Water Conservation Device

Sponsor:

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SI base unit

Base quantity	**Name**	**Symbol**
length	meter	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	Kelvin t/°C = T/K - 273.15.)	K
amount of substance	mole	mol
luminous intensity	candela	cd

SI derived units

Derived quantity	**Name**	**Symbol**
area	square meter	m^2
volume	cubic meter	m^3
speed, velocity	meter per second	m/s
acceleration	meter per second squared	m/s^2

Derived quantity	**Name**	**Symbol**	**Expression in terms of other SI units**	**Expression in terms of SI base units**
force	newton	N	-	$m \cdot kg \cdot s^{-2}$
pressure, stress	pascal	Pa	N/m^2	$m^{-1} \cdot kg \cdot s^{-2}$
energy, work, quantity of heat	joule	J	N·m	$m^2 \cdot kg \cdot s^{-2}$
power, radiant flux	watt	W	J/s	$m^2 \cdot kg \cdot s^{-3}$
electric potential difference, electromotive force	volt	V	W/A	$m^2 \cdot kg \cdot s^{-3} \cdot A^{-1}$

iv. Conversion of units

1 lb	=	0.453 kg
1 gal (US)	=	3.785 liter (l)
1 $ (USD)	=	0.67259 EUR (Nov 2009)

v. List of abbreviations

GPM	Gallon (US) Per Minutes
MUC	Munich (MUC Team)
PUH	Point of Use Heaters
QFD	Quality Function Deployment
SLO	San Luis Obispo (SLO Team)
WCP	Water Conservation Project

vi. Executive Summary

The ultimate goal of this project was to conserve water that is wasted while showering. Every time a shower is started with a conventional tank water heater, approximately 2 gallons of cold water is wasted down the drain until the shower reaches the user desired temperature. The solution to conserving this water is to eliminate the waste of the cold water stored in the hot water line before shower use.

Our design for this system is split into 2 separate parts:

Switching System

A manual button activates a valve block which then allows the cold water in the hot water line to drain into a reservoir. Once the water is heated to the required temperature the valve shuts down this flow and resets the valve allowing hot water to flow to the shower head.

Storage System:

A secondary reservoir installed in the toilet, to procure the cold water from the shower. This water can then be flushed, acting as the working water in the toilet operation, in addition to the normal water tank.

We initially proposed the manual hydraulic design mainly for its user integration and functionality. This system is simple to construct and this results in a very low risk factor. In addition, we felt that the user integration was a desired element in the system. With an automated system the consumer would be required to wait until the system had time to process the cold water. This wait time may be inconvenient to the consumer especially if they are waiting in the shower. Adding a manual aspect to our design allows the user to have a limited control over the system. With our design the user would know when hot water is ready for the shower. There would still be a waiting period as the cold water is flushed from the system, however when the hot water is ready the flow would not immediately start, it allows for the user to prompt the flow. This gives the consumer flexibility and prevents them from needing to adapt their personal routine to meet that of the system. Moreover, this system allows for the user to take a cold shower without disrupting the normal operation of the shower.

After further review on our manual hydraulic design we determined that this design is not feasible for production. The biggest deterrent for this design was the complex level of installation required. This design requires an additional waterline to connect the toilet reservoir with the hot waterline entering the shower. Installing this line would require demolition of bathroom walls in any existing house. The cost and inconvenience of this installation outweigh the benefit most consumers would gain from saving water. The other major obstacle that the hydraulic system faced was the need for a custom toilet reservoir. During our research on toilet reservoirs we found hundreds of different designs each with a unique shape and dimensions. Manufacturing these custom tanks is not feasible because there are too many styles on the market. It would require a large amount of capital to begin manufacturing our custom reservoir in multiple styles.

Therefore we designed a less expensive device that requires less time and effort to install. This device consists solely of a valve assembly spliced in-line with the hot and cold waterlines. This valve automatically drains water into the toilet reservoir after each flush. The water is normally drained from the hot water line, unless the water in the line is above a certain temperature. In that case the valve would force the water to be pulled from the cold waterline. This design focuses mainly on ease of installation, inexpensive production costs, and full automation. These principles make our device easier to produce as well as easier to market.

