperature of the shower water itself. Since all of the elements will be down flow of the drain they will need to withstand the heat of the grey water which is on average 95° F- 105 ° F [26]. The material that we have selected for piping is rigid PVC which has a temperature limit from the manufacturer between 110°F and 140°F depending on the dimensions [27]. Another component of the Hotshot which is subject to the grey water heat is the filter which comes in a variety of materials with differing temperature limits. For polypropylene felt bag filters the maximum temperature limit is 200°F according to the manufacturer, for polyester felt it is 300°F, and for Nylon mesh it is 325°F all of which are much higher than the expected operating temperature [28]. Lastly for the sliding adapter a flexible PVC will most likely be used which has a manufacturer rated maximum temperature of 120°F [4]. Based on the temperature ratings of each of these materials which have been selected we believe that they will be safe for the expected operating temperatures of the Hotshot.

Parameter Testing and Evaluation

Certain design parameters are difficult to evaluate because the Hotshot is a unique drain water heat recovery system. Limited research is available for residential grey water's effect on PHEs. There are also large errors associated with local convection coefficients and PHE performance is proprietary information. Similarly, liquid bag filtration has rarely been used to extract hair and shower debris. It is unknown how coarse a filter must be to effectively remove debris and maintain a satisfactory flow rate. To address this uncertainty several tests will be conducted. In this section we identify the information required to make design decisions. From this, we plan to construct a test stand to easily verify engineering specifications.

Heat exchanger performance: We have chosen to test a heat exchanger one level larger than the prototype Hotshot currently uses, the AIC LB31-40 which contains ten more plates than the current model. This model was chosen because it optimizes transfer area with respect to cost.

Furthermore, calculations on the Hotshot's performance have, up until this point, relied on the data sheets provided by the manufacturer. A proper analysis of the Hotshot will require independent testing. The results will provide Jack Griffith with data that can back up his energy saving claims and serve as a valuable marketing asset.

Variables that must be controlled during the test include flow rate, cold water inlet temperature, test duration, and whether the initial transient 'warm-up' period is included. These variables will be manipulated one at a time to determine their effect on performance, or heat transfer rate. With each test we will monitor the rise in temperature of the cold water. We would also like to measure the pressure drop across the cold water side to measure the PHE effect on shower performance.

Bypass location: The vertical location of the by-pass pipe is important; if it is too low the filter water could flow through it when the filter is not actually clogged. To determine the correct location of the bypass we plan on conducting a test with the filter full of debris. We know that the filter must pass 2.5 gpm (shower head standard). We will observe the height of column of water that passes 2.5 gpm.

PROTOTYPE DESCRIPTION

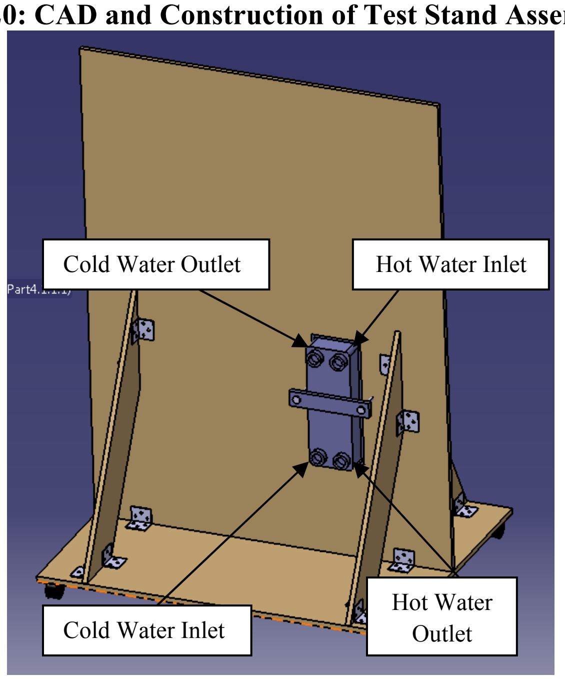
Now that the tests have been outlined, we can begin to discuss the physical apparatus required to complete our testing. We plan to build a test stand which contains the required measurement tools and controls to execute our plan and finalize design variables.

Test Stand Base

The components of our experimental setup will be mounted to a test stand base which will be constructed primarily out of a single 8' by 4' OSB plywood sheet. The dimensions for the various pieces which will be cut out of are on a layout of the plywood sheet can be found in Appendix I. Once the individual pieces have been cut out of the plywood they will be assembled using galvanized steel angle brackets and 112 - #6 ½" screws as shown in Fig. 20. The stand is supported by four 2" diameter caster wheels, two of which have brakes.

The main component which will be mounted onto the test stand base is the heat exchanger. The heat exchanger will be mounted to the plywood upright as shown in Fig. 20 above. The heat exchanger comes with a retaining bracket and two 3/8" bolts. A wooden box will also be constructed around the PHE for additional support. The PHE attachment method is identical to Mr. Griffith's shown in Fig. 1, p. 6.

Fig. 20: CAD and Construction of Test Stand Assembly



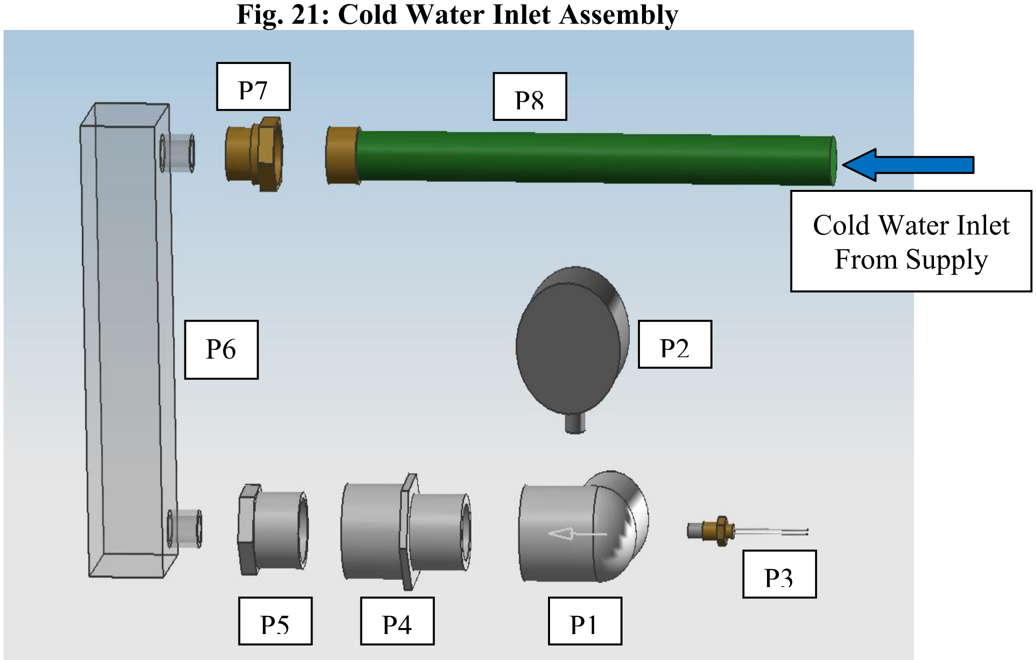
With the heat exchanger securely mounted to the test stand base the rest of the components may be assembled. These components can be grouped into four subassemblies (one for each inlet/outlet connection on the heat exchanger) which are described in greater detail in the following sections.

Cold Water Inlet

The first subassembly attached to the heat exchanger provides the plumbing for the incoming cold water supply as well as mounting points for the pressure gauge, thermistor, and flow meter. A description of each part which is used in this subassembly can be found in Appendix J.

The first step in the cold water inlets assembly is to drill and tap two ¼" NPT holes on the elbow, P1, which is then threaded directly onto the heat exchanger's cold water inlet. A pressure gauge, P2, and a thermistor, P3, will then be threaded into these tapped holes. Next, an adapter, P4, is threaded into the other side of the elbow which then allows for the bushing, P5, to be cemented into the 1" socket side of the adapter. The bottom ½" male NPT inlet of a flow meter, P6, can then be threaded into the bushing. On the outlet of the flow meter another adapter, P7, will be threaded on allowing the garden hose thread adapter, P8, to be attached. Finally, a hose can be connected to this inlet and then to a cold water source. Fig. 21 shows this assembly.

Fig. 21: Cold Water Inlet Assembly

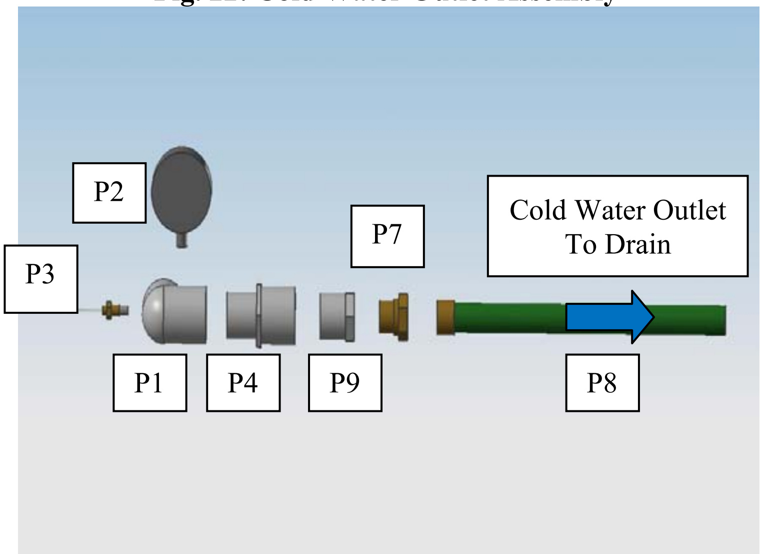


Cold Water Outlet

The second subassembly attached to the heat exchanger provides the plumbing for the outgoing cold water to a drain as well as mounting points for the pressure gauge and thermistor. A description and cost of each part which is used in this subassembly can be found in Appendix J

The first step in the cold water inlets assembly is to drill and tap one ¼" NPT hole on the elbow, P1, which is then threaded directly onto the heat exchangers cold water inlet. A thermistor, P3, will then be threaded into this tapped hole. A pressure gauge, P2, is also screwed into the elbow. Next, an adapter, P4, is threaded into the other side of the elbow which then allows for the bushing, P9, to be cemented into the 1" socket side of the adapter. Then another adapter, P7, will be threaded on allowing the garden hose, P8, to be attached. Fig. 22 on p. 30 shows the assembly process.

Fig. 22: Cold Water Outlet Assembly

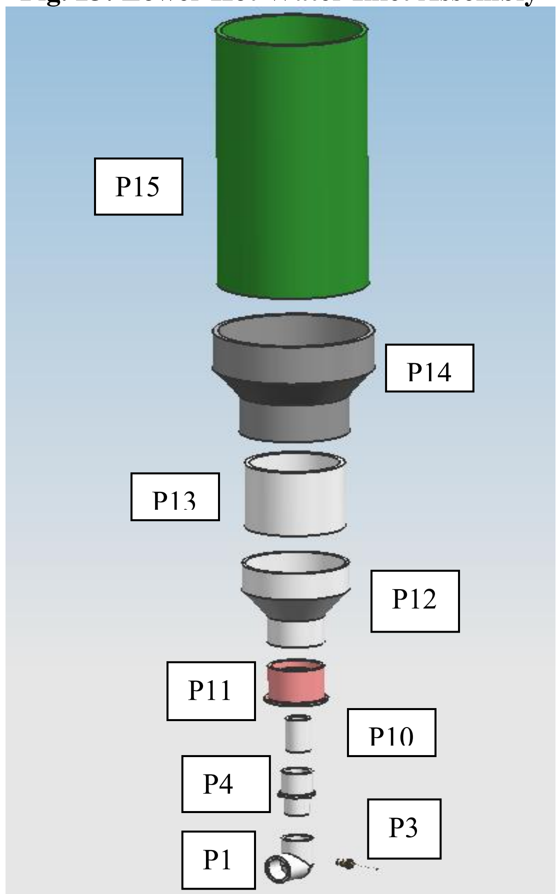


Hot Water Inlet

The third subassembly attached to the heat exchanger provides the plumbing for the incoming hot water, the filter assembly, and a mounting point for a thermistor. A description of each part used in this subassembly can be found in Appendix J.

The first step in the cold water inlets assembly is to drill and tap one ¼" NPT hole on the elbow, P1 which is then threaded directly onto the heat exchangers hot water inlet. It is critical to make sure that the elbow is positioned such that the open threaded end is facing up and the elbow itself is vertical. A thermistor, P3, will then be threaded into the tapped hole on the elbow. Next, an adapter, P4, is threaded into the other side of the elbow which then allows for a 1" diameter PVC pipe, P10, to be cemented into the 1" socket side of the adapter. The 2" to 1" reducing bushing, P11, can then be cemented onto the other side of the 1" pipe. The next step is to cement the 2" socket end of the 2" to 4" PVC Reducer, P12, onto the 2" diameter side of the bushing, P11. Once this is done, a 4" pipe, P14, can be cemented into the 4" socket end of the adapter, P12. Another reducer made of flexible PVC, P14, which reduces from 6" to 4" will then be clamped onto the open end of the 4" pipe. For the final step in the assembly of the lower hot water inlet subassembly a 6" diameter pipe, P15, will be clamped into the 6" end of the reducer, P14. This assembly is shown in Fig. 23 on p. 31.

Fig. 23: Lower Hot Water Inlet Assembly



Now that the lower hot water inlet subassembly is complete the upper portion which includes the attachment of the filter bag can be assembled and placed into the 6" Pipe, P16, which acts as the filter enclosure to collect the water which flows through it. First one of the three selected filter bags will be attached to the filter bag adapter, P17. A threaded ¾" pipe, P18, will then be screwed into the filter adapter. In order to see the water column height for Test 2, a clear length of ¾" pipe, P20, will be cemented into one end of the ¾" straight adapter, P19, which will have its other end cemented onto the open end of threaded pipe, P18. To attach a hose to this clear pipe another ¾" straight adapter, P21, will be cemented onto the upper end of the pipe. A ¾" to ½" female NPT bushing, P22, must then be cemented into the other side of the straight adapter. Once this has been done a garden hose thread adapter, P7, can then be threaded onto the assembly allowing a hose to be attached to the hot water inlet sub assembly and then to a hot water source.

Fig. 24 and Fig. 25 on p. 30 show the assembly process of the lower hot water inlet and the complete assembly of both upper and lower sections of the hot water inlet subassembly.

Fig. 24: Lower Hot Water Inlet Assembly

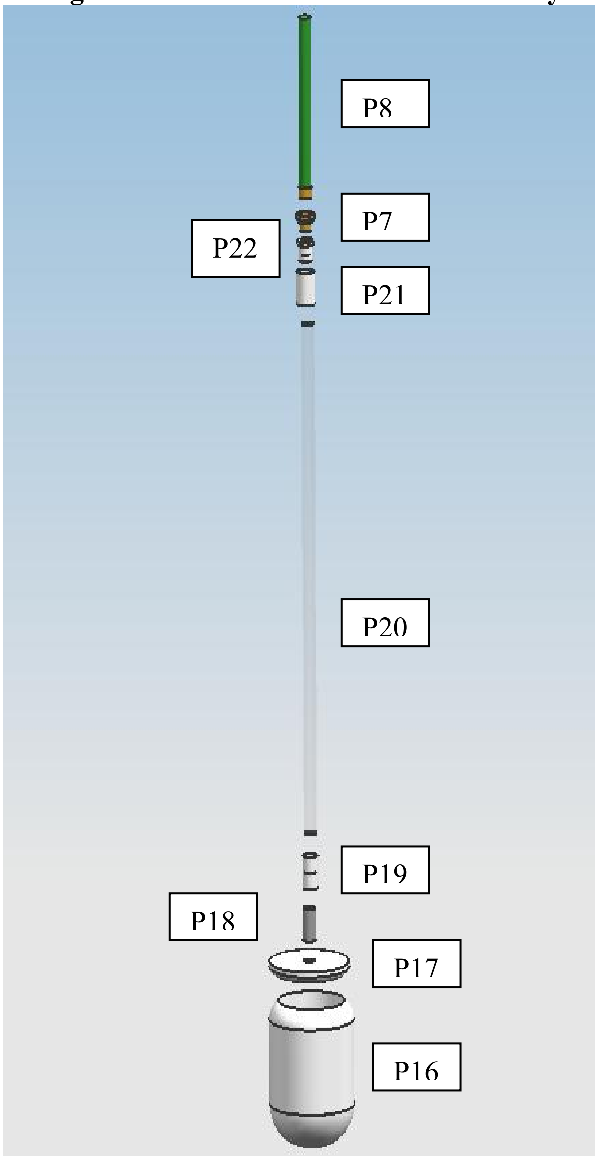
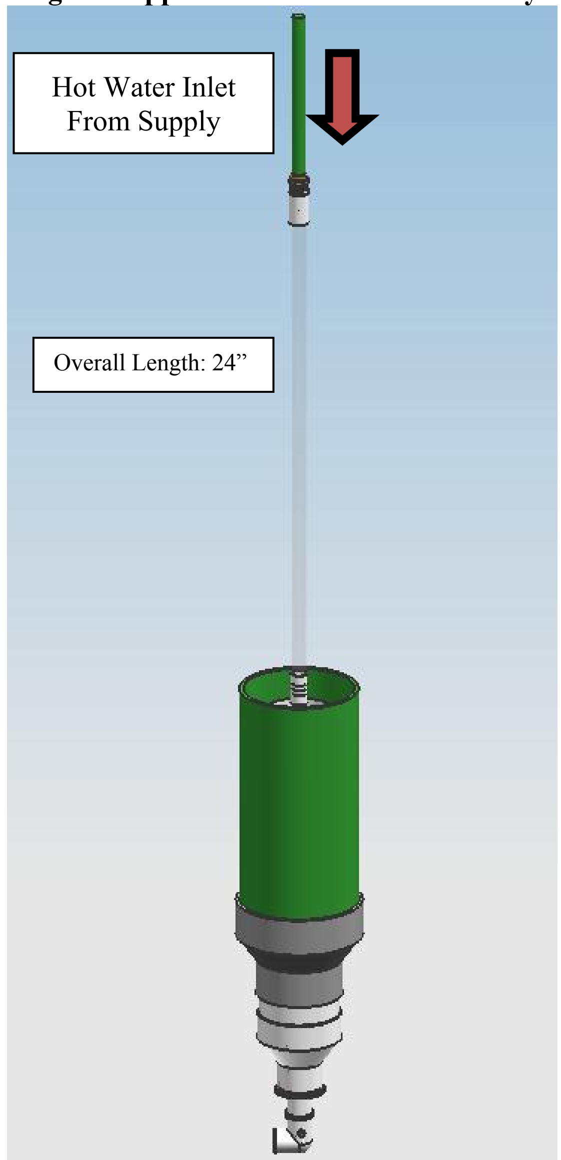


Fig. 25: Upper Hot Water Inlet Assembly

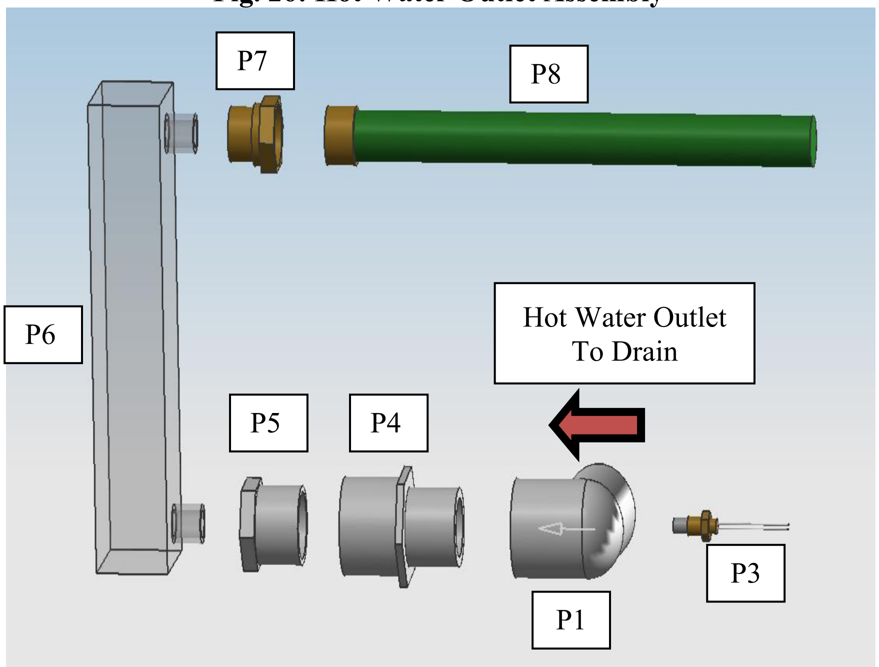


Hot Water Outlet

The final subassembly to be attached to the heat exchanger provides the plumbing for the outgoing cold water supply as well as mounting points for a thermistor and flow meter. The description and cost of each part which is used in this subassembly can be found in Appendix J.

The first step in the cold water inlets assembly is to drill and tap one ¼” NPT hole on the elbow, P1, which is then threaded directly onto the heat exchangers hot water outlet. A thermistor, P3, will then be threaded into this tapped hole. Next, an adapter, P4, is threaded into the other side of the elbow which then allows for the bushing, P5, to be cemented into the 1” socket side of the adapter. The bottom ½” male NPT inlet of a flow meter, P6, can then be threaded into the bushing. On the outlet of the flow meter another adapter, P7, will be threaded on allowing garden hose P8, to be attached. Fig. 26 on p. 33 shows the assembly process.

Fig. 26: Hot Water Outlet Assembly



All of the subassemblies will require additional support from the test stand base once attached to the heat exchanger. This support will be provided by additional plywood left from the creation of the test stand base. Cutout supports will be screwed into the base and then components needing support will be secured to these supports using metal strapping. To ensure that no leaks occur during testing all threaded components will have Teflon tape applied to their threads before installation.

Data acquisition

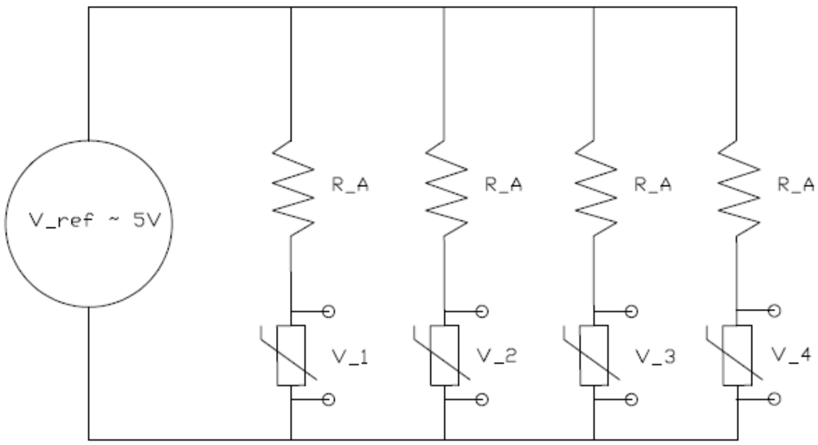
The water inlet and outlet temperatures are parameters that we need to simultaneously record. In order to do this efficiently and accurately, we will be logging all temperature data on the computer using LabVIEW 8.6 provided by Mr. Tom Bress of the University of Michigan. Four 1000 ohm thermistors (P3) will measure the water temperature at both inlets and outlets. Each thermistor is part of a simple voltage divider, as shown in Fig. 27 on p. 34. A USB data acquisition unit (DAQ) will record the voltage drop across each of the thermistors (V_1 through V_4) while the reference voltage will be known.

R_a represents 1000 ohm precision resistors (± 1% accuracy). The resistance of each thermistor can be found using Eq. 9 and the resistance temperature relation is shown in Eq. 10.

$$R_{T1} = \frac{V_1 R_A}{V_{ref} - V_1} \quad \text{(Eq. 9)} \qquad R_T = R_0(1 + AT + BT^2) \quad \text{(Eq. 10)}$$

Where R_T is the resistance of the thermistor, R_0 is the resistance at freezing (1000 ohms), T is the temperature in celcius, and A and B are constants of value $3.9083(10^{-3})$ and $-5.775(10^{-7})$ respectively. LabVIEW will be coded to compute and plot temperature automatically.

Fig. 27: The DAQ measures voltage drop across each of the thermistors.



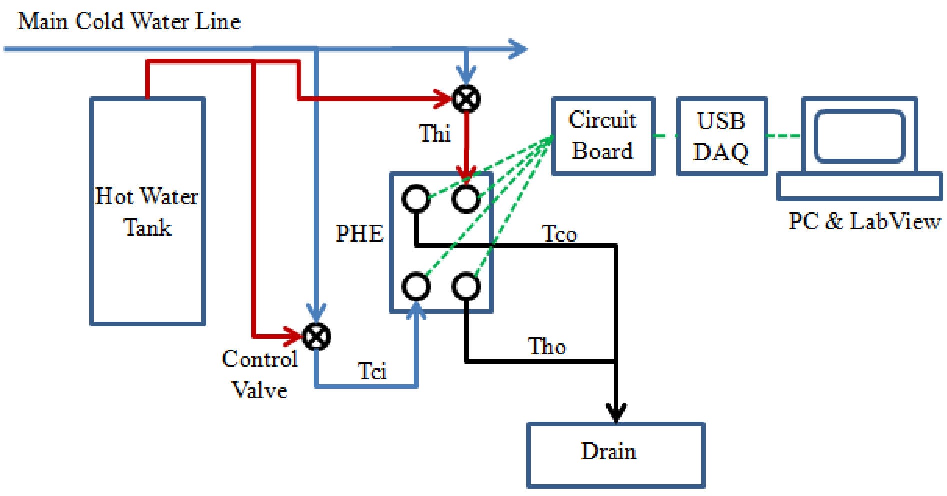
TESTING PROCEDURE

Testing was performed to verify the engineering specifications and gather information to optimize design. The test setup and procedures for testing are described in the following sections.

PHE Performance Test Setup

The setup for the heat exchanger performance testing is shown below in Fig. 28. Temperatures for cold inlet, cold outlet, hot inlet and hot outlet are referred to as Tci, Tco, Thi, Tho respectively in the figure. Hot water was supplied by a 77 gallon, natural gas hot water tank maintained at 120 °F (upper limit for Thi). Cold water was supplied by an Ann Arbor, Michigan residential water main at approximately 45 °F (lower limit for Tci). The PHE tested was the AIC LB31-40 with temperature and flow rate manually adjusted at the control valves. Note that Tci, Tco, Thi, Tho, cold flow and hot flow all depend on the same sources and cannot be controlled individually. Specific flow rates are controlled during testing for a range of temperatures. Temperature data was acquired with a USB DAQ 6009 at a sampling rate of 1 Hz. Each test lasted between five and ten minutes, with fifteen minutes between testing to allow the water tank to recharge. External water use was prohibited during testing to mitigate the effect of pressure disturbances on temperature and flow rate.

Fig. 28: PHE performance test setup



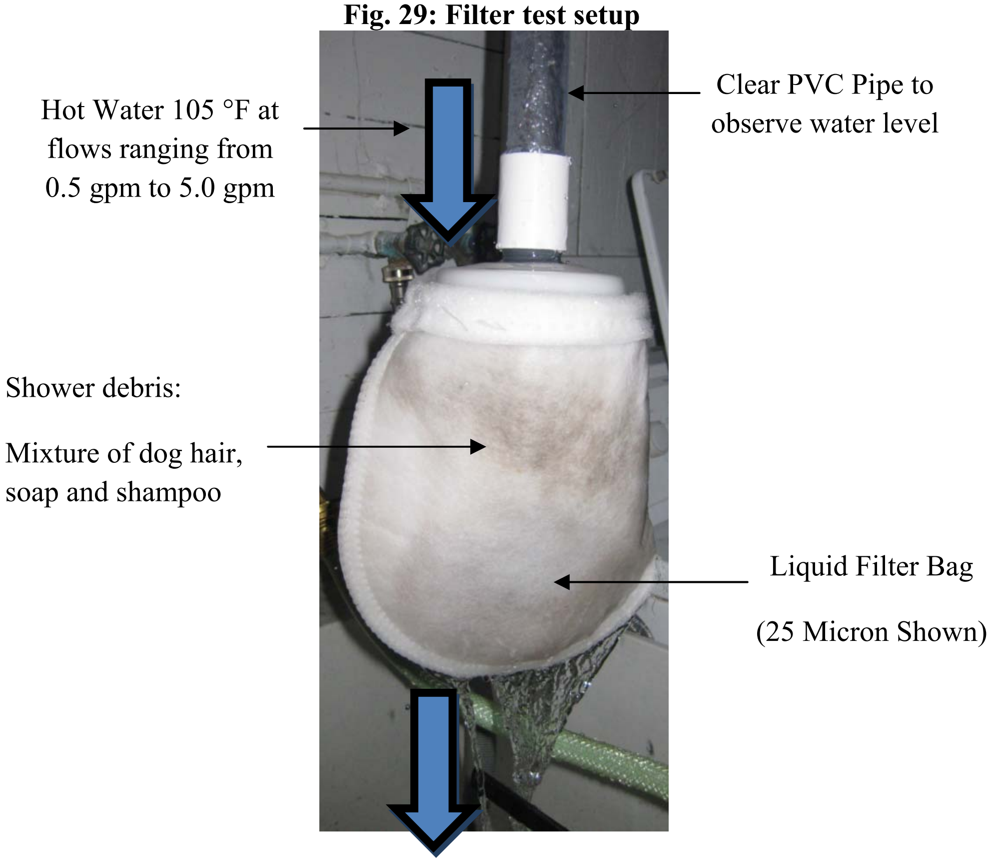
PHE Performance Test Procedure

Thirty separate tests were conducted to measure PHE effectiveness. For each test, the hot and cold flow rates were controlled and the resulting temperature and pressure drop were recorded. Cold flow rates varied from 0.50 gpm to 3.00 gpm and hot water flow rates ranged from 1.00 gpm to 3.00 gpm. Flow rates were measured with analog flow meters (± 0.125 gpm) at Tci and Tho. For each test, the cold flow rate never exceeded the hot flow rate since this is not possible under normal showering conditions. The temperature of Tci was varied from 45°F to 70°F and Thi was varied from 95°F to 120°F. Once the flows had been established, temperature data was continuously recorded for each port in LabView 8.6 (sampling rate 1 Hz). Temperature was measured as shown in Fig. 27 with four 1000 Ω thermistors, four 1000 Ω precision resistors and a 5 V power supply. Each parameter was verified with a digital millimeter prior to testing. Note that data was only taken once the system had reached a steady state for one minute, meaning all temperatures remained constant and deviated by no more than 3%. The pressure at each cold port (Tci and Tco) was measured with an analog pressure gauge (± 3 psi) once the system had reached steady state.

Filter Test Procedure

Filter testing was done on three separate liquid filter bags (25, 200 and 1000 microns). Each bag was filled with a mixture of debris consisting of dog hair, soap and shampoo. The bags was incrementally filled with the debris mixture and subjected to flows ranging from 0.50 gpm to 5.00 gpm. Flow was directed through a clear PVC tube to observe the build-up of a water column as shown in Fig. 29. Tests were repeated until the filter bag was full or flow was completely obstructed.

Fig. 29: Filter test setup



RESULTS

The following sections contain the testing results as well as a description of how the results were obtained.

Filter Performance

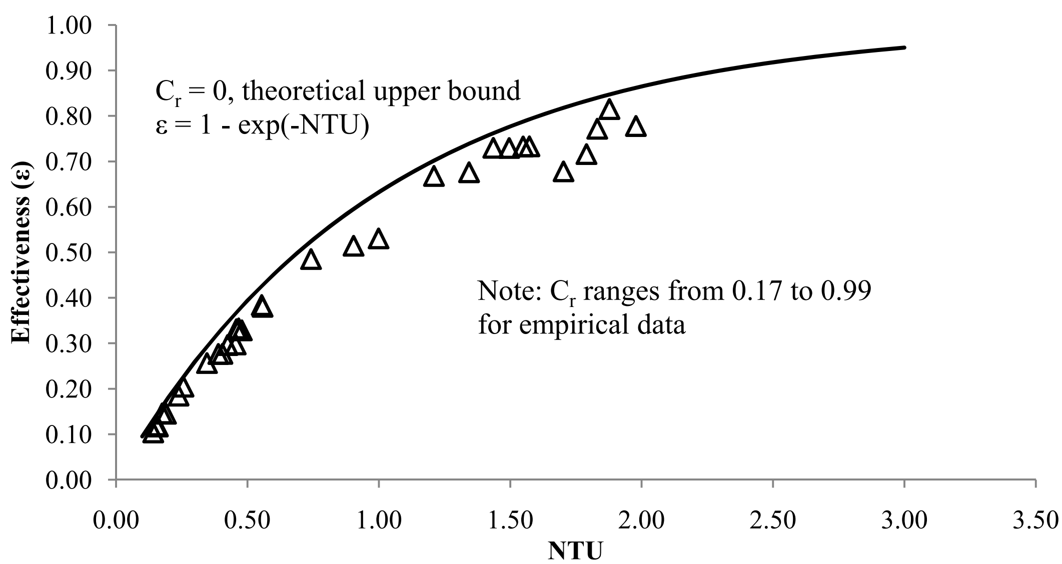
Prior to testing it was unclear if a hydrostatic pressure was required to force water through a partially obstructed filter. From the filter testing we did not observed a column of water until the filter was completely obstructed. Once the filter became impassable, the water level continuously rose, exceeding the three feet of clear PVC pipe. At this point water would back up into the shower and the filter would require maintenance. This was the case for all the filters tested, regardless of micron rating. Based on these results we conclude that the by-pass height should be placed directly above the filter. We also suggest using the 25 micron filter bag because it will prevent the smallest debris from entering the PHE

PHE Performance Results

For the range of tests, the maximum pressure drop across the PHE was 1 psi, which is much less than the 5 psi limit specified by our benchmarking. This value is also less than the expected pressure drop for a 30°/30° staggered corrugation configuration calculated in the parameter analysis section. According to the literature, 30°/60° staggered corrugation configurations are more restrictive but and better for heat transfer. Further testing should be done for a PHE with a 30°/60° staggered corrugation configuration to evaluate heat transfer and pressure drop.

PHE effectiveness was found to vary from 10% to 80% over the range of showering conditions as shown in Fig. 30. A tabular representation of the data is found in Appendix K. The majority of showering conditions had effectiveness values of 50% or lower (19 of 30 tests). Effectiveness values near 70% and 80% were only observed in cases with large inlet temperature differences (eg. Tci = 45°F, Thi = 120°F) and large flow rate difference (cold flow = 0.5 gpm, hot flow = 3.0 gpm). However, this does not imply that the selected PHE is not effective in terms of cost savings and CO2 offset. Larger PHE's will produce larger effectiveness values but will also cost more. A savings calculator was determined based off of the measured effectiveness data and energy information from the Department of Energy. However, more testing should also be completed for several different PHE models to compare cost and savings.

Fig. 30: AIC LB31-40 effectiveness ranges from 10% to 80% across the tested showering conditions



PHE effectiveness – NTU calculations: Effectiveness (ε) is a measure of the actual heat transfer (q) with respect to the maximum possible heat transfer (q_{max}). We were able to determine the effectiveness for our tests based on the cold inlet temperature (T_{ci}) the cold outlet temperature (T_{co}), the hot inlet temperature and heat capacity rates C_c and C_{min} as shown in Eq. 11 below. The heat capacity rates are defined as the product of density, heat capacity and volume flow rate where subscript c represents to cold side and subscript min represents the minimum heat capacity rate of the hot and cold sides. Fluid density and specific heat vary with temperature; exact values were interpolated based on the reference values found in Incorpera [29]. All the data was calculated using MATLAB R2008a and required code can be found in Appendix L.

$$\varepsilon = \frac{q}{q_{max}} = \frac{C_c(T_{co}-T_{ci})}{C_{min}(T_{hi}-T_{ci})} \quad \text{(Eq. 11)}$$

The number of thermal transfer units (NTU) is defined by the overall convective coefficient (UA) and the minimum heat capacity rate (C_{min}) as shown in Eq. 12. As shown in Fig. 30, larger values for NTU correspond to greater PHE effectiveness values. Heat exchangers with larger areas and lower thermal resistance will have larger overall convective coefficients and thus larger values of NTU.

$$NTU = \frac{UA}{C_{min}} \quad \text{(Eq. 12)}$$

The overall convective coefficient (UA) can be determine experimentally from the cold heat capacity rate and fluid temperatures as shown in Eq. 13. However, as discussed earlier, the convective coefficient is primarily a measure of thermal resistance where large values of UA correspond to small thermal resistances.

$$UA = \frac{C_c(T_{co}-T_{ci})}{\Delta T_{lm}} \text{, where } \Delta T_{lm} = \frac{(T_{hi}-T_{co})-(T_{ho}-T_{ci})}{\ln\frac{T_{hi}-T_{co}}{T_{ho}-T_{ci}}} \quad \text{(Eq. 13)}$$

The heat capacity gain ratio (C_r) is defined as the ratio of heat capacity rates C_{min} and C_{max} as shown below in Eq. 14.

$$C_r = \frac{C_{min}}{C_{max}} = \frac{\rho_c V_c c_{pc}}{\rho_h V_h c_{ph}} \quad \text{(Eq. 14)}$$

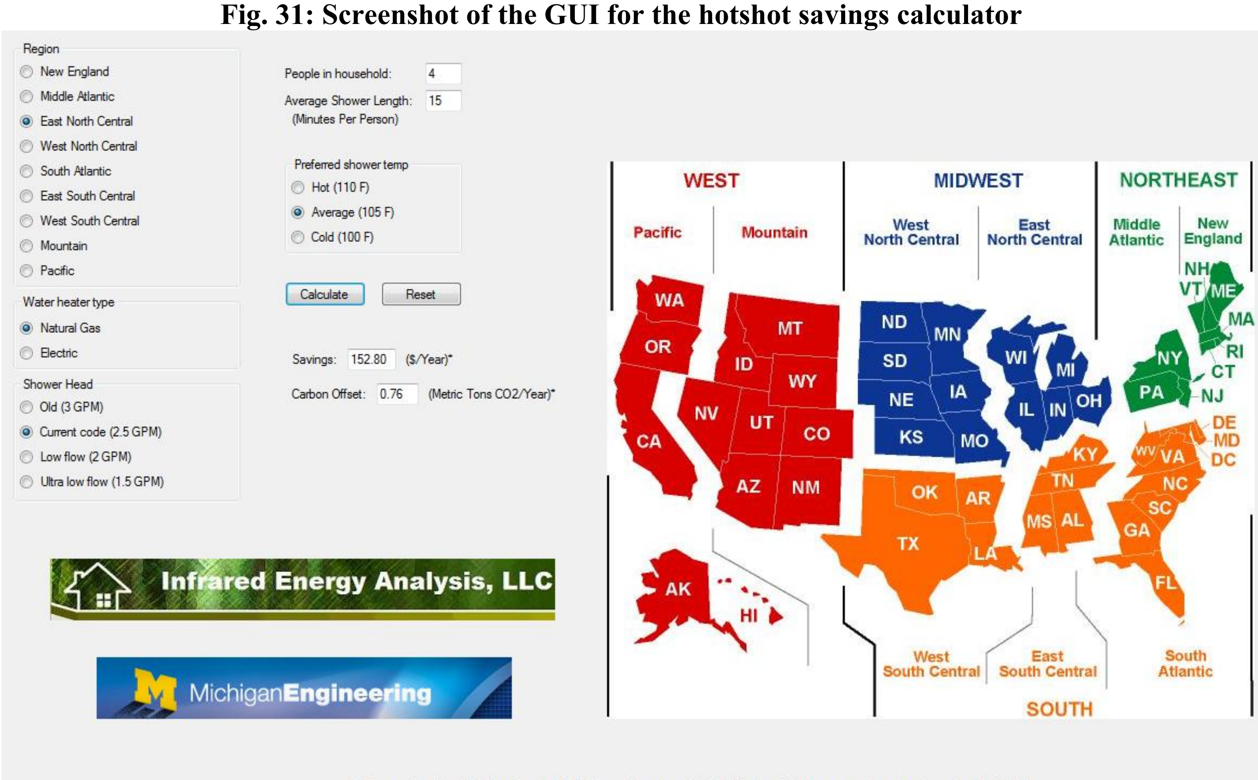
Since density (ρ) and heat capacity (c_p) do not vary much over the range of showering conditions (density ranges from 1000 kg/m^3 to 987 kg/m^3 and specific heat ranges from 4211 J/kg-K to 4182 J/kg-K), the most significant variables in C_r are cold volume flow rate (V_c) and hot water flow rate (V_h). Cold flow rate is always less than the hot flow rate thus C_{min} is equal to cold water heat capacity rate (C_c). This is significant because large effectiveness values are expected for smaller values of C_r, in fact, a maximum upper bound on effectiveness exists at C_r equal to zero as shown in Fig. 30. Thus, the Hotshot is expected to be most effective when V_c is smaller than V_h. However, the ratio of V_c to V_h is dictated by the user as he or she sets the desired shower temperature.

Savings calculator: Constructing a savings calculator which could inform potential customers of both their annual savings and carbon offset was an important outcome of our project. The ability to easily make accurate predictions on these two aspects of the Hotshots performance could prove to be an invaluable marketing tool.

The savings per year and carbon offset per year from use of the Hotshot are dependent on many parameters including the cold water inlet temperature, hot water inlet temperature, effectiveness, energy costs, and carbon emissions due to energy production. To calculate the savings and carbon offset for a particular consumer a graphical user interface (GUI) was created in which information could be gathered. The GUI for the savings calculator as well as the background calculation program were created using VisualBASIC 2005 and is shown below in Fig. 31.

All of the necessary data for the calculations is specified by the user. From the region entered the average cold water inlet temperature, energy costs and carbon emissions for both natural gas and electricity are known. The energy costs and carbon emissions for each region are based off of projected 2009 prices from the U.S. Energy Information Administration, EIA, energy outlook [40]. Depending on whether a user has a natural gas or electric water heater the corresponding values of cost and CO_2 emission values are used. The hot water inlet flow rate is determined by the type of shower head selected, which along with the number of people in the household and average shower length, gives the mass of water used in a typical year. With the hot water inlet temperature known as the users preferred shower temperature the reduction in BTU's needed to heat the total mass of water used in a year can be found knowing the properties of water, cold water inlet temperature, and the effectiveness of the heat exchanger for these particular parameters entered by the user. The effectiveness for a particular set of parameters is based on our own heat exchanger testing results. Then it is simply a matter of converting the BTU's saved in a year to dollars and carbon in metric tons using conversions based on the EIA information.

Fig. 31: Screenshot of the GUI for the hotshot savings calculator



In order to determine if the savings calculator was producing reasonable output values for the entered information, we examined several different example households. For instance, the first household is home to a family of four living in Michigan who take 10 minute showers on average at the average temperature of 105°F with a standard shower head (2.5 gpm) and a natural gas water heater. For this family their annual savings would be $101.87 and nearly half a metric ton of CO_2. On one end of the spectrum a large house for seven roommates attending the University of Michigan with an electric water heater and an old shower head could save $1143.80 and offset 9.45 metric tons of CO_2 per year. On the other end of the spectrum is a single man in a studio apartment located in Florida. He has a natural gas water heater and an ultra low flow shower head. Since he also takes fairly short and cold showers an individual such as this would only save $6.03 per year and would offset just 0.02 metric tons of CO_2. The rest of the results along with the examples described above can be found in Table 8 below.

These results seem reasonable given the initial findings of our Monte Carlo simulation which found an average savings for families of $160 per year for electric and $90 per year for natural gas using the less effective heat exchanger from Jack Griffith's prototype. Although some assumptions are made by potential consumers, we feel that Hotshot Savings Calculator results are representative of potential savings and are adequate for determining whether a Hotshot would be cost effective for a particular consumer.

Table 8: User input for example families and corresponding output from savings calculator

People in Household	*Region*	*Water Heater Type*	*Shower Head*	*Average Shower Length*	*Preferred Shower*	*Savings ($/Year)*	*Carbon Offset (Metric Tons CO2/Year*
4	East North Central	Natural Gas	Standard (2.5 GPM)	10	Average (105 F)	101.87	0.51
2	Middle Atlantic	Natural Gas	Standard (2.5 GPM)	15	Average (105 F)	92.65	0.38
5	Mountain	Electric	Low Flow (2.0 GPM)	10	Average (105 F)	150.54	1.47
3	Pacific	Electric	Old (3.0 GPM)	12	Hot (110 F)	449.68	0.69
1	South Atlantic	Natural Gas	Ultra Low Flow (1.5 GPM)	8	Cold (100 F)	6.03	0.02
7	East North Central	Electric	Old (3.0 GPM)	15	Hot (110 F)	1143.8	9.45

FINAL DESIGN

The final design incorporates all of the major functions and ideas resulting from our team's alpha design, engineering parameter analysis, and the results of our testing. The test results along with rest of the design process allowed our team to produce a final design which we believe meets all of the requirements of our sponsor as well as incorporates several additional features which improve the original Hotshot prototype.