Manufacturing of the device was split into two sections. The MUC students made two thermostat prototypes and the Cal Poly students made two valve prototypes and then the parts were exchanged for testing. Each group of team members created a testing rig so that more data could be collected and shared.

The MUC students focused on analyzing different hot water temperatures and maintained lower flow rates. The Cal Poly students tested both high and low flow rates at a constant hot water temperature. The results demonstrate that the amount of hot water dissipated is correlated with the flow rate. Therefore, it was determined that the primary factor in the efficiency of the device was the speed at which the thermostat responds. To begin this optimization a Fluent model of the thermostat was created to simulate the fluid flow characteristics. This will be valuable to future iterations as it shows regions of stagnant flow. In addition the spring and wax elements need to be optimized for the new flow to provide a quick reaction without inducing water hammer.

Testing of the valve showed that the flap was not closing off the flow of water from the cold water line. The final output actually showed approximately 60% of the output was from the hot water line and 40% was from the cold water line. Further analysis was done in order to determine whether or not a functioning flap increased the effectiveness of the system. In most situations it was found that a valve without the flap would be more cost effective, however this is also dependent on the amount of piping between the water heater and the valve.

Ultimately, the project demonstrated that the prototype functions. However, the device needs to be optimized in order to increase its effectiveness before it can become a consumer product.

1. Introduction

The Water Conservation Project (WCP) is a design concept to reduce the water consumption on startup of a shower. Every time a shower is started with a conventional tank water heater, approximately 7.5 liters of cold water is flushed down the drain without being used before the hot water reaches the faucet. For a city the size of San Luis Obispo, this amounts to approximately 121 million liter of water per year[1]. The main goal of this project was to devise a way to conserve the cold water that is contained in the hot water pipes before every shower. Ultimately, we searched to create a system that minimizes the amount of work required by the consumer, yet still allowed them the ability to shower conveniently. Wolfgang Kaml is the sponsor of WCP and the project was carried out by two collaborating teams at California Polytechnic State University San Luis Obispo and Munich University of Applied Sciences.

[1] From "Water Conservation Device" presentation by Wolfgang Kaml. Sept 24, 2009

2. Background

2.1. Market Analysis

Currently, the market provides several solutions to the problem such as Point of Use Heaters, tank-less water heaters, reverse-flow pumps, and hot water recirculation. Each solution has drawbacks that we will address in the following paragraphs for better clarification of our goals.

The first solution would be Point of Use Heaters (PUH) that heat water right behind the faucet to provide almost an instant amount of hot water right at the startup. The analyzed system (Powerstar AE 12) costs about $ 200 per unit and requires the installation to be done by a professional electrician. The PUH operates at 240 V and draws 50 A of current which often requires new wiring to be installed, adding to the cost. The capacity of the device is one gallon per minute (1 GPM = 3.785 liter per minute [l/min]) with a constant temperature rise of 22° C, the equivalent flow of a sink faucet. Thereafter, it's heating capacity decreases to 5.5° C at the maximum flow of about 9.5 l/min the necessary flow rate for a shower. Due to the low heating capacity, multiple units would need to be installed in a house, about one unit per fixture, and a higher capacity device would be needed for a shower. The dimensions are small enough to fit within a wall and it weighs 2.72 kg, making it space efficient[2]. Overall, using a PUH in a house with two sinks and a shower would require over $ 600 for the heating units labor from an electrician.

The tank-less water system is similar to the PUH in that it heats water on demand and acts as a replacement for the common tank water heaters. While PUH heats individual sinks and showers, the tank-less water system is located centrally and heats water for the entire house. Due to its location it also suffers the same pitfall as the tank water system; the cold water in the hot water line is wasted upon start up. The Rheem EcoSense On Demand 7.4 system costs about $ 1,200 per unit and requires a professional plumber for installation. It has a flow rate of 7.4 gallons (= about 28 l) and a heating capacity of 60° C. The unit's dimensions are larger than the PUH and do not fit within a wall, and it weighs approximately 20 kg.[3] Aside from these disadvantages, the tank-less water system provides an endless supply of hot water and is more efficient than a regular tank water heater.