Filter Assembly

The filter assembly makes use of a bag filter. Taking into consideration the results of our testing, we recommend that a 25 micron polypropylene felt filter bag for use in the Hotshot system. The 25 micron filtration size was the finest of the three filters tested and met the requirements of the Hotshot in terms of flow rate and static water column pressure needed to function properly. With all other areas being equal the ability to capture the smallest debris ensures the best performance of the PHE. For the assembly a standard 4 ½" diameter bag filter is used since this size is the most widely available. We also recommend the filter be 8" long. Unfortunately due to the budgetary constraints of our project we were unable to complete any lifetime tests to determine if the filter will last at least 6 months under real world conditions. For this reason we recommend that real world testing be completed on the filter to determine if the current 8" bag or the 16" length bag filter should be used. However, based on our previous analysis, we are confident the 8" filter will suffice. The recommended filter attachment method, the tapered end cap, will be manufactured out of PVC round stock. This process will involve turning the piece down as well as tapping threads with a CNC lathe. This end cap will thread directly into the upper drain pipe, which is also PVC. The filter rim will be fitted with an O-ring for a tight seal between the end cap and drain. The upper pipe is connected to the lower PVC drain pipe with a flexible rubber coupler. This coupler is secured to the pipes by way of two quick release clamps, creating a watertight seal as well as a simple way to access the filter for replacement. Fig. 13 on p. 19 shows a layout of these parts from our alpha design. If the tapered end cap is initially too expensive to produce at low volume an alternative assembly may be used which would incorporate the bag filter adapters used for our test stand as shown in Fig. 29 p. 34.

Bypass Assembly

The bypass will allow the shower to continue to function as normal if the filter becomes clogged with debris. The bypass consists of a plumbed connection between the shower drain pipe above the filter assembly and the hot water outlet at the heat exchanger which then continues on to the main drain of the home. As shown in Fig. 16, p. 20 in the prototype description section, the upper bypass connection should consist of a pipe splitting off of the main shower drain at an upward angle to ensure that water only takes this path in the event of a backup. From our testing we were able to determine that a column of water only builds when the filter is completely obstructed. Thus, we recommend that the upper bypass connection be made 1" above the filter assembly. The position of the lower connection is also only dependant on the packaging dimensions and should be connected 1" from the heat exchanger outlet to ensure a compact Hotshot unit.

Heat Exchanger Assembly

The heat exchanger will be connected to the lower drain pipe from the filter as well as additional lines for the grey water outlet and the cold water inlet and outlet, similarly to what is shown for our test stand in Fig. 20, p. 28. The heat exchanger model required is dependent on many factors including the consumer habits and region, heat exchanger prices for mass production, and energy costs all of which are factors which contribute to the cost versus savings optimization. The components necessary for these connections will be purchased off the shelf, but are dependent on our choice of heat exchanger, filter and bypass location.

Hotshot Assembly

The design of our piping connections will allow us to enclose the Hotshot system inside a cabinet with only four standard plumbing connectors coming out, meaning a much simpler installation. This steel cabinet will include a simple hinged door for filter assembly access as well as installation brackets to assist in mounting. This size of this cabinet is dependent on the size of our heat exchanger, bypass and pipe fittings, and is dependent on the heat exchanger selected for a particular consumer or region depending on how the Hotshot is marketed and distributed. Insulation may be added to the cabinet if it proves to be cost effective

DISCUSSION

This section will discuss an evaluation of our final design. We will also estimate the potential energy savings of our product.

Design Critique

The main criticism we face concerns testing the parameters of our design. First, our test setup could be improved to facilitate testing and improve upon accuracy. Second, more thorough testing could be completed if more time were available. That said, there are also several high points to our design.

<u>Test stand improvements</u>: Our physical test setup could be improved in several ways. As discussed earlier, we were required to wait nearly fifteen minutes between testing while the hot water tank recharged. A new test stand would incorporate external heat sources so that water temperatures could be controlled more precisely and testing could be conducted more efficiently with respect to time. Ideally a new test stand would draw water from two independent sources. In our current test setup, all cold water is obtained from the water main and all the hot water is obtained from a hot water tank. Any change in flow or temperature directly impacts flow and temperature at the other ports. This would eliminate the effect of pressure disturbances due to residential water consumption. Testing accuracy could also be increased through the use of digital flow meters and closed loop parameter control. Closed loop parameter control would allow us to specify temperature and flow instead of only controlling flow and letting the system dictate temperature. Under certain testing conditions, separation was observed in the analog flow meters which may result in variations in flow rate. We were forced to assume the flow rates were constant since our DAQ only had four channels, all of which were occupied four temperature readings. A digital flow meter coupled with a higher capacity DAQ may produce more accurate data.

Additional testing: In the future there are several tests we would like to have conducted. As previously mentioned, we would run the Hotshot over a long period of time while simultaneously injecting soap, shampoo and other showering liquids into the flow. The purpose of this test would be to give us an idea of how shower debris contributes to fouling and performance degradation. This test would also be conducted again with various filters to evaluate the filter performance more thoroughly. Determining the fouling factor would also require modeling the local convective coefficient. This test was not conducted because of the time required for such a test and the financial concern of heating such a large quantity of water. We would also like to conduct performance tests on several different heat exchanger models to evaluate the effect of different plate sizes, materials and corrugation angles. Similarly we would also like to evaluate the performance of competitive DWHR systems to ensure that the Hotshot is competitive. Similarly these tests were not conducted due to budgetary concerns associated with purchasing multiple heat exchangers. Our team also had the idea to test the effect of adding insulation to the PHE and evaluating the benefit of such a change versus the cost.

Design strengths: The main strength of our design is that it is elegant and simple. Unlike other 'green technologies' that go to extreme lengths to reduce our environmental impact, the Hotshot examines an everyday activity and asks 'how can this be made more efficient?'. The Hotshot reduces energy consumption without sacrificing any convenience. The system requires no energy input and only requires maintenance every six months. The use of a liquid filter bag is an innovative way to lengthen PHE life and extend the required maintenance interval. The implementation of the by-pass is also an innovative way to maintain shower performance while simultaneously providing feedback to the consumer that the filter needs to be changed. Our team was able to provide insight into the problem of heat exchanger selection and filtering to guide Mr. Griffith's business.

Sustainability

The Hotshot obviously produces a carbon offset, however we need to evaluate several less obvious consequences of the Hotshot to ensure the carbon offset is not negated.

Hotshot vs. Low Flow: From our savings calculator we determined that the Hotshot is more effective at larger flow rates. This may diminish the incentive of those who wish to switch to low flow shower heads. Thus we compared the savings possible with a Hotshot to those obtainable from simply switching shower heads (standard 2.5 gpm to a low flow 2.0 gpm). Looking at the six scenarios from Table 8, we determined the amount of water drawn from the water heater at 120° F for both standard and low flow conditions. From this we were able to calculate the amount of hot water and therefore BTU's saved by switching to a low flow showerhead. Using the same data as used in our savings calculator, we found the money each family could save annually, as shown in Table 9 on pg. 40.

Table 9: Savings from switching to a low flow shower head are 33% of those from the Hotshot

Household	Hotshot Savings ($/Year)	Low Flow Savings ($/year)	Low Flow Savings compared to Hotshot (%)
1	101.87	35.71	35%
2	92.65	32.48	35%
3	348.67	114.05	33%
4	327.89	106.18	32%
5	21.84	7.26	33%
6	776.15	272.65	35%

This table shows that the Hotshot saves more money annually than the low flow shower head. However, it is also important to think about the upfront cost of each of these solutions. A new shower head may only cost 5% of the Hotshot but only saves up to 35% of a Hotshot. Note that the low flow shower head reduces water consumption (20%) while the Hotshot does not. The larger savings associated with the Hotshot also contribute to larger emissions reductions, which could attract more customers. From this analysis, the Hotshot can be considered the more environmentally sustainable purchase for all six scenarios.

Hotshot energy content: One of the primary goals of the Hotshot is to offset the consumption of energy; however there is a certain amount of energy associated with producing the Hotshot. The constituent materials and the associated energy content are shown below in Table 10, representative values were taken from Ashby Materials.

Table 10: Hotshot energy content [31]

Material	Function	Energy Content per Material (GJ/m^3)	Energy Content in the Hotshot (GJ)	Relative Weight
AISI Stainless Steel and Manufacturing	PHE Plates	900	2.77	92.33%
PVC	Filter Housing	120	0.10	3.33%
Synthetic Rubber	O-rings/Sleeve	115	0.12	4.00%
Polypropylene	Filter	100	0.01	0.33%

From this table we can see that the PHE makes up the majority of the energy content of the Hotshot. Manufacturing also contributes to the energy required to create the Hotshot. We assumed that the plates were stamped by a standard stamping press which consumes 10 kW of electricity [28]. We conservatively estimated that it would take 10 minutes to stamp all 40 plates for the LB31-40 PHE. This only contributes 0.01 GJ to the overall production of the Hotshot. Note that the filter is only aspect of the Hotshot that can be considered as energy consumed by the system. For the purpose of the following analysis we assume that the Hotshot requires another filter every six months and thus consumes another 0.01 GJ.

From Table 10 we can calculate how long it would take a consumer of the Hotshot to break even on energy consumption. However, as we have noted previously, the energy offset by the Hotshot depends heavily consumer showering habits. Thus we have calculated the breakeven point for three separate households as shown in Table 11. Rows 1 and 3 represent extreme consumers where row 2 represents an average consumer. The rows are the same as households 5, 1 and 6 in Table 8 on p. 37.

Table 11: Hotshot energy break even points

Household	People Per Household	Average Shower Duration (mins)	Climate	Hotshot Breakeven Days	Filter Breakeven Days
5	1	8	South Atlantic	9754 (26.7 Years)	19.0
1	4	10	East North Central	208 (7 Months)	0.5
6	7	15	East North Central	39 Days	0.1

For our expected average costumer (Household 1) the Hotshot makes sense from an environmental point of view. It takes nearly 7 months to break even on the up front energy content. After 7 months that consumer is only fighting the energy consumption due to the filter, which can be offset by the savings of less than a day's worth of showering. The Hotshot will obviously work well for Household 6 but not so well for Household 5. This information needs to be reflected in advertising to ensure the Hotshot is reducing overall energy consumption. There are still a large number of people, particularly families in cold climates who can benefit from the Hotshot.

National carbon offset: Using our savings calculator, we are also able to estimate the environmental effect of the Hotshot if it was accepted nation-wide. From our Monte Carlo analysis, we have estimated that nearly 25 million homes could benefit from the Hotshot, that's nearly 25% of homes in the US. Let's assume that at some time in the future this is the case. We can also assume the average showering trends and energy consumption as listed in Appendix B (references also shown in Appendix B). For instance, each of the 25 million homes has 2.59 people who on average take 8.2 minute showers 0.75 times per day according to US Census and REUW data. We can also assume an average cold water inlet temperature of 55 °F and a shower temperature of 105 °F. Let's also assume that every house has a standard 2.5 gpm shower head. According to our effectiveness data, this corresponds to 7.3 kW of power offset. Given the average shower consumption this corresponds to 1.9 kWh of energy offset per day per average household. We also know that nearly 58% of houses use natural gas water heaters and we can assume that the balance of homes have electric water heaters according to the US Department of Energy. We also know that nationally 117 lbs of CO_2 are emitted for every 100,000 Btu and 1.43 lbs of CO_2 are emitted for every kWh (DOE). From this we can determine that the Hotshot would offset 23.4 million metric tons of CO_2 annually. That's the equivalent of removing 4.3 million cars from the road or closing 5 coal fired power plants. These numbers are obtained from the EPA who claims one car emits 5.46 metric tons of CO_2 per year and one coal fired power plant emits 4.6 million metric tons of CO_2 per year [14].

RECOMMENDATIONS

With the information gathered during our background research and testing of the Hotshot we feel confident in making the following recommendations to improve the Mr. Griffith's prototype. A filter assembly which makes use of a 25 micron polypropylene bag filter should be integrated into the Hotshot unit. We found that this type of filter functioned without any backup issues and the polypropylene material is capable of withstanding the various chemicals including liquid drain cleaner. We recommend that a filter with the standard dimensions of 4 ½" in diameter and 8" in length be tested under real world conditions in order to ensure a six month maintenance interval and satisfactory PHE performance. For the filter subassembly, we recommend that Jack use off the shelf parts, such as the adapter used in our prototype (P17), for further testing. This adapter and the corresponding enclosure should also be used during initial start-up period, as the manufactured end cap will not be cost effective for small scale production. Once demand for the Hotshot has been firmly established and larger scale production and distribution is feasible we recommend using the tapered end cap described in the alpha design section, p. 19, which would require further manufacturing development.

In addition to the filtration improvements we recommend that a bypass system be incorporated into the Hotshot unit which would create an alternative route from above the filter around the heat exchanger and back to the drain. In the event that the bag filter becomes fully clogged, this addition will ensure that waste water does not flow back to the shower. We concluded from our testing that the bypass upper mounting point should be just above the filter attachment preferably within 1" as should the lower connection at the heat exchangers hot water outlet. Having the bypass connections at these points will help the Hotshot be a compact unit while not affecting the utility of the bypass itself. Also, because our tests showed less than a 1 psi pressure drop across the heat exchanger, we can also recommend using a higher corrugation angle, 60 degrees, to maximize heat transfer across the plates. Finally, we recommend testing additional heat exchangers to determine whether higher performance will be worth the expected higher cost. Coupled with this, we suggest Mr. Griffith perform an extensive search for a cheaper heat exchanger supplier. It is possible that some suppliers may be able to provide similar models at much lower prices, especially in bulk orders.

CONCLUSIONS

The Hotshot is a drain water heat recovery system prototype developed by our sponsor Mr. Jack Griffith. The problems with this system include an unsatisfactory filter maintenance interval, insufficient heat exchanger knowledge, and incomplete energy savings analysis. Currently with the Hotshot prototype installed Mr. Jack Griffith's backs up every few weeks. When these backups occur the filter assembly must be disassembled in order to clean out the current grate filter. In addition, He must also clean out the heat exchanger every few months due to debris passing through the grate and catching on the heat exchanger plates.

We have developed a filter system design for the Hotshot that not only extends the maintenance interval, but also will keep much finer debris from reaching the heat exchanger. We have chosen to replace the current metal grate filter with a bag filter which is commonly used in industrial liquid filtration systems. The shape of the bag filter is such that as debris is collected a large volume needs to be filled before the filters surface area is completely covered. The bag filter we have chosen for our design is made of a polypropylene felt with a micron rating of 25, and is intended to be replaced once every 6 months. The polypropylene filter is ideal for this application as it will be able to withstand the various chemicals that are commonly poured down a shower drain. Also, from our testing we found that despite the fine filtering of the 25 micron rating at normal operating conditions flow was sufficient to prevent backups as long as the filter is not fully blocked by debris.

To incorporate the bag filter into the Hotshot unit, we designed a tapered end cap for our alpha design which would allow a bag filter to be easily slipped in and out of before being threaded onto the main shower drain pipe. However, we decided to pursue additional testing and analysis over the course of the semester and thus this design was not fully developed. Further manufacturability and mass production cost analysis needs to be pursued. For initial, low volume sales a product could be constructed entirely from off the shelf parts.

In the event that the bag filter becomes filled with debris we would still like to maintain normal showering performance. For this reason we incorporated a bypass into our final design. This will allow water to circumvent the heat exchanger in the event of complete filter blockage. This way the user will be alerted to change the filter by an increase in the amount of hot water necessary to reach their usual shower water temperature and not by their shower losing function. We have concluded that this filter will not cause any significant backup of water until it is completely clogged, so the recommended bypass pipe can be placed within close proximity of the filter.

Mr. Griffith also does not have the proper data to back up the savings he claims for the Hotshot. The heat exchanger model we tested, the LB31-40 from AIC, will perform in a range of effectiveness from 10% to 80% under normal shower operating conditions. For this range, the average family will still be saving enough money annually to make the Hotshot system cost effective, but larger heat exchangers should be tested to determine whether they will be more or less cost effective. A savings calculator was created using the data obtained from this testing and will allow Jack Griffith to accurately estimate the amount of annual savings and carbon offset a particular customer could expect from the Hotshot. This program is a valuable marketing tool that can help a prospective Hotshot buyer determine if the purchase will be cost effective.

ACKNOWLEDGEMENTS

Several people contributed to the success of this project, and we would like to take time to thank them here. First we would like to thank our sponsor, Jack Griffith. Without him, we would not have had the opportunity to work on the Hotshot this semester. Next we would like to thank Dan Johnson, the ME 450 Graduate Student Instructor for this semester. Dan spent much of his time dealing with administrative aspects of this course as well as often holding extended office hours to assist us in completing our projects in a professional and timely manner.

We would also like to thank Bob Coury and Marv Cressey for the use of their facilities on campus. When it came time to put together our testing prototype, we needed a way to collect temperature data with our thermistors. Tom Bress, coordinator of undergraduate experimental labs, was able to help us jump this hurdle with little trouble. He provided us with a student edition of LabVIEW to use in our testing as well as a one hour tutorial on the things we would need for our data collection program. In this hour, our group learned more about LabVIEW than we had in the previous three and a half years, and we cannot thank him enough.

Last but not least, we would like to thank our Professor and our friend, Steven J. Skerlos. His mentoring throughout the semester has been an invaluable resource. He always demanded a level of professionalism and integrity from us that is displayed in our results and will carry us beyond ME 450. We look forward to his guidance as we attempt to publish this report.

TEAM BIOGRAPHIES

Scott Bartkowiak

Scott is from Waterford, Michigan and graduated from Waterford Kettering High School in 2005. He chose to become a Mechanical Engineer because of his interest in automobiles. Scott has held several summer internships with automotive companies. Scott worked at Ford Motor Company in the summer of 2007 where he conducted Head Impact Testing on the 2009 F150 Instrument Panel. Scott worked at Ford again in the summer of 2008 in the Transmission Controls department. Scott also held a co-op position at Toyota where he worked in Engineering Design on seats and restraints. Scott plans to pursue a Master's Degree in Mechanical Engineering and recently applied to the SGUS program at the University of Michigan. Scott is considering pursuing a PhD in Mechanical Engineering or an MBA after his Master's Degree. Scott would like to work in the automotive industry after graduation but is also interested in the aerospace, energy and financial industries. Scott has been a member of the Engineering Honor Council since 2005.

Ryan Fisk

Ryan grew up in Fenton, Michigan where he graduated from Lake Fenton High School. He is currently a senior in the University of Michigan's mechanical engineering undergraduate program. Ryan plans to graduate spring of 2009 and then begin working in the automot ive industry. This past summer of 2008 Ryan interned at Tecat Engineering, a small business in Ann Arbor, where he worked on the controls system and user interface for an automated machine which removes the covers of paperback books which are to be rebounded with hard covers. In his spare time Ryan enjoys various activities such as hockey, golf, snowboarding, and wakeboarding. He also enjoys spending time working on cars whether it is his own or his friends. This is one of the reasons why he has decided to attain a mechanical engineering degree and seek out a job in the automotive field.

Andrew Funk

Andrew is a senior undergrad pursuing a BSE in Mechanical Engineering. He plans to graduate in April, 2009 and go into industry. Andrew is still searching for job opportunities that will keep him relatively close to Michigan, but he is not entirely opposed to moving away. He was born and raised in Rochester Hills, Michigan, graduating from Rochester Adams High School in 2005 as one of the top scholars. Andrew has also considered returning to grad school in a few years to complete his master's degree, if it will fit into his plans well. He got interested in mechanical engineering due to a high interest and success level in mathematics and physics courses in high school, as well as a general sense of problem solving and a joy of hands on problems. Andrew currently lives just east of central campus in Ann Arbor with 5 other guys. He has enjoyed the freedom and responsibility of this living style and is looking forward to moving out and getting his own apartment. In his spare time, Andrew enjoys playing intramural sports such as soccer and broomball, as well as many video games, especially the Guitar Hero and Rock Band series. Andrew volunteers some of his free time to help moderate an online score-tracking community devoted to these games. In September, 2008, several of the staff members on this site were flown out to Los Angeles to preview the newest Guitar Hero game, and Andrew was one of them. Lastly, Andrew hopes that his work in ME450 can have a successful impact on the world, however big or small that may be.

Jonathan Hair

Jonathan Hair was born and raised in Waterford Michigan and attended Waterford Mott High School before enrolling at the University of Michigan. After a childhood of playing with Legos it seemed the obvious choice to become a mechanical engineer. His interests include working on and racing cars, running, and cycling. This past summer Jonathan bought a 1990 Mazda Miata as a project car to have fun with and fix up. He now believes that every engineer should be required to see what fails on a car after 20 years of abuse! For the last two summers Jonathan has worked at Bolton Conductive Systems, a small engineering and manufacturing firm that specializes in low volume production of a variety of products. Working at a small company allowed him to appreciate the entire process of bringing a product to market, from initial design and prototyping to setting up a production line and dealing with customers. Ideally, Jonathan would like to work in the auto industry and have a hands-on job.

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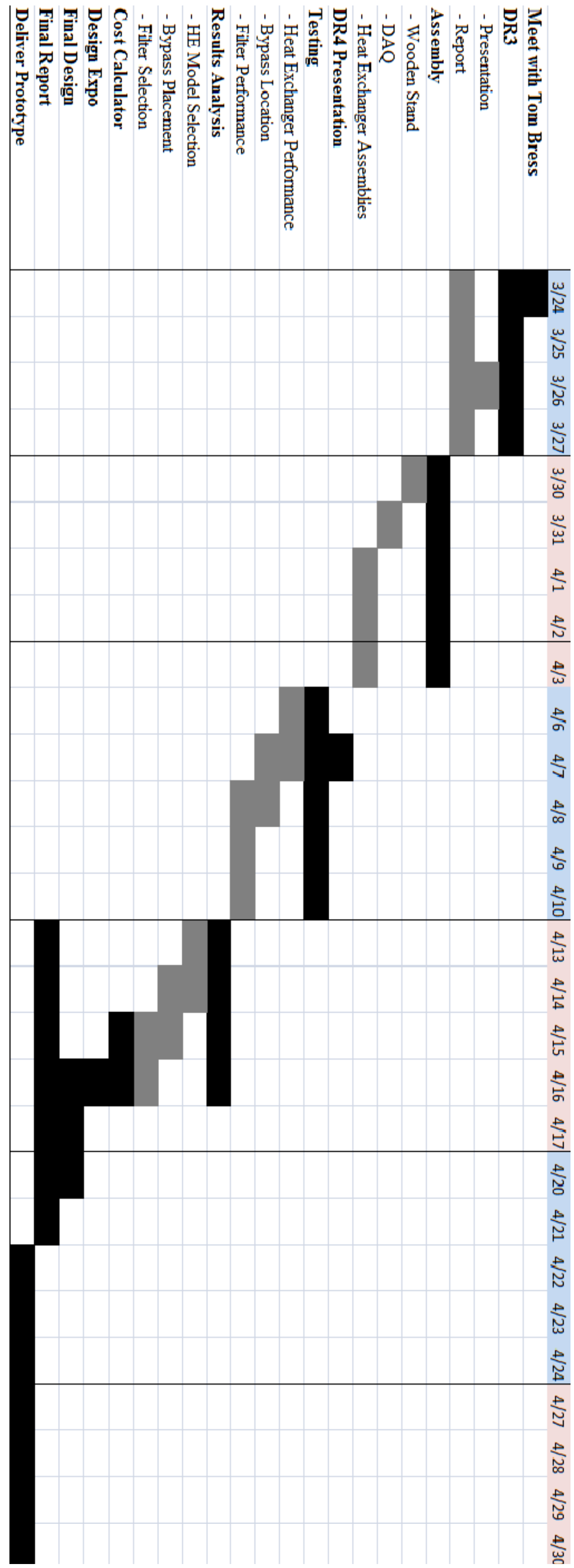
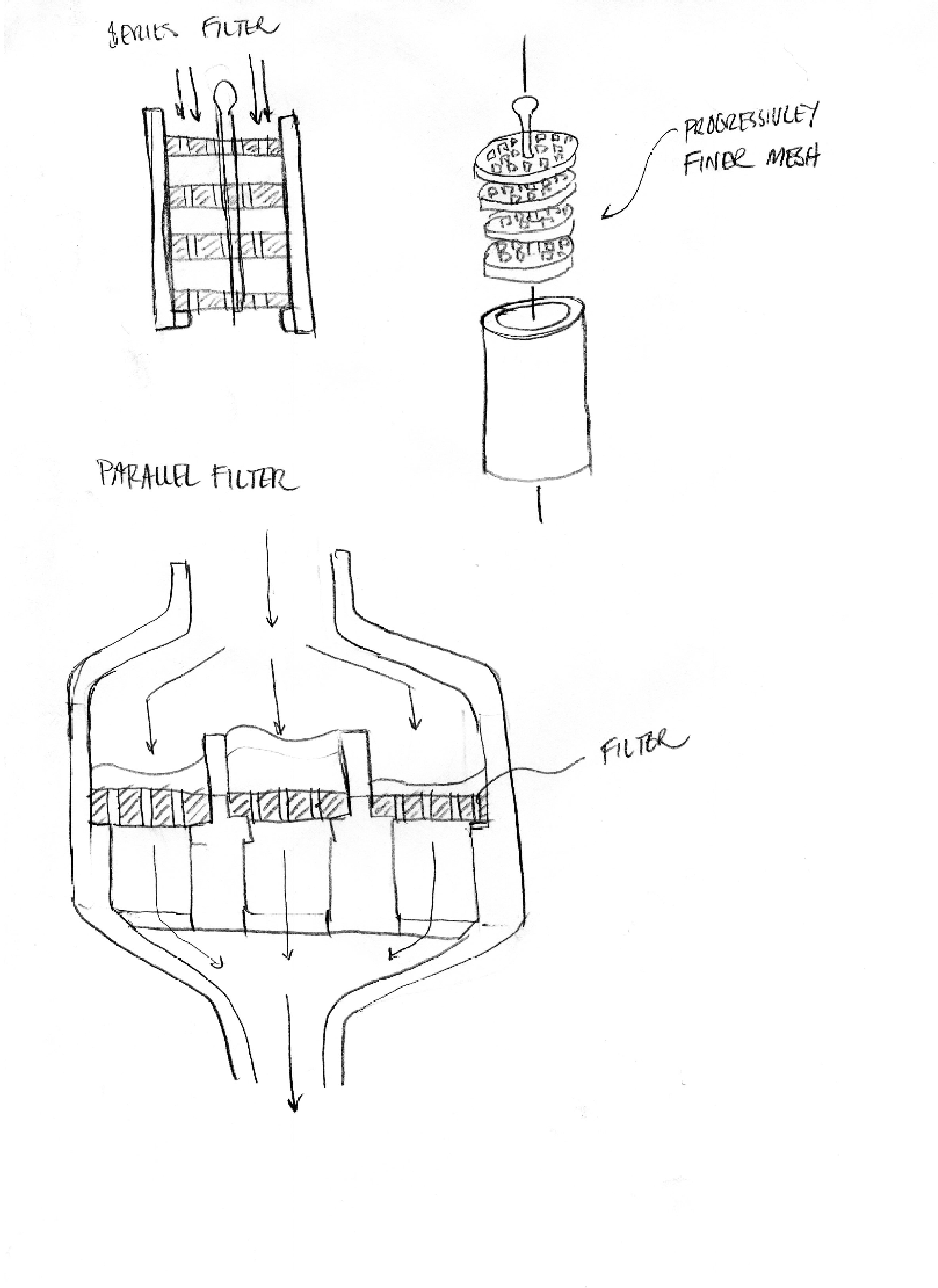
APPENDIX A: GANTT CHART



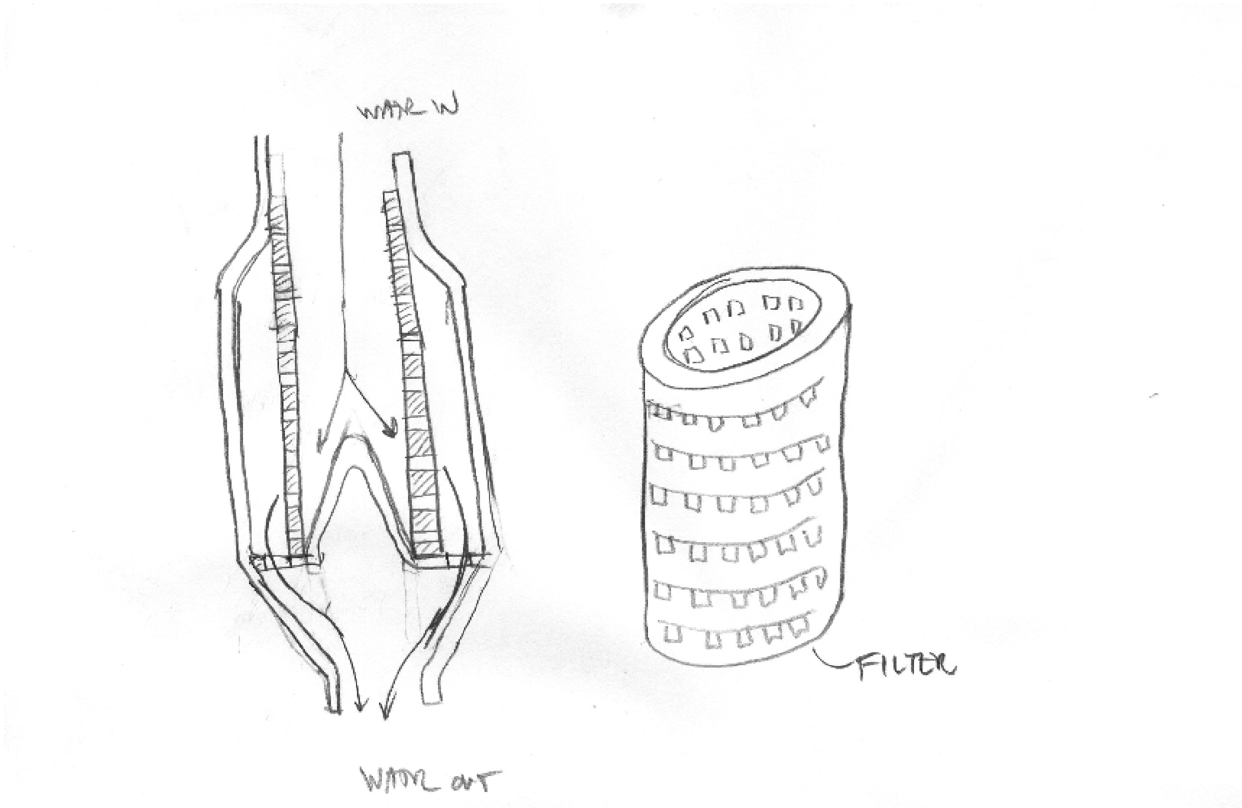
APPENDIX B: SHOWER USE DATA SHEET

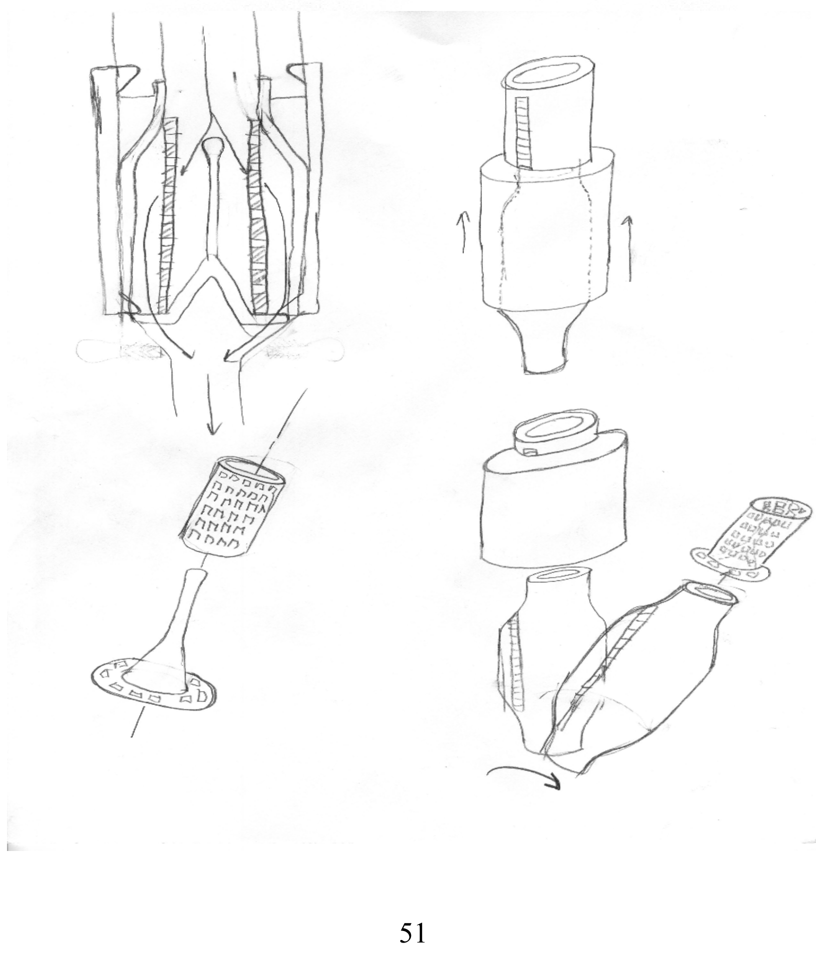
Parameter	Mean	Stdev	Units	Source
Shower Duration	8.2	4.5	minutes	Residential End Uses of Water (REUW)
Shower Use Per Household	31.1	20.8	gpd	Residential End Uses of Water (REUW)
Shower Use Per Capita Per Day	17.2	10.6	gpcd	Residential End Uses of Water (REUW)
Average Shower Flow Rate	2.22	0.95	gpm	Residential End Uses of Water (REUW)
1993 National Building Code Shower Flow Rate (at 80 psig)	2.5		gpm	Residential End Uses of Water (REUW)
US Population	299,398,484		people	US Census (Estimation for 2006)
Average Showers per day	0.75		Showers	Residential End Uses of Water (REUW)
Electricity Rate	0.1129		$/kWh	Department of Energy (DOE)
Natural Gas Rate	1.092		$/100,000 btu	Department of Energy (DOE)
Water and Wastewater Rate	2.48		$/1000 gallons	Department of Energy (DOE)
Percent of Water Heaters Using Natural Gas	58			Shower Energy Savings
Electric Water Heater Efficiency	0.98			Shower Energy Savings
Natural Gas Water Heater Efficiency	0.75			Shower Energy Savings
Inlet Cold Water Temperature	41		Degrees F	Shower Energy Savings
Average Shower Temperature	105		Degrees F	Shower Energy Savings
Housing Units	105,480,101			US Census (2000)
Persons Per Household	2.59			US Census (2000)
US Electricity Consumers (Residential)	122,471,071		People	Department of Energy (DOE)
US Average Household Electricity Consumption (Residential)	920		kWh/month	Department of Energy (DOE)
CO2 per KwH	1.43		lbs/kWh	Department of Energy (DOE)
CO2 per BTU	117		lbs/100,000 BTU	Department of Energy (DOE)