Reverse flow pumps like the Chili Pepper are another solution. This device links the cold and hot waterlines together with an electric pump. It requires the user to push a button to activate the pump, which then pumps the cold water from the hot waterline into the cold waterline until the desired temperature is achieved in the hot waterline. It pumps at a rate of 5.7 l/min, which would take 1 min and 20 sec for the average faucet to receive hot water. The cost of this system is $ 180 and requires about 285 W to run. International Association of Plumbing and Mechanical Officials (IAPMO) regulations no longer allow residences to flow water backwards in order to protect the public water supply. Newer houses come with flow arrestors to prevent reverse flow from occurring. The disadvantages with this system are obvious in that they require user intervention, cannot be used with newer houses, and have a long wait time for hot water[4].

Hot water recirculation systems, a fourth option, continuously pump water in a loop with the water heater in order to maintain hot temperatures in the hot water line. These systems are cumbersome because they require piping to go from the water heater to the faucet and back to the heater. The cost of this system comes mainly from the extra piping that is necessary and must be laid by a professional plumber. This being a permanent system, in a retrofit situation, the

[2] Information taken from www.Boschhotwater.com
[3] Information taken from www.rheem.com
[4] Information taken from www.chilipepperapp.com

additional cost varies according to the amount of structural changes necessary to add the piping. Additional costs include the pump that is required to move the water and the electricity costs to run the system. From personal experience, the running of the pump also creates noise that can be heard unless the pump is placed far enough away from the living spaces[5].

2.2. Patent Research

We have also conducted research on current patents that affected our decision process for the design and found many solutions. For example, US Patent 7073528 uses a thermostatic valve and pump to deliver the cold water to household appliances such as washing machines and dishwashers. US Patent 6581218 has the consumer direct the shower head towards a bucket to collect the water for later use. One of the more interesting patents, US Patent 6260273 and 6182703, use a Venturi based vacuum to draw the cold water out of the hot water line. German Patent DE000019910096C1 has a storage tank that collects the cold water from the hot water line as it comes to temperature, and once the correct temperature is achieved, the stored water is mixed into the cold water line during use. Finally the Patent DE4406150A1 functions by draining the hot waterline after use with the result of not having to drain any cold water from the line at the start of the next use. Through the patent research that we conducted, we narrowed down our solutions, avoiding those that are already in existence, which eft us with only a few unique solutions.

All the solutions presented above were considered when designing our unique system. Unlike some of the mentioned solutions, our goal was to use minimal or no electricity in order to maximize the savings for the end consumer and help the environment. We aimed to market to both older and newer houses thus creating a backflow based system was not an option due to regulations.

2.3. Objectives

The goal of this project was basic in nature. When people turn on the shower in the morning there is a delay between the moment the water starts flowing and when hot water actually comes out the faucet. This waste has a detrimental effect on society; however it is a problem that has potential solutions. Ultimately, we developed a system to conserve the cold water wasted as hot water is pumped through the pipes.

Consequently, we did not want to develop a system that accomplishes this goal while simultaneous wasting another resource. In order to determine how we would achieve this goal we have developed a set of requirements that our system must adhere to. These specifications are summarized in Figure 1 shown below. We developed these specifications into a detailed requirement list presented in Appendix A.

The customer requirements are a summary of what conditions are required for the project. We then translated these requirements into a set of engineering specifications through use of the QFD method. These are values that we can measure, test, and observe which helped us quantitatively determine the effectiveness of our solution. We felt that the device needed to have certain qualities in order to be a feasible option. The device needed to work early in the morning therefore the device should work automatically in order to provide convenience for the customer. Ease of use would help entice people to use our product. Moreover, we needed the system to be feasible to install both in existing houses and ones being built. The customer requirements and engineering requirements and their relations in full are shown in Appendix C.