APPENDIX C.1: PARALLEL AND SERIES FILTERS

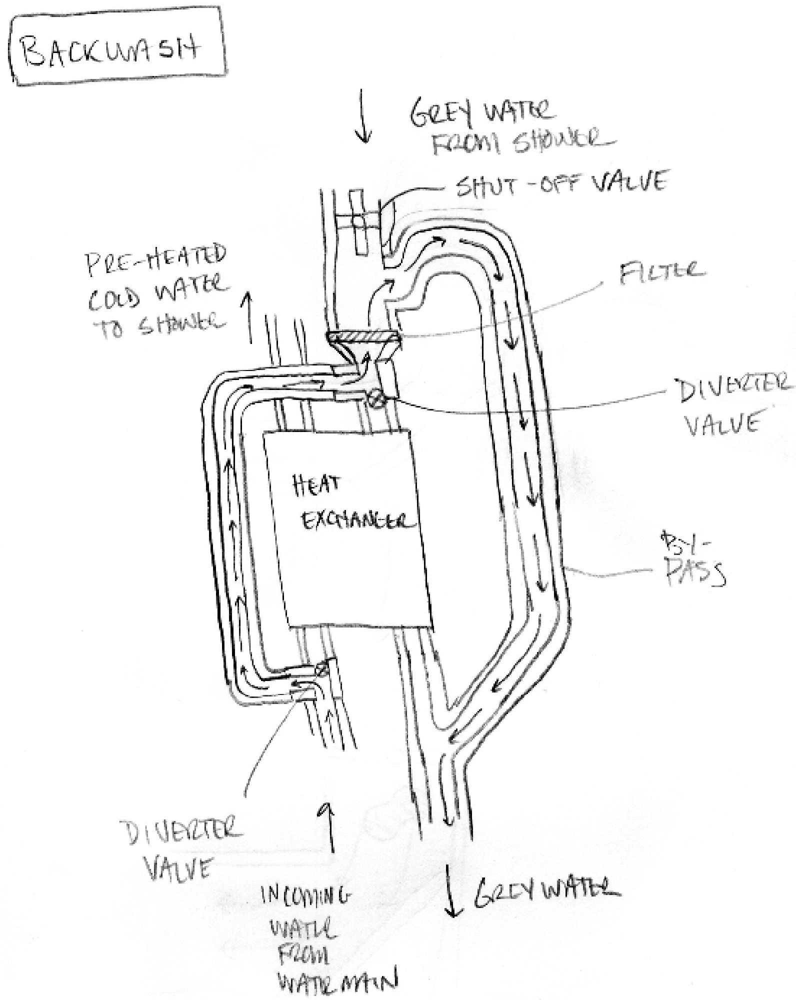


APPENDIX C.2: CYLINDER FILTERS

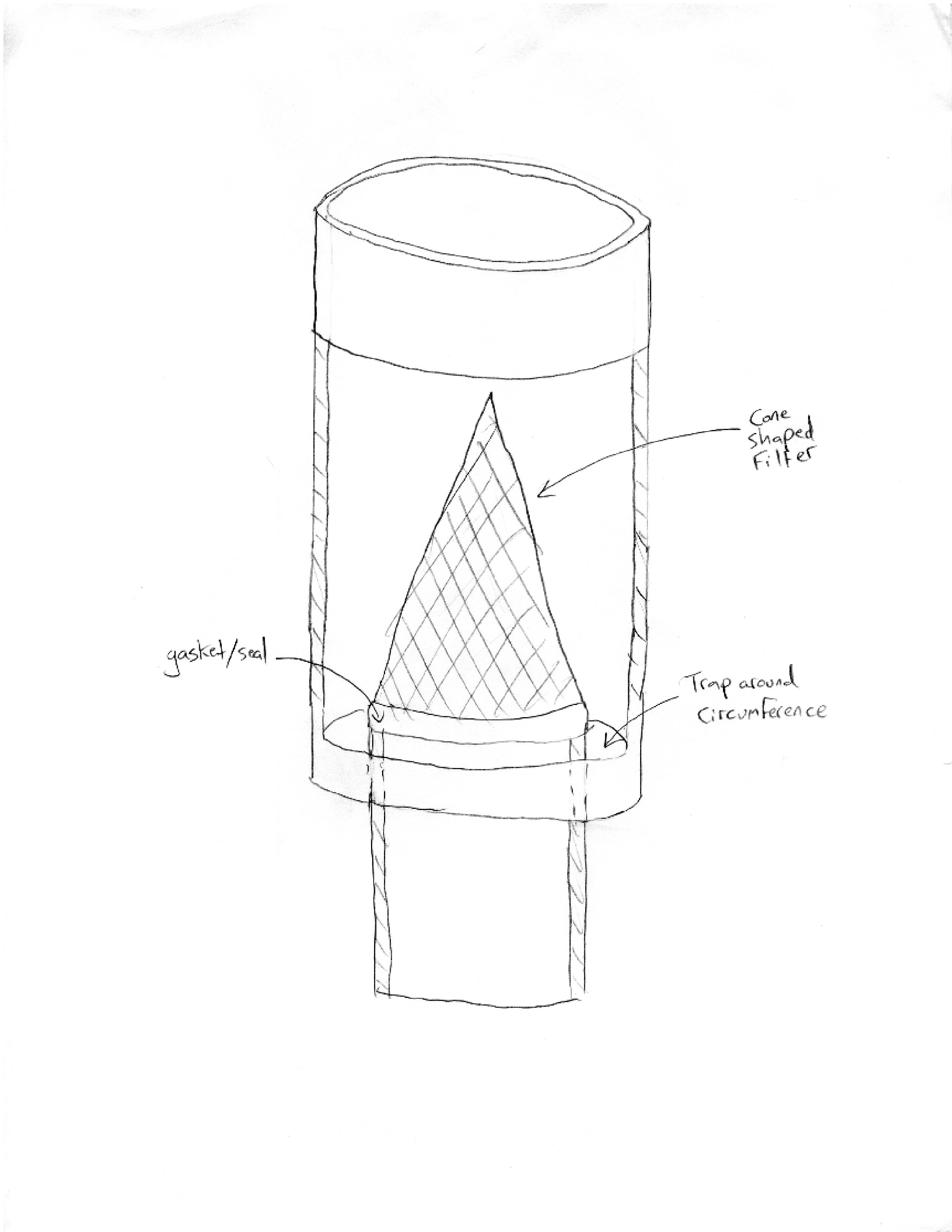




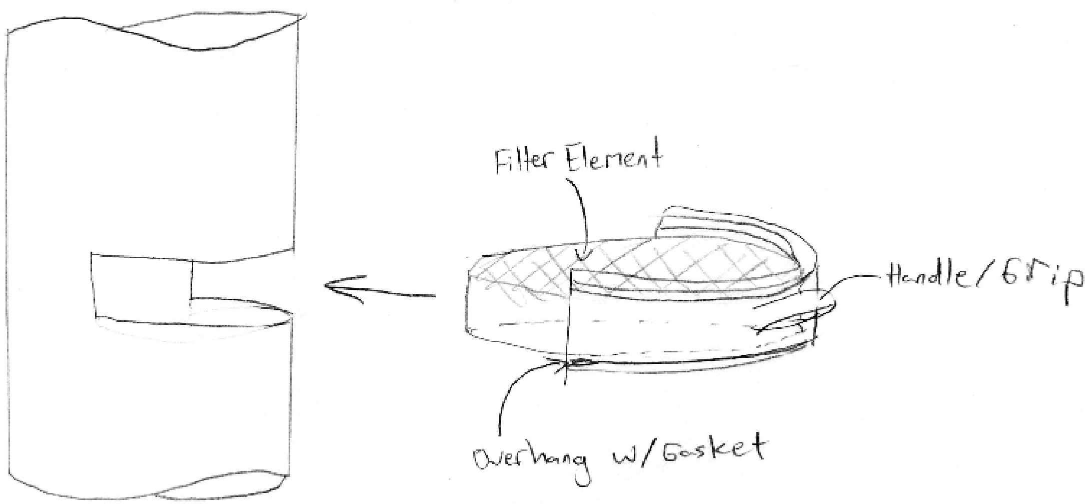
APPENDIX C.3: BACKWASHING SYSTEM



APPENDIX C.4: CONE FILTER

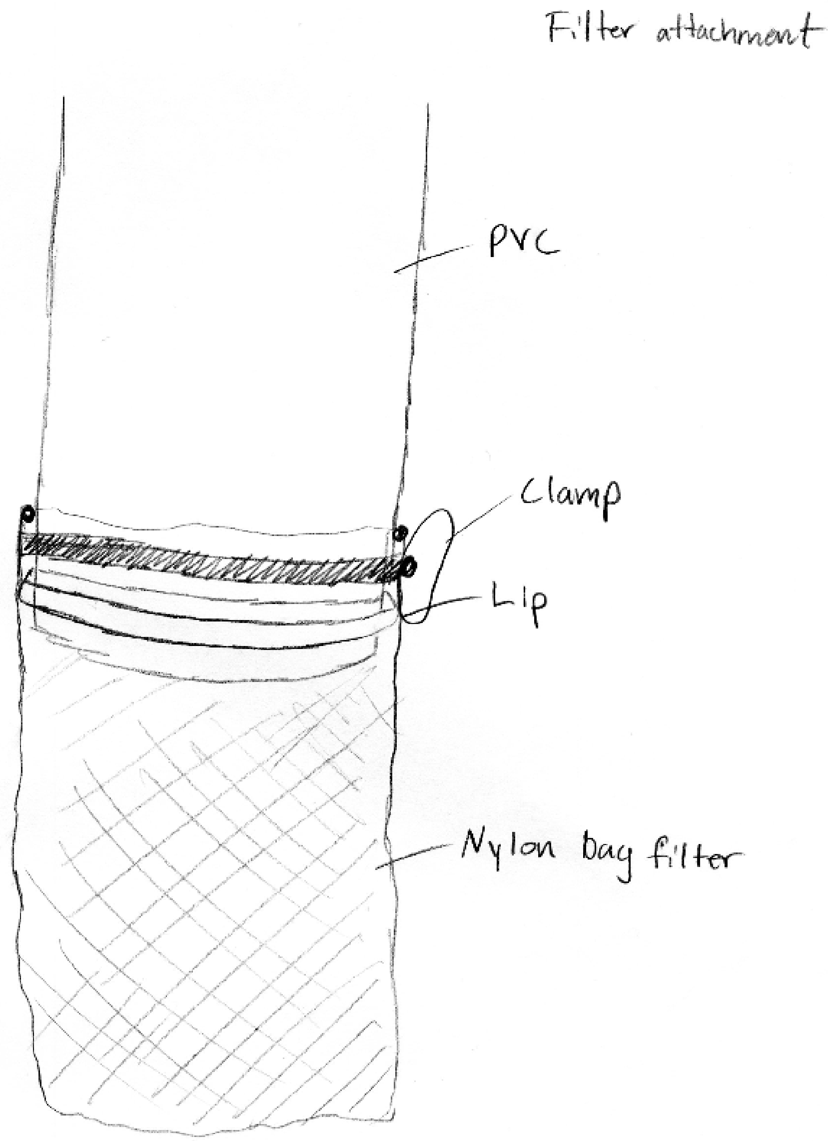


APPENDIX C.5: CARTRIDGE FILTER

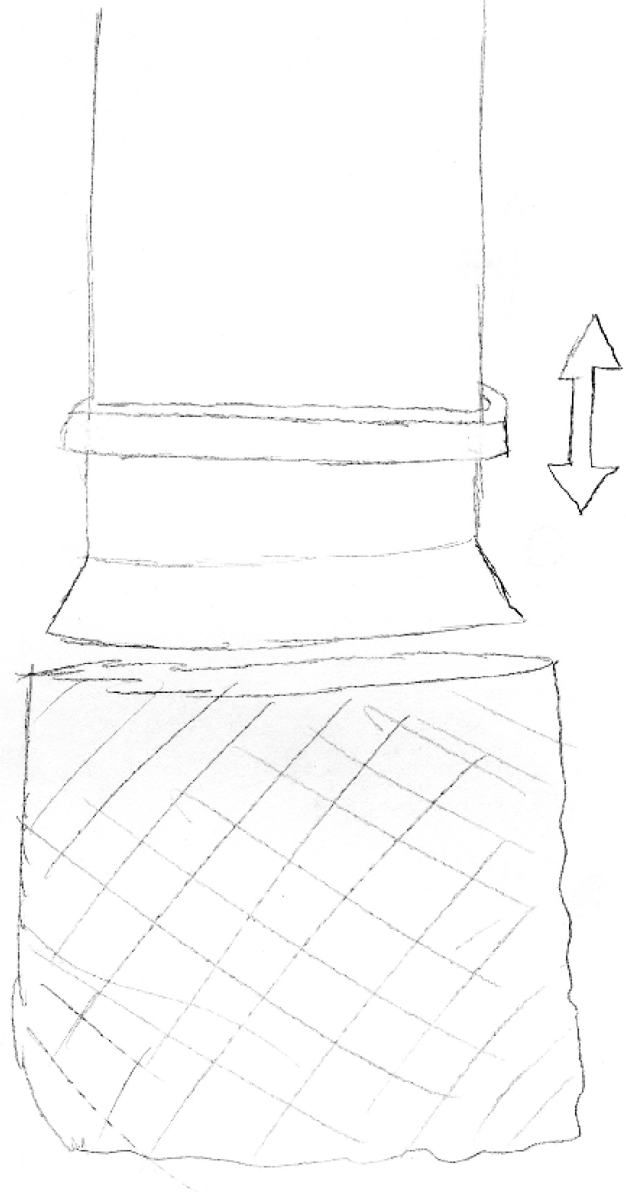


Coffee Filter Style Access to Horizontal Filter

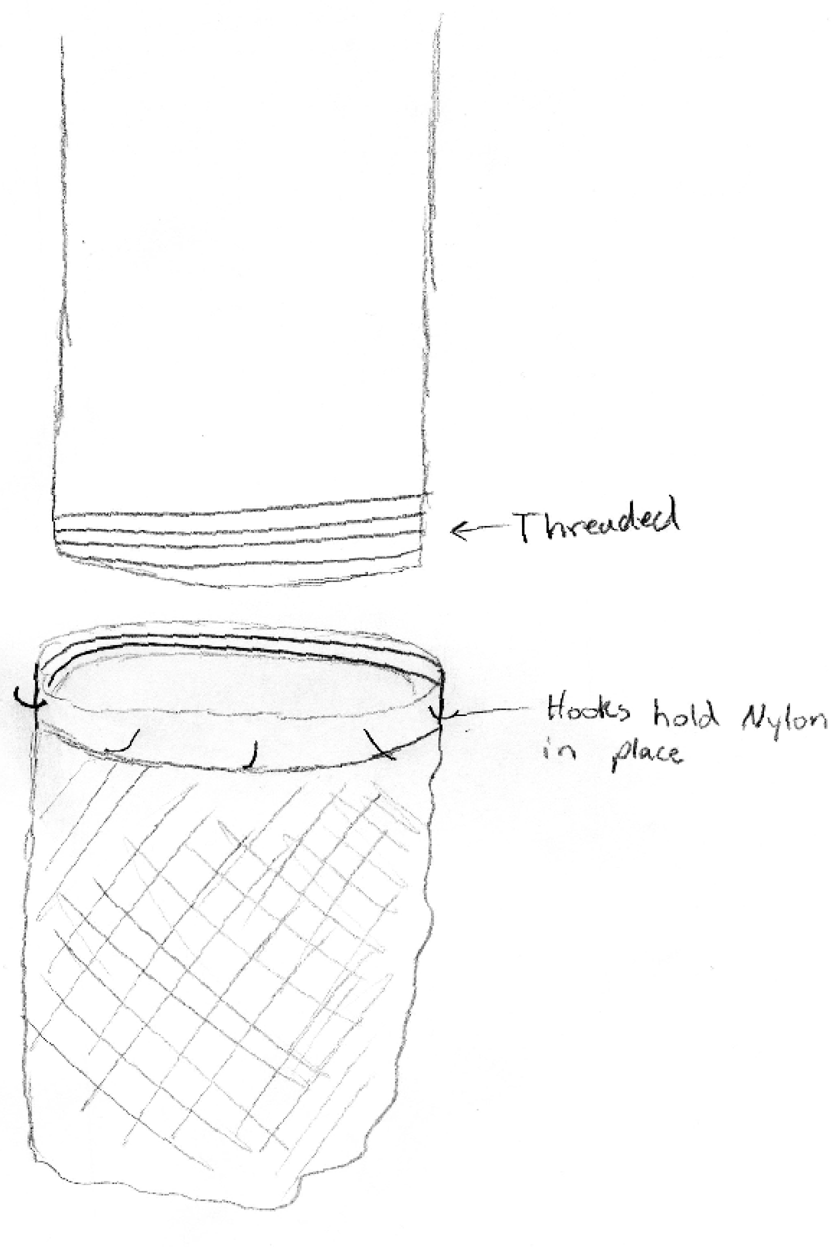
APPENDIX C.6: HOSE CLAMP AND LIP HOLD THE BAG IN PLACE



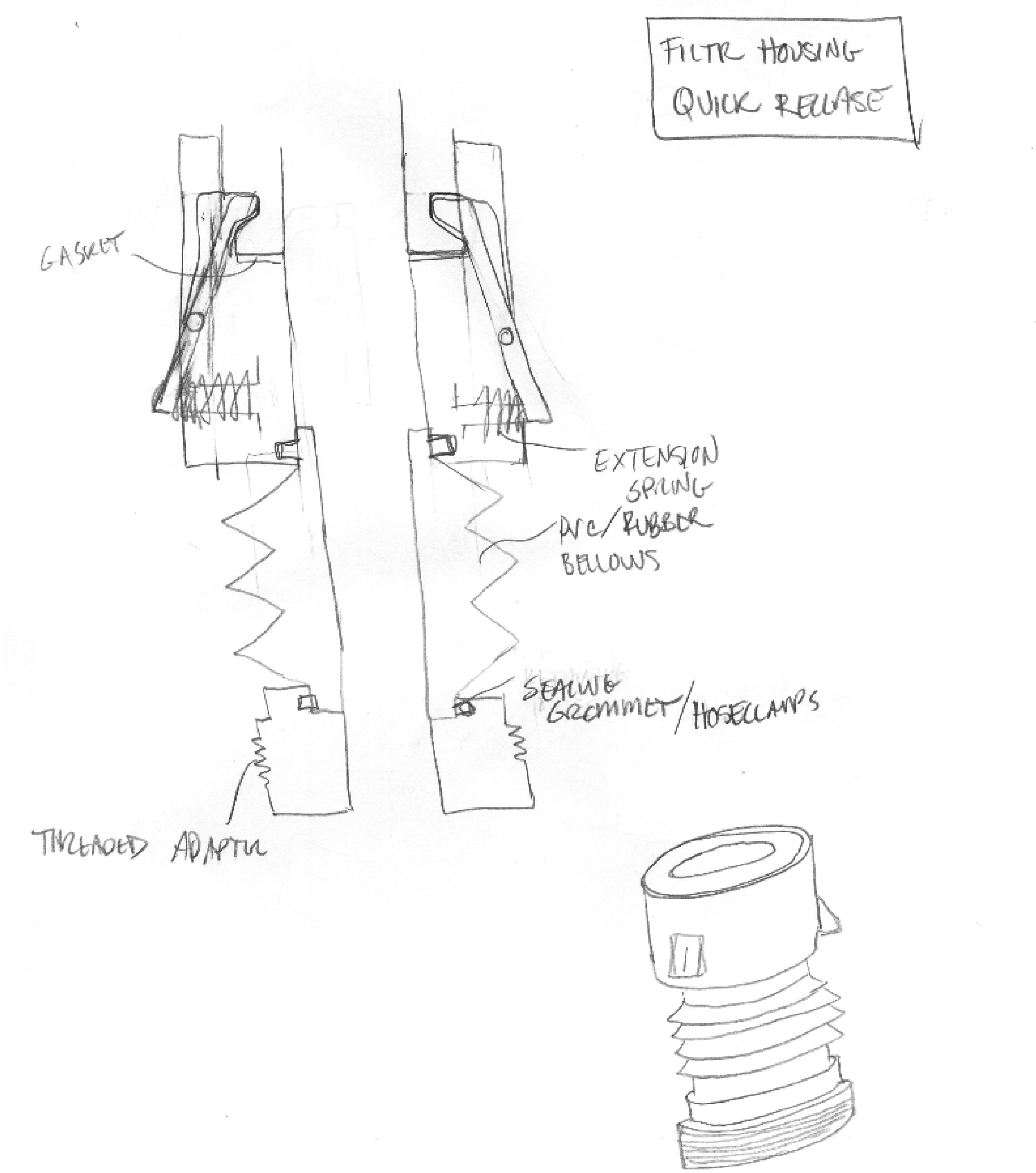
APPENDIX C.7: A TAPERED PIPE AND RETAINING RING



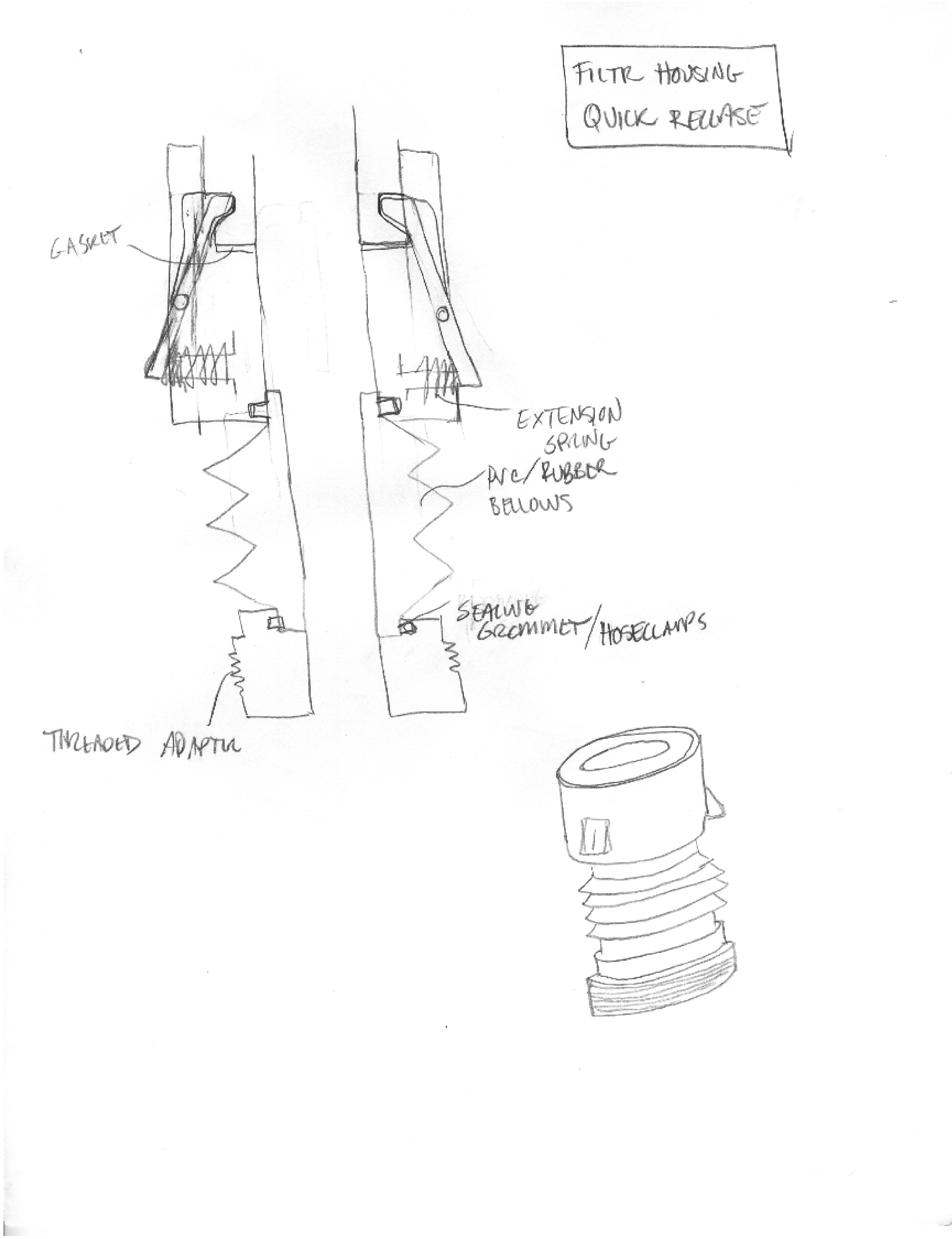
APPENDIX C.8: A THREADED DRAIN PIPE



APPENDIX C.9: FILER QUICK RELEASE



APPENDIX C.10: RETAINING RING ATTACHMENT



APPENDIX D: LB31 SPEC SHEET

aic SAHARA
2300 Bristol Circle, Unit4
Oakville, Ontario
L6H 5S3 Canada
T: 905-829-4666, F: 905-829-4646

DATE:	5/7/2007
PROJECT:	Energy Recovery
CONTACT:	Jack Griffith
COMPANY:	Infrared
CALC. NO.:	K070507-15-04
PREPARED BY:	Mo Kazemi

HEAT EXCHANGERS CALCULATION SHEET

PROJECT DATA SHEET

Heat Load	44187 BTU/h	
LMTD	10.60 deg. F	
Min. Oversizing	0 %	
	Hot Side-	**Cold Side-**
Fluid	Water	Water
Inlet Temperature	91.00 deg. F	41.00 deg. F
Outlet Temperature	60.35 deg. F	86.00 deg. F
Mass Flow	1441.686 lb/h	980.248 lb/h
Inlet Volume Flow	2.898 USGal/min	1.956 USGal/min
Outlet Volume Flow	2.883 USGal/min	1.969 USGal/min
Max. Pressure Drop	14.50 psi	14.50 psi

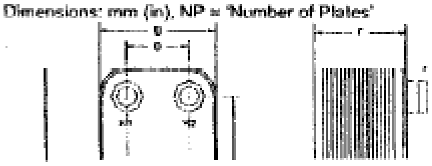
HEAT EXCHANGER SELECTION

Heat Exchanger Type	LB60 - 30	
# of Units Parallel	1	
Heat Transfer Area	17.48 ft2	
Fouling Factor	0.00 ft2hF/BTU	
OHTC Clean	282 BTU/ft2hF	
OHTC Fouling	282 BTU/ft2hF	
Oversize	0 %	
	Hot Side-Water	**Cold Side-Water**
Calculated Pressure Drop	0.32 psi	0.19 psi
Heat Transfer NTU	-	-

PHYSICAL PROPERTIES

	Hot Side	**Cold Side**
Fluid	Water	Water
Pressure	100.00 psig	100.00 psig
Reference Temperature	75.68 deg. F	63.50 deg. F
Density	62.1873 lb/ft3	62.3030 lb/ft3
Heat Capacity	1.0000 BTU/lbF	1.0017 BTU/lbF
Thermal Conductivity	0.3519 BTU/fthF	0.3461 BTU/fthF
Dynamic Viscosity	0.9116 cP	1.0760 cP

Dimensions: mm (in), NP = 'Number of Plates'



APPENDIX E: PROJECTED BUDGET

Part	Description	Vendor	Part Number	Price($)	
Piping					
4" PVC Unthreaded	4 1/2' Length, 4.215" OD, 4.075" ID, Gravity Flow, Max 140F	Mcmaster-Carr	2426K25	7.53	
6" PVC Unthreaded	4 1/2' Length, 6.275" OD, 6.075" ID, Gravity Flow, Max 140F	Mcmaster-Carr	2426K27	14.64	
8" PVC Unthreaded	5' Length, 8.625" OD, 7.943" ID, 160psi, Max 140F	Mcmaster-Carr	48925K26	60.84	
1-1/4" PVC Threaded	2' Length, 1-1/4" Pipe/Thread Size, Max 260psi, Max 110F	Mcmaster-Carr	4687T16	10.74	
2" PVC Unthreaded	5' Length, 2.375" OD, 2.049" ID, Max 280 Psi, Max 140F	Mcmaster-Carr	48925K96	9.32	
2" PVC Threaded	2' Length, 2" Pipe/Thread Size, Max 200psi, Max 110F	Mcmaster-Carr	4687T18	16.69	
Pipe Adapter					
Rigid PVC 6"-4" Reducer	6" reduced to 4", Gravity Flow, Max 140F, Reducing Coupling	Mcmaster-Carr	9102K264	9.69	
Flexible PVC 6"-4" Reducer	6" reduced to 4", 6" Length, Gravity Flow, Max 120F, Includes 2 Stainless Steel Clamps	Mcmaster-Carr	4511K86	17.92	
Flexible PVC 8"-6" Reducer	8" reduced to 6", 6" Length, Gravity Flow, Max 120F, Includes 2 Stainless Steel Clamps	Mcmaster-Carr	4511K65	27.02	
6" Diameter Flexible Coupler	6" Length, 6"Diameter, Gravity Flow, Max 120F, Includes 2 Stainless Steel Clamps	Mcmaster-Carr	4511K83	16.46	
Rigid PVC 4"-2" Reducer	4" Reduced to 4", Gravity Flow, Max 140F	Mcmaster-Carr	2389K7	10.66	
Polypro Threaded Fitting 2" to 1-1/4"	2" Threaded to 1-1/4" Threaded, Max 150psi, Max 150F, NPT to NPT Connection	Mcmaster-Carr	46885K225	11.68	
Filter Bags					
Polyester w/Steel Ring (25)	4-3/32" Dia X 8" Length, 25 Micron, Polyester Felt, Works w/Threaded Adaptor	Mcmaster-Carr	98295K5	2.85	*2.08 Each 10&Up
Polyester w/Steel Ring (100)	4-3/32" Dia X 8" Length, 100 Micron, Polyester Felt, Works w/Threaded Adaptor	Mcmaster-Carr	98295K8	2.85	*2.08 Each 10&Up
Polyester w/Steel Ring (200)	4-3/32" Dia X 8" Length, 200 Micron, Polyester Felt, Works w/Threaded Adaptor	Mcmaster-Carr	98295K9	2.85	*2.08 Each 10&Up
Polypro w/Steel Ring (25)	4-3/32" Dia X 8" Length, 25 Micron, Polypropelyne Felt, Works w/Threaded Adaptor	Mcmaster-Carr	9308T15	3.50	*2.41 Each 10&Up
Polypro w/Steel Ring (100)	4-3/32" Dia X 8" Length, 25 Micron, Polypropelyne Felt, Works w/Threaded Adaptor	Mcmaster-Carr	9308T18	3.50	*2.41 Each 10&Up
Polypro w/Steel Ring (200)	4-3/32" Dia X 8" Length, 200 Micron, Polypropelyne Felt, Works w/Threaded Adaptor	Mcmaster-Carr	9308T19	3.50	*2.41 Each 10&Up
Nylon w/Steel Ring (50)	4-3/32" Dia X 8" Length, 50 Micron, Nylon Monofilament, Works w/Threaded Adaptor, Reusable	Mcmaster-Carr	98295K34	3.31	*2.42 Each 10&Up
Nylon w/Steel Ring (100)	4-3/32" Dia X 8" Length, 100 Micron, Nylon Monofilament, Works w/Threaded Adaptor, Reusable	Mcmaster-Carr	98295K36	3.31	*2.42 Each 10&Up
Nylon w/Steel Ring (200)	4-3/32" Dia X 8" Length, 200 Micron, Nylon Monofilament, Works w/Threaded Adaptor, Reusable	Mcmaster-Carr	98295K38	3.31	*2.42 Each 10&Up
Nylon w/Steel Ring (300)	4-3/32" Dia X 8" Length, 300 Micron, Nylon Monofilament, Works w/Threaded Adaptor, Reusable	Mcmaster-Carr	98295K41	3.31	*2.42 Each 10&Up
Nylon w/Steel Ring (400)	4-3/32" Dia X 8" Length, 400 Micron, Nylon Monofilament, Works w/Threaded Adaptor, Reusable	Mcmaster-Carr	98295K42	3.31	*2.42 Each 10&Up
Nylon w/Steel Ring (600)	4-3/32" Dia X 8" Length, 600 Micron, Nylon Monofilament, Works w/Threaded Adaptor, Reusable	Mcmaster-Carr	98295K44	3.31	*2.42 Each 10&Up
Nylon w/Steel Ring (800)	4-3/32" Dia X 8" Length, 800 Micron, Nylon Monofilament, Works w/Threaded Adaptor, Reusable	Mcmaster-Carr	98295K46	3.31	*2.42 Each 10&Up
Nylon w/Steel Ring (1000)	4-3/32" Dia X 8" Length, 1000 Micron, Nylon Monofilament, Works w/Threaded Adaptor, Reusable	Mcmaster-Carr	98295K49	3.31	*2.42 Each 10&Up
MISC					
Threaded Bag Adapter	Polypro Adapter Head for 4-3/32" Dia, 1-1/4" NPT Grab-on Filter Bag	Mcmaster-Carr	98295K13	15.21	
4" Quick Release Hose Clamp	Hose Quick Release Clamp, 304 Stainless Steel, Inside Dia 4 In, Width 7/8 In	Grainger	2TA48	14.06	
6" Quick Release Hose Clamp	Hose Quick Release Clamp, 304 Stainless Steel, Inside Dia 6 In, Width 7/8 In	Grainger	2TA49	15.2	
8" Quick Release Hose Clamp	Hose Quick Release Clamp, 304 Stainless Steel, Inside Dia 8 In, Width 7/8 In	Grainger	2TA50	15.51	
			Total	72.34	

APPENDIX F: HEAT EXCHANGER SELECTION

Model	Supplier	Surface Area per Plate (sq. ft)	Depth (in)	Width (in)	Height (in)	Number of Plates	Effective Transfer Area (sq. ft)	Cost	cost/sq.ft	Hydraulic Diameter
8456T17	McMaster- Carr		10.94	7.50	24.31		85.50	$2,030.49	$23.75	11.46
8456T15	McMaster- Carr		6.06	4.38	20.69		27.90	$671.19	$24.06	7.22
8546T25	McMaster- Carr		5.31	4.38	20.69		22.30	$642.86	$28.83	7.22
BP415-42 LCA	Granger	0.57	4.47	4.37	20.70	42	23.77	$720.00	$30.29	7.22
BP415-42 LCA	Granger	0.57	4.47	4.37	20.70	42	23.77	$720.00	$30.29	7.22
LB31-60X	AIC Alliance	0.34	5.89	5.00	12.00	60	20.40	$630.00	$30.88	7.06
LB31-50X	AIC Alliance	0.34	4.99	5.00	12.00	50	17.00	$544.00	$32.00	7.06
LB60-30X	AIC Alliance	0.62	3.19	5.00	19.90	30	18.60	$623.00	$33.49	7.99
8546T24	McMaster- Carr		4.00	4.38	20.69		14.50	$493.88	$34.06	7.22
LB31-40X	AIC Alliance	0.34	4.09	5.00	12.00	40	13.60	$468.00	$34.41	7.06
8456T14	McMaster- Carr		4.19	4.38	20.69		16.70	$583.67	$34.95	7.22
8456T16	McMaster- Carr		5.69	7.50	24.31		32.00	$1,140.82	$35.65	11.46
BP415-28 LCA	Granger	0.57	3.12	4.37	20.70	28	15.85	$580.00	$36.60	7.22
BPR415-28 LCA	Granger	0.57	3.12	4.37	20.70	28	15.85	$580.00	$36.60	7.22
LB31-30X	AIC Alliance	0.34	3.19	5.00	12.00	30	10.20	$386.00	$37.84	7.06
35115k67	McMaster- Carr		6.88	9.81	20.31		63.00	$2,457.45	$39.01	13.23
BP410-60 LCA	Granger	0.28	6.62	4.37	12.20	60	16.86	$694.00	$41.16	6.44
BP410-60 LCA	Granger	0.28	6.22	4.37	12.20	60	16.86	$694.00	$41.16	6.44
35115k65	McMaster- Carr		7.25	4.88	12.19		22.20	$959.71	$43.23	6.96
8456T13	McMaster- Carr		5.13	4.38	12.19		11.20	$497.74	$44.44	6.44
BP410-50 LCA	Granger	0.28	5.25	4.37	12.20	50	14.05	$628.00	$44.70	6.44
LB31-20X	AIC Alliance	0.34	2.29	5.00	12.00	20	6.80	$313.00	$46.03	7.06
35115k64	McMaster- Carr		5.38	4.88	12.19		14.60	$681.06	$46.65	6.96
BP410-40 LCA	Granger	0.28	4.28	4.37	12.20	40	11.24	$525.00	$46.71	6.44
BP412-40 LCA	Granger	0.28	4.28	4.37	12.20	40	11.24	$565.00	$50.27	6.44
BP412-40 LCA	Granger	0.28	4.28	4.37	12.20	40	11.24	$565.00	$50.27	6.44
8456T12	McMaster- Carr		4.19	4.38	12.19		8.40	$426.53	$50.78	6.44
8546T23	McMaster- Carr		4.56	4.38	12.19		8.90	$461.22	$51.82	6.44
LA14-30X	AIC Alliance	0.13	3.09	3.10	7.60	30	3.90	$215.00	$55.13	4.40
BP411-30 LCA	Granger	0.28	3.31	4.37	12.20	30	8.43	$468.00	$55.52	6.44
BP412-30 LCA	Granger	0.28	3.31	4.37	12.20	30	8.43	$490.00	$58.13	6.44
35115k66	McMaster- Carr		4.94	9.81	20.31		36.80	$2,202.45	$59.85	13.23
BP410-30 LCA	Granger	0.28	3.31	4.37	12.20	30	8.43	$540.00	$64.06	6.44
BP411-20 LCA	Granger	0.28	2.34	4.37	12.20	20	5.62	$384.00	$68.33	6.44
8456T11	McMaster- Carr		4.56	3.06	8.19		5.70	$391.84	$68.74	4.46
BP410-20 LCA	Granger	0.28	2.34	4.37	12.20	20	5.62	$395.00	$70.28	6.44
35115k63	McMaster- Carr		3.44	4.88	12.19		6.90	$485.01	$70.29	6.96
LB31-10X	AIC Alliance	0.34	1.39	5.00	12.00	10	3.40	$242.00	$71.18	7.06
BP400-40 LCA	Granger	0.13	3.64	3.10	8.20	40	5.04	$367.00	$72.82	4.50
BP400-40 LCA	Granger	0.13	3.64	3.10	8.20	40	5.04	$367.00	$72.82	4.50

Model	Supplier	Surface Area per Plate (sq. ft)	Depth (in)	Width (in)	Height (in)	Number of Plates	Effective Transfer Area (sq. ft)	Cost	cost/sq.ft	Hydraulic Diameter
BP412-20 LCA	Granger	0.28	2.34	4.37	12.20	20	5.62	$417.00	$74.20	6.44
BP400-30 LCA	Granger	0.13	2.83	3.10	8.20	30	3.78	$319.00	$84.39	4.50
BP400-30 LCA	Granger	0.13	2.83	3.10	8.20	30	3.78	$319.00	$84.39	4.50
BP410-14 LCA	Granger	0.28	1.76	4.37	12.20	14	3.93	$346.00	$87.95	6.44
BP410-14 LCA	Granger	0.28	1.76	4.37	12.20	14	3.93	$346.00	$87.95	6.44
8546T22	McMaster- Carr		2.69	4.38	12.19		3.30	$308.16	$93.38	6.44
3253K21	McMaster- Carr		4.94	9.81	20.31		36.80	$3,475.78	$94.45	13.23
35115k62	McMaster- Carr		2.56	4.88	12.19		3.10	$297.88	$96.09	6.96
BP400-20 LCA	Granger	0.13	2.02	3.10	8.20	20	2.52	$275.00	$109.13	4.50
35115k61	McMaster- Carr		2.75	3.31	7.81		2.00	$222.50	$111.25	4.65
BP410-10 LCA	Granger	0.28	1.37	4.37	12.20	10	2.81	$320.00	$113.88	6.44
8546T21	McMaster- Carr		2.31	4.38	12.19		2.20	$275.51	$125.23	6.44
3253K14	McMaster- Carr		4.94	4.94	12.19		14.60	$2,490.24	$170.56	7.03
3253K13	McMaster- Carr		4.19	4.94	12.19		10.70	$1,860.98	$173.92	7.03
BP400-10 LCA	Granger	0.13	2.80	3.10	8.20	10	1.26	$225.00	$178.57	4.50
BP400-10 LCA	Granger	0.13	1.21	3.10	8.20	10	1.26	$225.00	$178.57	4.50
3253K12	McMaster- Carr		3.25	4.94	12.19		6.90	$1,419.51	$205.73	7.03
3253K11	McMaster- Carr		2.44	4.94	12.19		3.10	$973.17	$313.93	7.03

APPENDIX G: DIMENSIONAL ANALYSIS FOR CONVECTION COEFFICIENT

Table A2.1: Nomenclature [37]

Nomenclature

A	Cross-sectional area, m^2
A_s	Surface area, m^2
c_p	Specific heat at constant pressure, kJ kg^{-1} K^{-1}
D_h	Hydraulic diameter, m
f	Friction factor
H	Height of channel, m
h_x	Local heat transfer coefficient, kJ m^{-2} K^{-1}
j	Coburn factor
k	Thermal conductivity, kJ m^{-1} K^{-1}
$\dot{m}$	Mass flow rate, kg s^{-1}
Nu_m	Average Nusselt number
Nu_x	Local Nusselt number
P	Wetted perimeter, m
Pr	Prandtl Number
Q	Heat transfer rate, kW
R	Radius of curvature, m
Re	Reynolds number
T_b	Bulk temperature, K
T_m	Mean temperature, K
T_w	Wall temperature, K
V	Average velocity, m s^{-1}
W	Width of channel, m
x, y	Coordinates
λ	Wave length, m
β	Corrugated angle
ρ	Density of air, kg m^{-3}
μ	Viscosity of air, N s m^{-2}
$\Delta\theta_{fw}$	Temperature difference between flow and wall, K
ϕ	Coefficient of determination
ξ	Relative error

$$D_h = \frac{4A}{P} = \frac{2WH}{W+H} \quad \text{(Eq. A2.1)}$$

APPENDIX H: THERMAL RESISTANCE CALCULATIONS

Cold side	
Ambient temperature (k)	298.00
Cold inlet temperature (f)	41.00
Cold inlet temperature (k)	278.00
Mean inlet temperature (k)	288.00
Specific heat (j/kg k)	4189.00
Thermal conductivity (w/mk)	0.59
Volume flow rate (gpm)	2.50
Volume flow rate (m3/s)	0.0002
Cold mean velocity (m/s)	0.01

Hot side	
Ambient temperature (k)	298.00
Hot inlet temperature (f)	105.00
Hot inlet temperature (k)	314.00
Mean hot temperature (k)	306.00
Specific heat (j/kg k)	4178.00
Dynamic viscosity (ns/m2)	0.00
Volume flow rate (gpm)	2.50
Volume flow rate (m3/s)	0.0002
Hot mean velocity (m/s)	0.01

Hot side fluid properties	
Density (kg/m3)	995.02
Thermal conductivity (w/mk)	0.62
Prandlt number	5.20
Reynolds hot	1887.84
Nusselt hot	25.64
Hot convection coefficient	88.66
Surface temp (k)	298.00

Plate geometry	
Plate length (m)	0.13
Plate height (m)	0.30
Plate area (m2)	0.04
Number of plates	10.00
Bend radius (m)	0.05
Corrugation angle (rad)	0.52
Hydraulic diameter	0.18
Transfer area (m2)	0.35

Cold inlet temperature (k)	Specific volume	Density (kg/m3)	Viscosity (ns/m2)	Fluid thermal conductivity (w/mk)	Prandlt number	Reynolds cold	Dimensionless temperature	Nusselt cold	Cold convection coefficient	Thermal resistance (m2k/w)
275.00	1.000	1000.00	1.65e-03	0.57	12.22	883.18	9.41e+13	11.29	36.15	0.03
280.00	1.000	1000.00	1.42e-03	5.82e-01	10.26	1026.03	1.17e+14	13.22	42.92	0.02
285.00	1.000	1000.00	1.23e-03	5.90e-01	8.81	1191.03	1.34e+14	15.34	50.47	0.02
290.00	1.001	999.00	1.08e-03	5.98e-01	7.56	1349.58	1.22e+14	16.99	56.68	0.02
295.00	1.002	998.00	9.59e-04	6.06e-01	6.62	1518.35	6.60e+13	17.73	59.92	0.02

APPENDIX I: TEST STAND CONSTRUCTION

Fig. I1: Plywood Sawing Operations

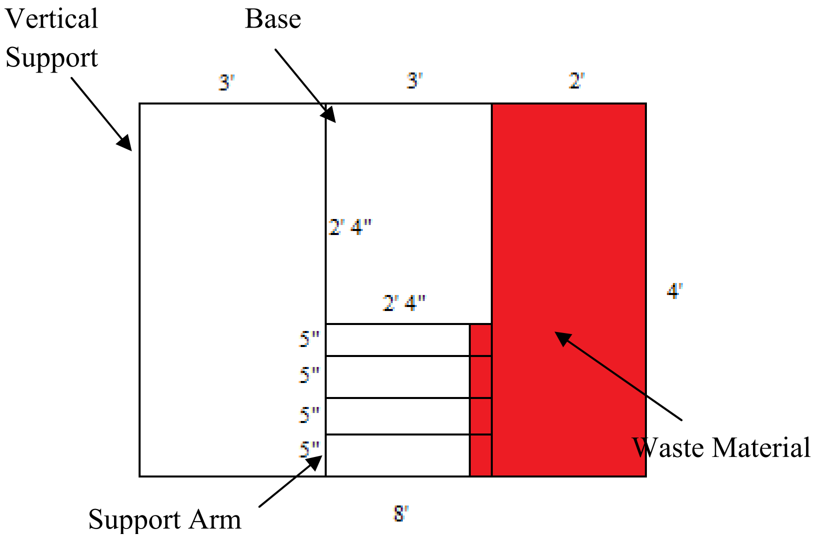


Fig. I.2: Stand Assembly

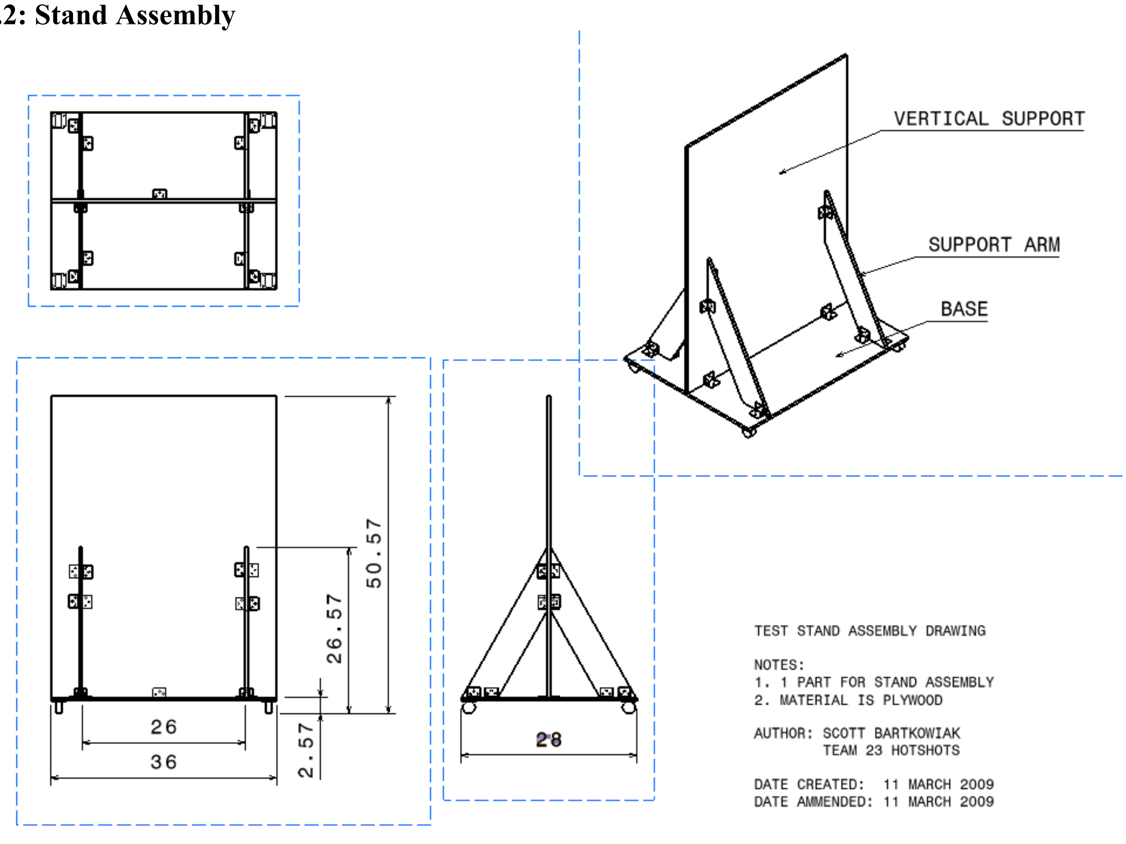


Fig I.3: Support Arm

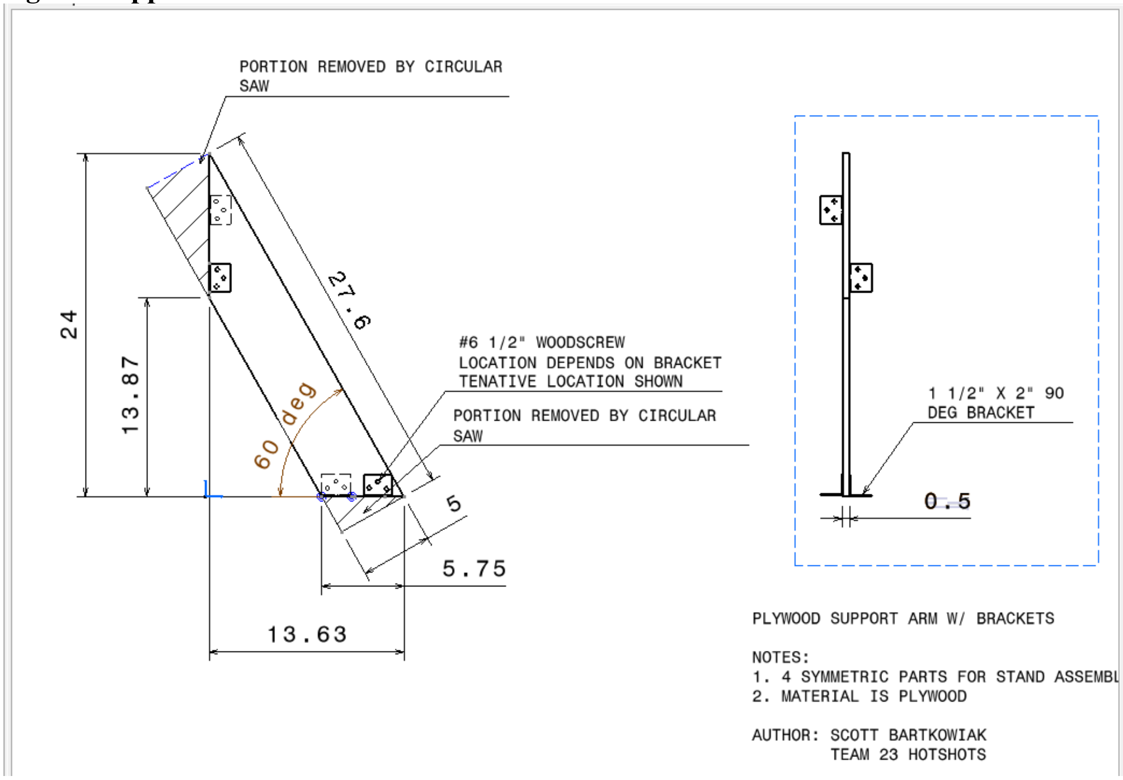


Fig. I.4: Stand Base

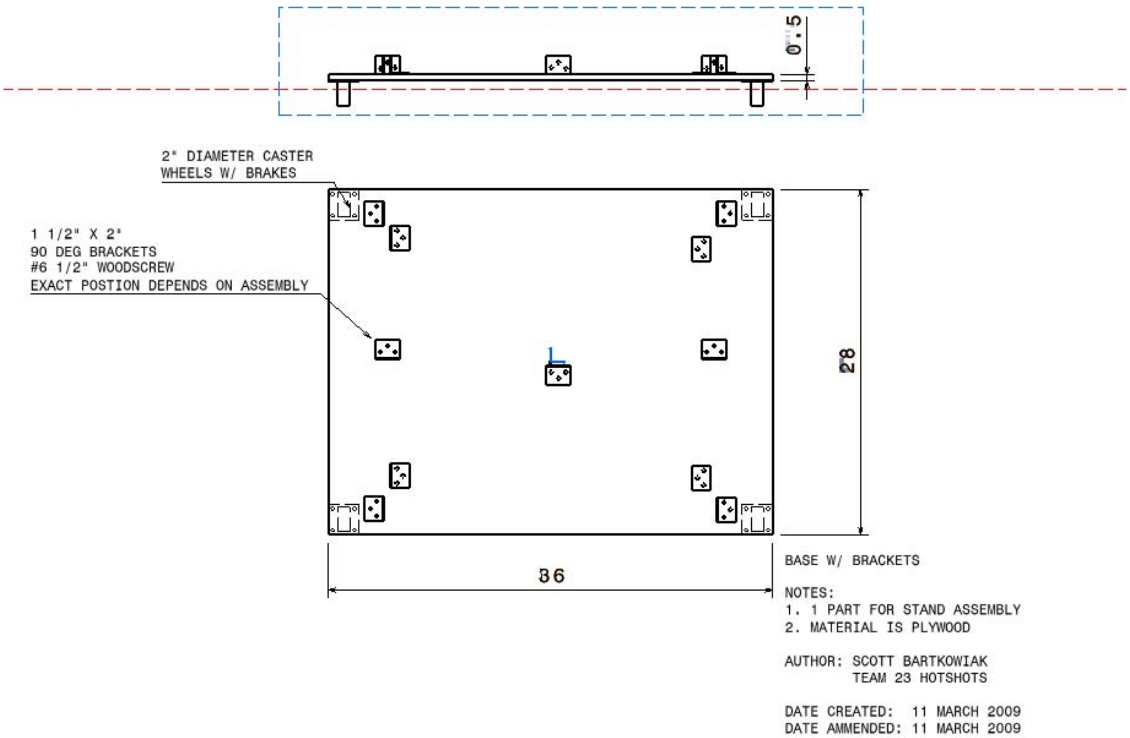
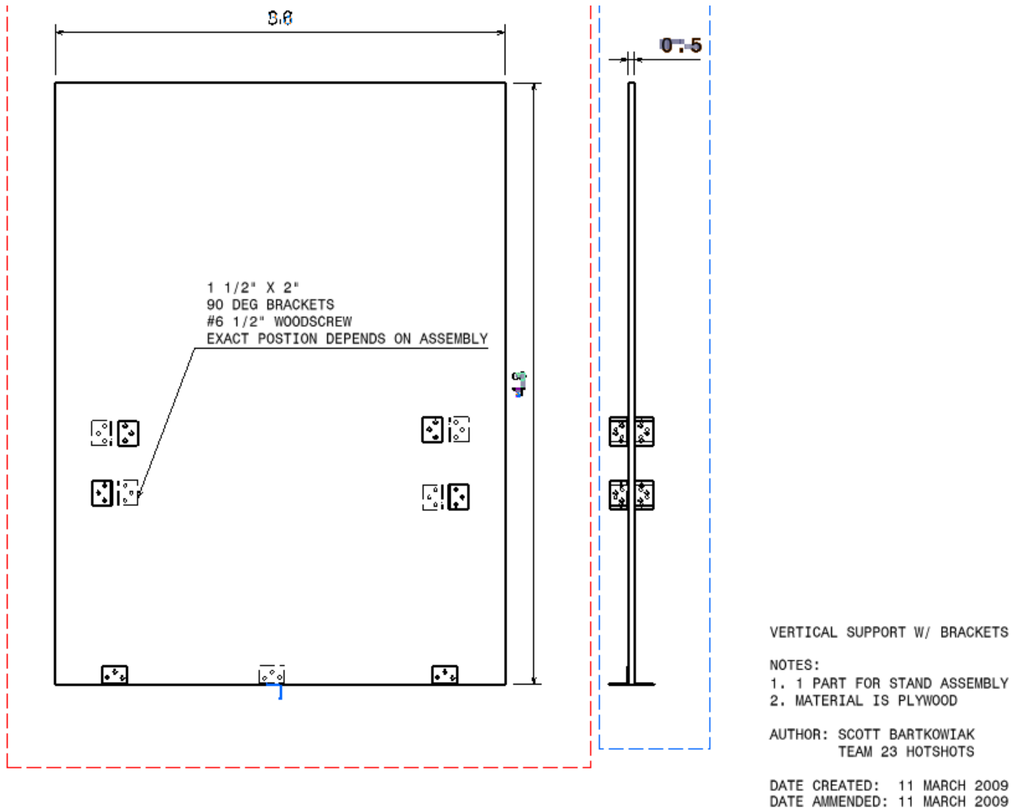


Fig. I.5: Vertical Support



APPENDIX J: TEST STAND PARTS LIST

ID	Part	Description	Vendor	Part Number	Qty	Unit Price($)	
	Stand						
P1	Plywood	1/2"x4'x8' OSB Sheating	Home Depot	N/A	1	6.67	
P2	Angle Brackets	2" x 4" Steel	Home Depot	N/A	16	3.06	
P3	Caster Wheels	2" Rubber wheel with swivel plate and brakes	Home Depot	N/A	4	3.98	
P4	T Brackets	Steel	Home Depot	N/A	2	0.53	
P5	Woodscrews	#6 1/2" Galvanized woodscrews	Home Depot	N/A	1	6.19	Box of 100
	Heat Exchanger						
P6	Flat Plate Heat Exchanger	Liquid to Liquid, 40 Plates, 4.09" x 5.00" x 12", 0.34 in^2 Surface Area per Plate, 7.06 Hydrolic Diameter	AIC	LB31-40	1	468.00	
	Cold Water Inlet						
P7	90 Degree Elbow	1" FNPT x 1" FNPT, 90 Degree Elbow, White PVC	Stadium Hardware	N/A	1	3.29	
P8	Pressure Gauge	1-100PSI, 2PSI Resolution, 1/4" MNPT	Stadium Hardware	N/A	1	4.99	
P9	Thermistor	RTD, Pt 100 Ohm, Temp Range -40 to 250 F, Wire Length 72 In, Material 304 SS, Probe Length 6 In	Grainger	2HMR1	1	26.55	
P10	1" MNPT to 1" Pipe	White PVC Adapter, 1" MNPT to 1" Pipe	Stadium Hardware		1	0.59	
P11	1" Pipe to 1/2" FNPT	White PVC Bushing, 1" Pipe to 1/2" FNPT	Stadium Hardware	N/A	1	0.79	package of 2
P12	Flow Meter	0.5-50 GPM, Vertical Mount, Injection Molded Acrylic Body, Stainless Steel Float and Internals	Freshwater Systems	PMF-0505	1	50.77	
P13	1/2" FNPT to 3/4" FGHT	Garden Hose-to-Pipe Rigid Connectors 3/4" Female Garden Hose, 1/2" NPT Female Connection	McMaster	73605T82	1	13.28	package of 4
P14	Garden Hose	3/4" MGHT and FGHT, 15' Length	Stadium Hardware	N/A	1	7.49	
	Cold Water Outlet						
P7	90 Degree Elbow	1" FNPT x 1" FNPT, 90 Degree Elbow, White PVC	Stadium Hardware	N/A	1	3.29	
P8	Pressure Gauge	1-100PSI, 2PSI Resolution, 1/4" MNPT	Stadium Hardware	N/A	1	4.99	
P9	Thermistor	RTD, Pt 100 Ohm, Temp Range -40 to 250 F, Wire Length 72 In, Material 304 SS, Probe Length 6 In	Grainger	2HMR1	1	26.55	
P10	1" MNPT to 1" Pipe	White PVC Adapter, 1" MNPT to 1" Pipe	Stadium Hardware		1	0.59	
P11	1" Pipe to 1/2" FNPT	White PVC Bushing, 1" Pipe to 1/2" FNPT	Stadium Hardware	N/A	1	0.79	package of 2
P15	1/2" MNPT to 3/4" FGHT	Garden Hose-to-Pipe Rigid Connectors 3/4" Female Garden Hose, 1/2" NPT Male Connection	McMaster	73605T84	1	10.75	package of 4
P14	Garden Hose	3/4" MGHT and FGHT, 15' Length	Stadium Hardware	N/A	1	7.49	
	Hot Water Inlet						
P7	90 Degree Elbow	1" FNPT x 1" FNPT, 90 Degree Elbow, White PVC	Stadium Hardware	N/A	1	3.29	
P9	Thermistor	RTD, Pt 100 Ohm, Temp Range -40 to 250 F, Wire Length 72 In, Material 304 SS, Probe Length 6 In	Grainger	2HMR1	1	26.55	
P10	1" MNPT to 1" Pipe	White PVC Adapter, 1" MNPT to 1" Pipe	Stadium Hardware		1	0.59	
P16	1" Pipe to 2" Pipe	UV-Resistant Std-Wall Beige PVC Pipe Fitting 2" X 1" Pipe Size, Reducer Bushing Schedule 40	McMaster	4738T56	1	5.76	
P17	2" Pipe to 4" Pipe Adapter	White PVC Reducer, 4" Reduced to 2"	Stadium Hardware	N/A	1	6.29	
P18	4" Pipe	Unthreaded White PVC	Stadium Hardware	N/A	1	3.29	per foot
P19	4" Pipe to 6" Pipe Adapter	Gravity-Flow Flexible Pipe Coupling Reducing, for 6" X 4" Pipe Size, 6" Length	McMaster	4511K86	1	17.92	
P20	6" Pipe	Sewer & Drain Thin-Wall PVC Pipe Non-Perforated, 6" X 4-1/2' L, Light Green	McMaster	2426K27	1	14.64	
P21a	Filter Bag (25)	Grab-on Polypropylene Felt Filter Bag 25 Micron, 4-3/32" Diameter X 8" Length	McMaster	9308T15	1	3.50	2.41 for > 10
P21b	Filter Bag (200)	Grab-on Filter Bag Polyester Felt, 200 Micron, 4-3/32" Diameter X 8" H	McMaster	98295K9	1	2.85	2.08 for > 10
P21c	Filter Bag (600)	Grab-on Filter Bag Nylon Mesh, 1000 Micron, 4-3/32" Dia X 8" Height	McMaster	98295K49	1	3.31	2.42 for > 10
P22	Filter Bag Adapter	Polypro Adapter Head for 4-3/32" Dia, 3/4" NPT	McMaster	98295K11	1	15.21	
P23	3/4" Threaded Pipe	Thk-Wall (Sch 80) Dark Gray PVC Threaded Pipe 3/4" Pipe X 24" Length, Threaded Ends	McMaster	4687T14	1	5.62	
P24	3/4" Straight Coupler	Std-Wall (Schedule 40) White PVC Pipe Fitting 3/4" Pipe Size, Coupling, 1-11/16" Length	McMaster	4880K72	1	0.29	
P25	3/4" Clear PVC Pipe	Std-Wall (Schedule 40) Clear PVC Unthrd Pipe 3/4" Pipe Size X 4' Length	McMaster	49035K24	1	10.40	
P26	3/4" Pipe to 1/2" FNPT Bushing	Std-Wall (Schedule 40) White PVC Pipe Fitting 3/4" Pipe End Male X 1/2" NPT Female, Hex Bushing	McMaster	4880K201	1	0.54	
P15	1/2" MNPT to 3/4" FGHT	Garden Hose-to-Pipe Rigid Connectors 3/4" Female Garden Hose, 1/2" NPT Male Connection	McMaster	73605T84	1	10.75	package of 4
P14	Garden Hose	3/4" MGHT and FGHT, 15' Length	Stadium Hardware	N/A	1	7.49	
	Hot Water Outlet						
P7	90 Degree Elbow	1" FNPT x 1" FNPT, 90 Degree Elbow, White PVC	Stadium Hardware	N/A	1	3.29	
P9	Thermistor	RTD, Pt 100 Ohm, Temp Range -40 to 250 F, Wire Length 72 In, Material 304 SS, Probe Length 6 In	Grainger	2HMR1	1	26.55	
P10	1" MNPT to 1" Pipe	White PVC Adapter, 1" MNPT to 1" Pipe	Stadium Hardware		1	0.59	
P11	1" Pipe to 1/2" FNPT	White PVC Bushing, 1" Pipe to 1/2" FNPT	Stadium Hardware	N/A	1	0.79	package of 2
P12	Flow Meter	0.5-50 GPM, Vertical Mount, Injection Molded Acrylic Body, Stainless Steel Float and Internals	Freshwater Systems	PMF-0505	1	50.77	
P13	1/2" FNPT to 3/4" FGHT	Garden Hose-to-Pipe Rigid Connectors 3/4" Female Garden Hose, 1/2" NPT Female Connection	McMaster	73605T82	1	13.28	package of 4
P14	Garden Hose	3/4" MGHT and FGHT, 15' Length	Stadium Hardware	N/A	1	7.49	
	DAQ system						
P27	DAQ Unit	USB 4 Channel Data Acquistion Unit, Provided by the University (Tom Bress)	N/A	N/A	1	N/A	
P28	Computer w/ labview	Labview Software, Provided by the University (Tom Bress)	N/A	N/A	1	N/A	
P29	Voltage dividers	Contructed from 1000 Ohm Resistors, Provided by Team 23	N/A	N/A	4	N/A	
P30	Power supply	5V Power Supply, Provided by Team 23			1	N/A	

APPENDIX K: MATLAB CODE FOR CALCUATIONS

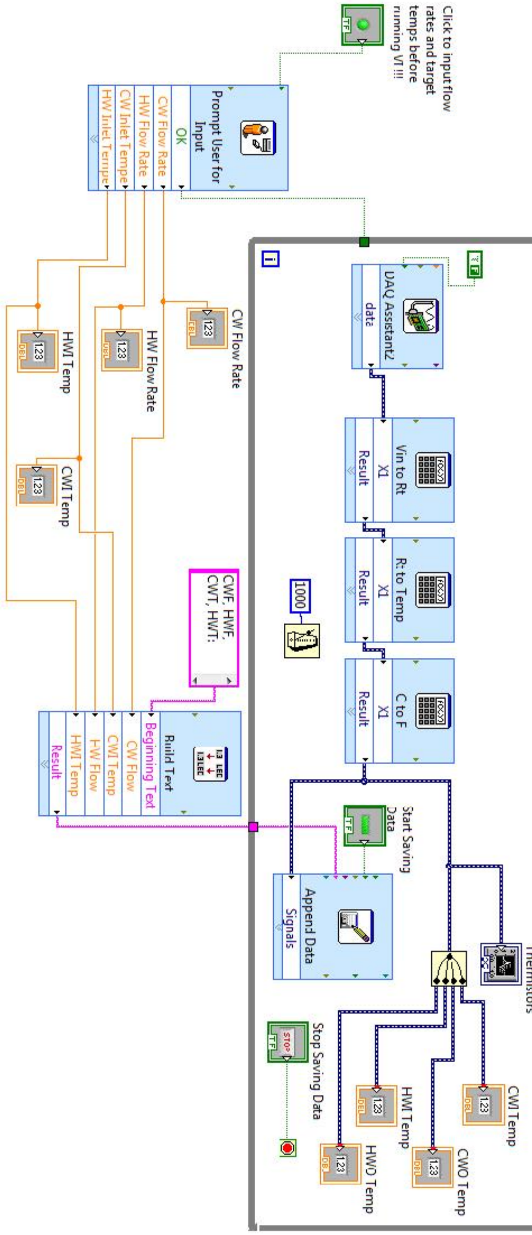
```
% Author Scott Bartkowiak
% ME 450 Final Data Analysis
% Main file

load tests4 %loads parsed data saved in *.mat file
[m n] = size(tests)
% Initialized storage matrcies
NTU_store = [];
eff_store = [];
Cr_store = [];
trial_store = [];

for ii = 1:m % Loops thru all data in tests4 and calcuates Cr, NTU and
effectiveness
    [Cr, NTU, eff] = ntu(tests(ii,5), tests(ii,6), tests(ii,2), tests(ii,3),
tests(ii,4), tests(ii,1));
    NTU_store(end+1) = NTU;
    eff_store(end+1) = eff;
    Cr_store(end+1) = Cr;
    trial_store(end+1) = ii;
end

% Writes calcuated values to excel file
B = [trial_store' Cr_store' NTU_store' eff_store'];
xlswrite('NTU1.xls',B)
%====================================================================
function [Cr, NTU, eff] = ntu(Tci, Tco, Thi, Tho, Vc, Vh)
% Author Scott Bartkowiak
% Calculates Cr, NTU and effectiveness given temperatures in F and flow
% rates in gpm

    hot_flow = Vh*3.78/(60*1000); % convert gpm to m3/s
    cold_flow = Vc*3.78/(60*1000);

   % read reference data from Incorpera for interpolation
    ref = xlsread('PHE_data.xls','Sheet4');
    temp_ref = ref(:,1)';
    density_ref = ref(:,2)';
    cp_ref = ref(:,3)';
    mu_ref = ref(:,4)';
    k_ref = ref(:,5)';
    pr_ref = ref(:,6)';

    % AIC LB31-40 PHE Specs
    N_plates = 40; % Number of plates
    p_spacing = 0.002; % Plate spacing (m)
    p_height = 0.2788; % Plate height (m)
    p_width = 0.1148; % plate width (m)
    p_area = 0.032; % total plate area (m2)
    p_corr = pi()*(30)/180; % plate corrugation angle
    p_enlar = 1; % plate enlargement factor
    Dh = 2*p_spacing/p_enlar; % calcuation of hydarulic diameter
```

```
    cold_tm = (f2k(Tci)+f2k(Tco))/2; % average cold temperature

    for ii = 1:length(temp_ref) % Interpolate values for cold side
        if temp_ref(ii) <= cold_tm && temp_ref(ii+1) >= cold_tm
            density = interpolate(cold_tm,temp_ref(ii), temp_ref(ii+1),…
            density_ref(ii), density_ref(ii+1));
            cp = interpolate(cold_tm,temp_ref(ii), temp_ref(ii+1),…
            cp_ref(ii), cp_ref(ii+1));
            mu = interpolate(cold_tm,temp_ref(ii), temp_ref(ii+1),…
            mu_ref(ii), mu_ref(ii+1));
            k = interpolate(cold_tm,temp_ref(ii), temp_ref(ii+1), k_ref(ii),…
            k_ref(ii+1));
            pr = interpolate(cold_tm,temp_ref(ii), temp_ref(ii+1),…
            pr_ref(ii), pr_ref(ii+1));
            break % break once values are found
        end
    end

    hot_tm = (f2k(Thi)+f2k(Tho))/2; % average hot temperature

    for ii = 1:length(temp_ref) % interpolate properties for hot stide
        if temp_ref(ii) <= hot_tm && temp_ref(ii+1) >= hot_tm
            density_h = interpolate(hot_tm,temp_ref(ii), temp_ref(ii+1),…
            density_ref(ii), density_ref(ii+1));
            cp_h = interpolate(hot_tm,temp_ref(ii), temp_ref(ii+1),…
            cp_ref(ii), cp_ref(ii+1));
            mu_h = interpolate(hot_tm,temp_ref(ii), temp_ref(ii+1),…
            mu_ref(ii), mu_ref(ii+1));
            k_h = interpolate(hot_tm,temp_ref(ii), temp_ref(ii+1),k_ref(ii),…
            k_ref(ii+1));
            pr_h = interpolate(hot_tm,temp_ref(ii), temp_ref(ii+1),…
            pr_ref(ii), pr_ref(ii+1));
            break
        end
    end

    %log mean temperature difference
    LMTD = ((Thi - Tco)-(Tho - Tci))/log((Thi - Tco)/(Tho - Tci));
    % overall convective coefficient
    UA = density*cold_flow*cp*(Tco-Tci)/LMTD;
    Cc = density*cold_flow*cp; % Cold heat capacity rate
    Ch = density_h*hot_flow*cp_h; % hot heat capacity rate
    Cr = Cc/Ch; % heat capacity gain ratio

    % Calculate NTU
    NTU = UA/(min(Cc,Ch));

    % Cacluate effectiveness
    if Cc <= Ch
        eff = (Tco - Tci)/(Thi - Tci);
    else
        eff = (Cc*(Tco - Tci))/(Ch*(Thi - Tci));
    end
end
```

APPENDIX L: PHE PERFORMANCE TEST DATA

NTU	ε	Cr	Hot Flow (gpm)	Thi (°F)	Tho (°F)	Cold Flow (gpm)	Tci (°F)	Tco (°F)
0.14	0.10	0.75	2.00	84.43	76.17	1.50	64.23	66.33
0.16	0.12	0.99	2.00	102.82	87.07	2.00	63.27	67.88
0.15	0.12	0.76	2.00	106.43	89.24	1.50	52.25	58.72
0.19	0.15	0.76	2.00	110.17	94.61	1.50	62.22	69.18
0.18	0.15	0.50	2.00	104.07	94.55	1.00	55.17	62.30
0.24	0.19	0.76	2.00	101.90	87.18	1.50	45.31	55.78
0.26	0.20	0.50	2.00	104.15	95.63	1.00	62.11	70.72
0.35	0.26	0.40	2.50	104.08	94.41	1.00	67.15	76.62
0.39	0.28	0.60	2.50	99.39	83.98	1.50	48.66	62.69
0.41	0.28	0.60	2.50	90.10	80.87	1.50	64.09	71.29
0.42	0.30	0.61	2.50	123.58	105.33	1.50	64.58	82.05
0.46	0.30	0.80	2.50	91.89	76.29	2.00	52.40	64.14
0.48	0.33	0.80	2.50	84.72	73.39	2.00	47.00	59.39
0.46	0.33	0.50	2.00	106.37	93.03	1.00	46.58	66.36
0.47	0.33	0.50	2.00	102.48	91.52	1.00	56.89	72.06
0.56	0.38	0.40	2.50	105.10	90.20	1.00	46.17	68.57
0.55	0.38	0.40	2.50	109.33	95.04	1.00	45.79	70.19
0.74	0.49	0.20	2.50	103.79	97.67	0.50	70.59	86.70
0.90	0.51	0.60	2.50	97.71	80.22	1.50	46.04	72.62
1.00	0.53	0.80	2.50	99.10	77.78	2.00	46.07	74.21
1.21	0.67	0.20	2.50	96.09	88.89	0.50	47.08	79.82
1.34	0.68	0.40	2.50	126.49	105.23	1.00	45.05	100.11
1.70	0.68	0.92	3.00	88.03	74.04	2.75	60.83	79.27
1.79	0.72	0.99	3.00	114.48	82.22	3.00	44.78	94.39
1.50	0.73	0.20	2.50	84.98	77.30	0.50	47.04	74.71
1.44	0.73	0.20	2.50	104.11	96.26	0.50	49.36	89.31
1.55	0.73	0.34	3.00	112.91	97.02	1.00	45.48	94.89
1.57	0.73	0.40	2.50	102.04	87.83	1.00	46.20	87.14
1.83	0.77	0.50	3.00	114.47	93.94	1.50	45.75	98.78
1.98	0.78	0.43	3.50	88.53	74.27	1.50	49.44	79.85
1.88	0.82	0.17	3.00	111.17	100.98	0.50	45.84	99.09

APPENDIX M: LABVIEW CODE



APPENDIX N: DESIGN ANALYSIS ASSIGNMENT

There are two major components of the Hotshot; the flat plate heat exchanger and the drain water filter. The material choice for both of these components has a direct bearing on the performance and longevity of the Hotshot. Throughout the selection process considerations must be made for cost, durability, parts availability, thermal conductivity, and strength. Our sponsor, Jack Griffith, plans to build the Hotshot from off the shelf parts. As such, we are ultimately limited to materials chosen by the respective manufacturers of each component.

Functional Performance – Heat Exchanger

Material Index $M = \frac{k}{C}$, where *k* is thermal conductivity and *C* is cost per kilogram

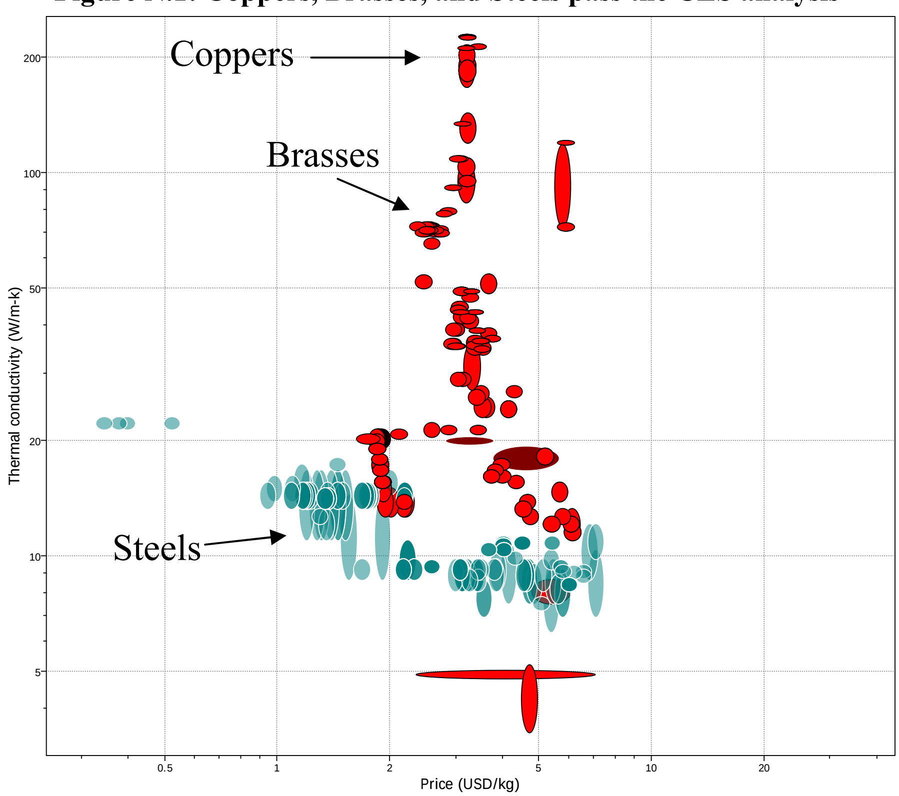
Design requirements for the heat exchanger:

Function: Heat exchanger, must transfer heat at a given rate
Objective: Maximize thermal conductivity while minimizing cost
Constraints: (a) Mass *m* specified
(b) Cost C < \$25 / kg
(c) Corrosion resistance *R* high

CES Analysis:

CES was used to try and narrow acceptable heat exchanger materials. Limits were set for cost (C < \$25 / kg), corrosion resistance, and thermal conductivity (k > 5 W/m-k). CES plotted price versus thermal conductivity for all passing materials. The best materials will have low price at high thermal conductivities.

Figure N.1: Coppers, Brasses, and Steels pass the CES analysis



As expected, typical heat exchanger materials such as stainless steels, brasses, and copper passed the constraints. These materials, along with nickel, represent the selection of flat plate heat exchangers offered by AIC, Grainger, and McMaster Carr. A comparison of each can be found below:

Table N.1: Stainless steel is the best compromise of price, corrosion resistance, and conductivity

Material	Thermal conductivity, k, (W/m-k)	Price ($/kg)	M=k/c	Total cost @ 9kg ($)	Comment
Copper-cadmium	351.19	7.48	46.8	67.4	Poor corrosion resistance
Brasses	128.02	5.51	23.22	49.6	Poor corrosion resistance
316 stainless steel	16.98	9.97	1.70	89.8	
201 nickel	89.96	42.66	2.10	384	Very expensive

While stainless steel has the worst conductivity to price ratio, it is the best overall compromise. Copper and brass both have exceptional conductivities but suffer from corrosion. As a result, there are few copper and brass heat exchangers on the market. Nickel may be the best choice if cost is of no concern, however, it would cost nearly $400 in material alone to build the Hotshot's heat exchanger out of nickel. By no coincidence the majority of flat plate heat exchangers available are made from stainless steel. We choose a heat exchanger from AIC that was made from 316 stainless steel.

Functional Performance – Filter

Material index $M = \frac{\sigma}{C}$ where σ is ultimate strength and *C* is cost.

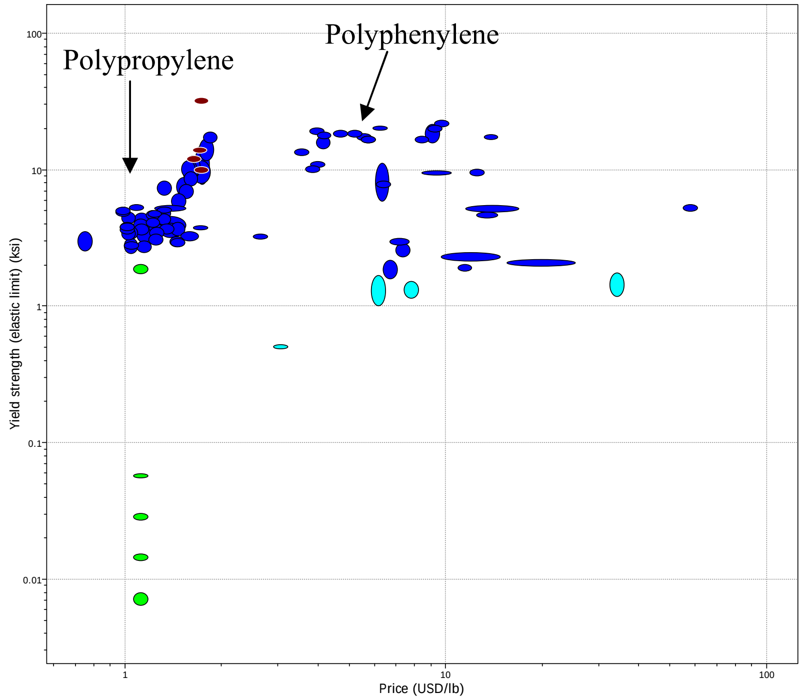
Design requirements for the filter:

Function: Filter, must stand up to chemical abuse and be strong enough to trap debris
Objective: Maximize chemical resistance of polymer filter while minimizing cost
Constraints: (a) Cost $C <$ \$25 / kg
(b) Chemical resistance *R* high

CES analysis:

As with the heat exchanger, CES was used to determine the best material choices for the bag filter. Results were limited to polymers that had high resistance to acids, alkalis, and solvents. The passing materials were plotted with cost versus ultimate strength.

Figure N.2: Polypropylene is the best choice for filters



There are three different materials of bag filter commonly offered; nylon, polypropylene, and polyphenylene. According to CES, nylon does not stand up well to acids and did not pass the constraints. Both polypropylene and polyphenylene pass the durability constraints. Of the two, polypropylene is less expensive and no less strong; it is thus our choice of bag filter.

Environmental Performance – Heat Exchanger

The two heat exchanger materials that will be compared for their environmental impacts are nickel 201 and stainless steel 316. Due to cost, we determined earlier that we had to choose stainless steel for our project, but that does not mean it is necessarily more environmentally friendly. The mass of the heat exchanger, regardless of material, is approximately 9 kg. The results of a SimaPro comparison can be found the figures below:

Figure N.3: Emmisions Nickel Vs. Stainless Steel

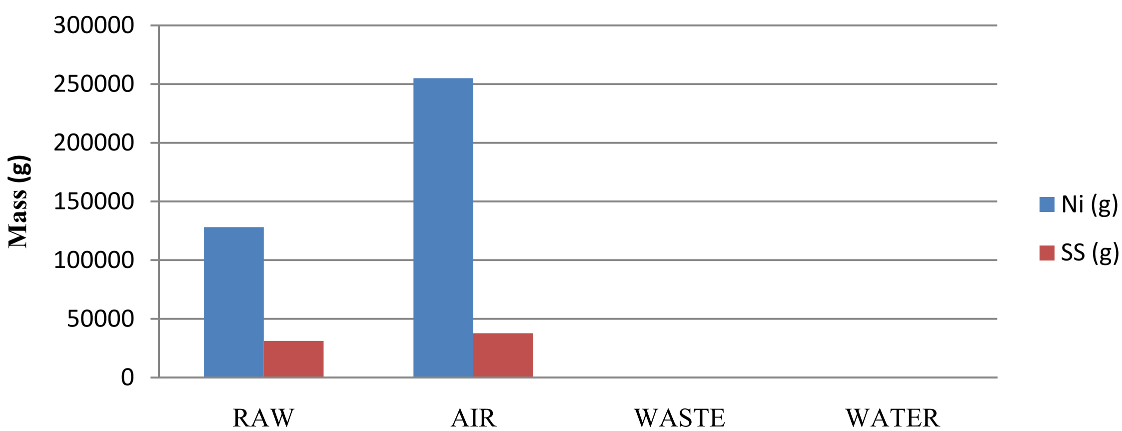


Figure N.4: Characterization

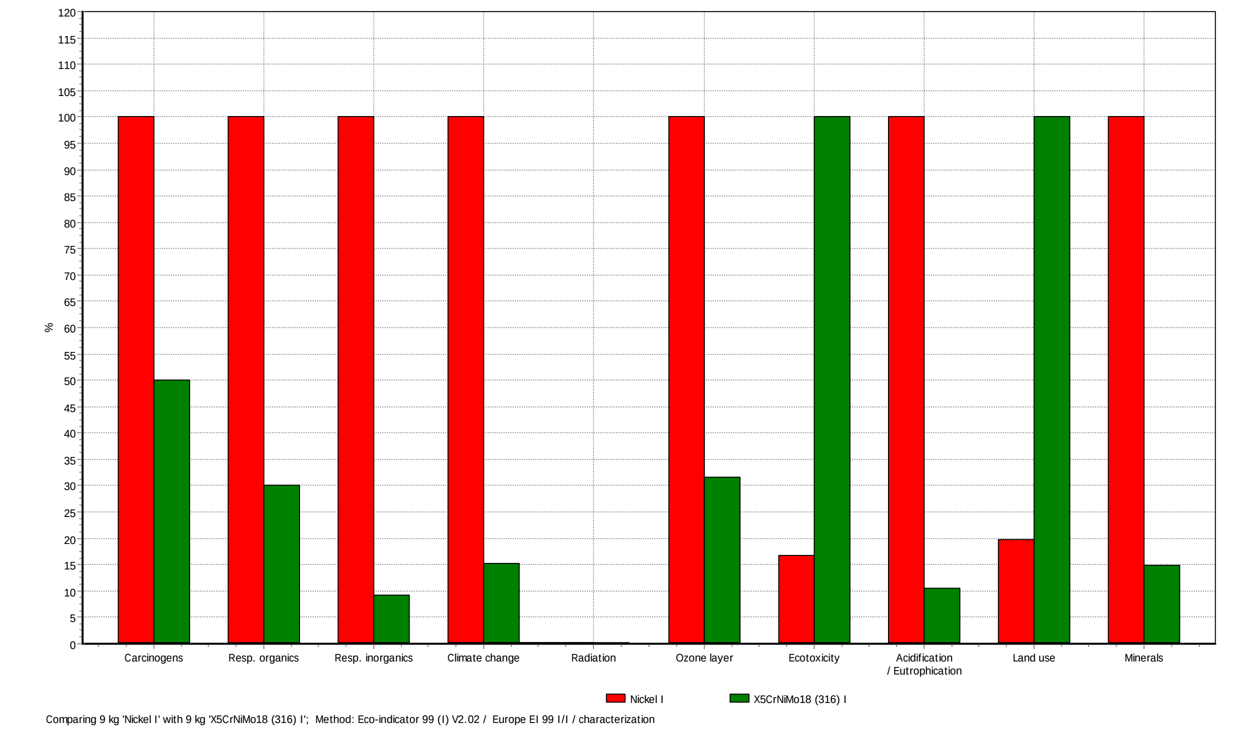


Figure N.5: Normalized Score

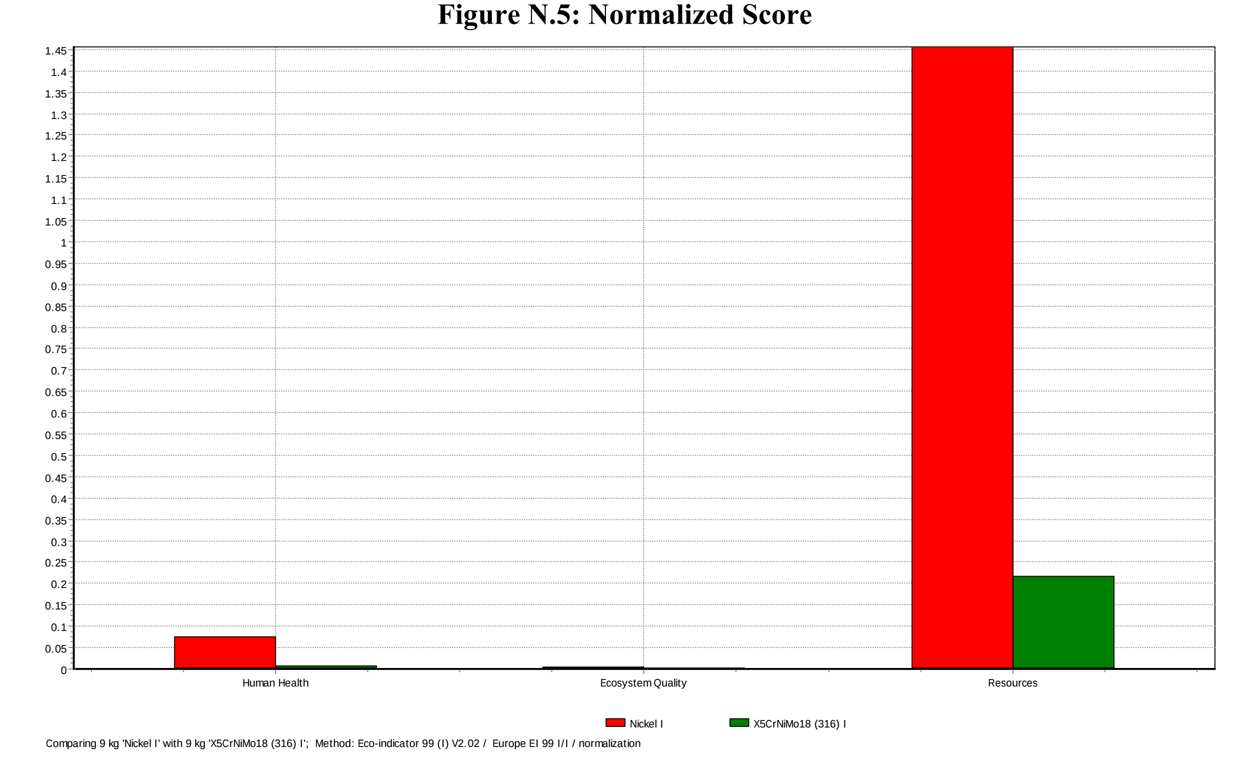
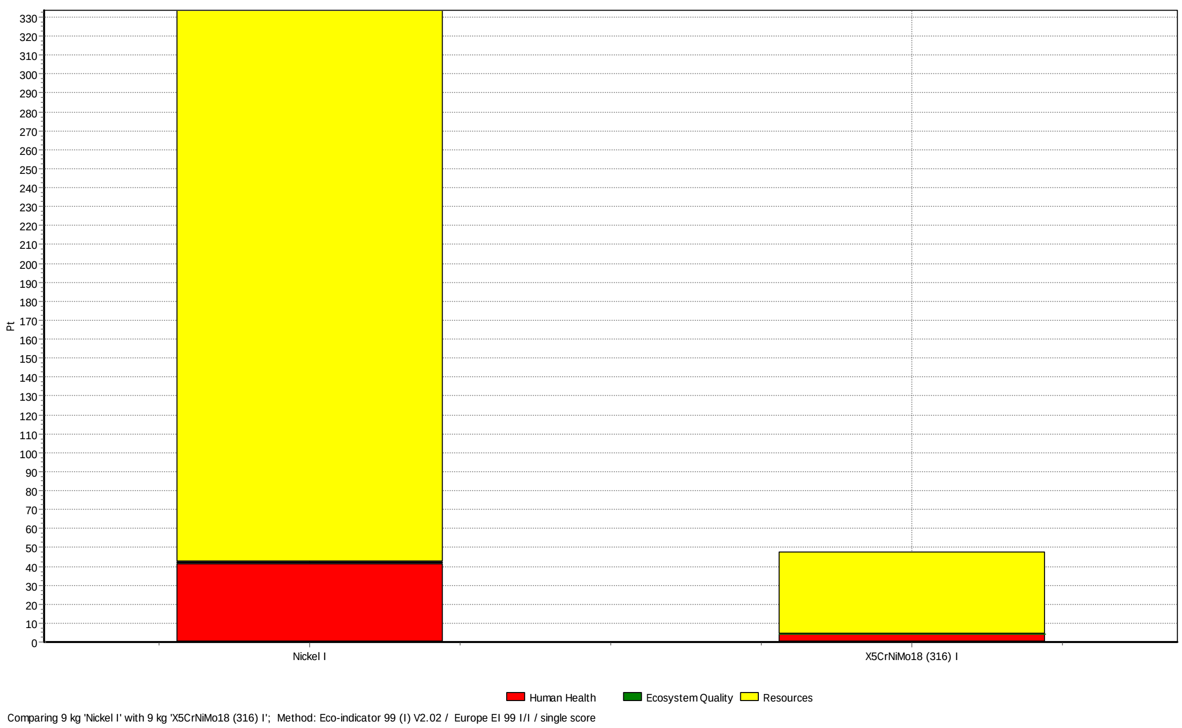


Figure N.6: Overall Relative Comparison



Of the two possible heat exchanger materials available, nickel 201, and stainless steel 316, it is clear that the stainless steel has far less environmental impact. In every comparison done on SimaPro, except for 'Land use' and 'Ecotoxicity', the stainless steel comes out favorably. While neither material is particularly friendly to the environment, the nickel produces drastically more emissions and has a far greater impact on resources. Stainless steel trumps nickel in all three of the major meta-categories ('human health', 'ecosystem quality', and 'resources'). Since we are limited to the materials offered by heat exchanger manufacturers we must choose between the lesser of the two evils; stainless steel.

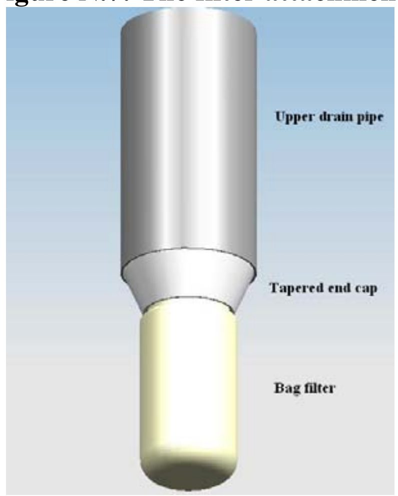
Manufacturing Process Selector

The Hotshot is a fairly simple device. It is made up of two sub systems; the stainless steel flat plate heat exchanger, and the filter assembly. Both subsystems, up until this point, have been made from off the shelf parts exclusively. Initially, should the Hotshot make it to market, production volumes will be small (in the order of 1000's) until it proves to be a viable product. Ultimately, however, we can envision drain water heat recovery systems like the Hotshot installed in millions of households across the country. Of the two subsystems, only the filter assembly was designed from the ground up and is thus the only part that we would consider manufacturing ourselves. Regardless of volume, the heat exchanger should be purchased from an off the shelf supplier.

Based on our Monte Carlo analysis (pg. 11) of Hotshot consumers we determined that roughly 10% of households with natural gas water heaters and up to 50% of consumers with electric water heaters could benefit from buying a Hotshot. Assuming that every person benefiting from the Hotshot buys one, and considering the over 100 million households in the US, this equates to approximately 23 million Hotshots sold. This represents a best case scenario, but for the sake of advancement we will base our production numbers on it.

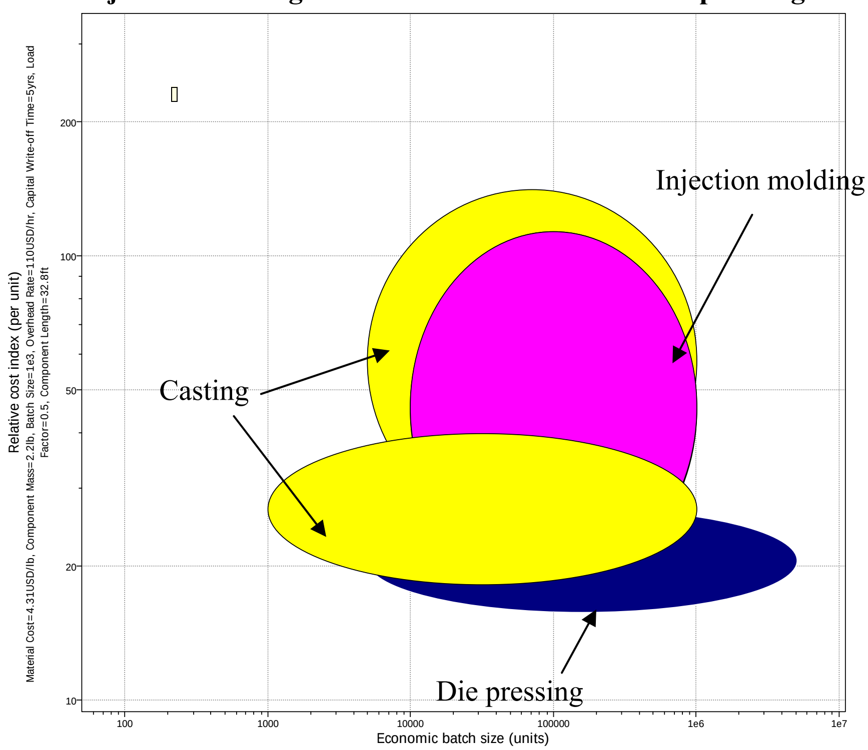
The prototype filter attachment was purchased from McMaster-Carr for $12. With production numbers in the millions it would be more advantageous to have this part manufactured custom. Our proposed design can be seen in Figure M.7 as the 'tapered and threaded end cap':

Figure N.7: The filter attachment



Using CES we inputting constraints based on size, mass, basic geometry, tolerance, and production volumes. CES narrowed down the possible processes to three: Injection molding, casting, and die pressing. These were plotted with production volumes versus relative per unit cost:

Figure N.8: Injection molding is the best choice for the end cap at large volume



Of these processes, injection molding is the likely choice. Any mold has high tooling costs, in the tens of thousands of dollars, however at high volumes, such as these, this becomes negligible. The end cap could be made from either thermoplastic or thermoset. Since thermoplastics can be recycled we would likely chose it in production.

APPENDIX O: CHANGES SINCE DR3

The nature of our project allowed us to create a sound design early in the semester. The only two aspects of our final design that have changed since our alpha design are the filter size and type as well as the bypass location. The final design these parts were dependant on the results of our testing which had not been completed previously. We have selected the 25 micron polypropylene filter to be used. The 25 micron filtration size was the finest of the three filters tested and met the requirements of the Hotshot in terms of flow rate and static water column pressure needed to function properly. With all other areas being equal the ability to capture the smallest debris ensures the best performance of the PHE. We have also determined that the bypass can be placed at any point above the filter, and we have selected to place the upper connection 1 inch above the filter for a more compact design. The position of the lower connection is also only dependant on the packaging dimensions and should be connected 1” from the heat exchanger outlet.