Within our list of engineering requirements we have also associated a degree of risk with each specification. This helps differentiate which objects will be easy to control against requirements that will prove to be difficult. We associated high

[5] Information taken from www.askthebuilder.com

risk to three specifications; cost, energy input, and time for system to run. As we stated in the **Background** section there are already various systems that attempt to solve this problem. However, in each one there is always a tradeoff between these three core values. Some machines are very expensive, but work quickly and require lots of energy. Other systems do not require energy; however they take a long time to run. Our goal was to devise a way to solve the ultimate problem without sacrificing any of these core values. We wanted to develop a machine that is cost effective, meaning both reasonable production cost in addition to no energy required to run. The idea of this project was not to trade water conservation for a wasting of energy, which is another important factor.

Table 1 shows the engineering specifications defined with values, risk factors, and methods of testing. Appendix B provides a description of Compliance abbreviations.

Specifications					
Spec #	Parameter Description	Requirement or Target (Units)	Value	Risk	Compliance
1	Hot Water Line Temperature	°C	40.55 < x < 48.89	L	A, T
2	Size	Must fit within wall space (m^3)		M	A, I
3	Weight	kg		L	A, I, S
4	Cost	$	200 - 400 *	H	A, S
5	Flow Rate	kPa	344.74 < x < 689.48	M	A
6	Energy	none		H	I
7	Time for System to Work	sec	1 minute (max)	H	A, S, T
8	Backflow	none		L	A, I
9	Steps to Install	hour	1	M	A, S
10	Steps to Replace	hour	5	L	A, S
11	Corrosion	None		L	I

3. Design Development – Process of Finding Concepts

The first goal for the team was to understand the current plumbing system of an average house or apartment. The initial three weeks were spent looking to find the specifications for the average pipe size, line pressure, faucet and shower design, and analysis of the fluid dynamics that occur within the piping. This allowed us to better create solutions that require no electricity and exploit the mechanical properties already present in the system, unlike the current designs. To better understand the fluid dynamics that drive the system, we needed to build a mock up of shower piping to take measurements and form key concepts. Once we had the data that we needed, we formulated a design for a prototype that we built. This allowed us to perform iterations that perfect the design to deliver a fully functioning model.

3.1. Brainstorming

For our initial brainstorming we started by defining the main solutions:

1) Constantly heat the water in the hot waterline

- Heating the water requires a lot of additional energy, so it does not fit to the established requirements.

2) Reuse the water in the cold waterline

- Reusing the cold water in the cold line is the best solution for effectively using the water. Unfortunately, this creates the problem of transporting the water from the hot line into the cold line. Without backflow, the water would have to be stored in a reservoir and then pumped into the cold line while the line is in use. This process would require a lot of power to run the pump.

3) Use the conserved water in household appliances

- Using the water for household appliances was also a good solution, though as noted in the background, this concept is already patented.

4) Store the water into a reservoir for future use.

- The solution that we chose is to feed the cold water into a reservoir. After looking at various reservoir options we concluded that using the toilet is the most feasible option due to its convenience.

The full brainstorming can be seen in Appendix D.

3.2. Concepts

Our concept selection process was split into two parts: 1) water extraction, and 2) water use. We decided that we are solving two separate problems that are independent of each other.

3.3. Functional Analysis and Morphological Box

For finding concepts we split the main function into sub-functions and added auxiliary functions and additional functions. The Functional Analysis is shown below.

Functional Analysis

Table 2 shows the analysis of the various functions and their degree of importance.

Main function		**to bypass water from hot-water-pipe as long as desired termperature is recieved**

Sub-function	1	to measure temperature
	2	to gather water
	3	to bypass water flow
	4	to interrupt water flow
	5	to generate power / load
	6	to save water
	7	to use the water

Auxiliary function	1	The user shall have the possibility to start the system
	2	provide fastening
	3	provide connection to pipes

Additional function	1	to reduce noise

In the Morphological Box we listed all solutions for the sub-functions. We combined the most effective options for our concepts.

Table 3 shows the morphological box showing possible solutions for each subfunction.

Subfunctions \ Solutions		1	2	3	4	5	6	7
1	**to measure temperature**	thermometer	hand	thermo-element	strain gauge	laser	infrared	
2	**to gather water**	hopper	tube	pipe				
3	**to bypass water flow**	T-pipe	3-way-valve	butterfly valve	gate valve	3-way-ball-valve		
4	**to interrupt water flow**	valve	butterfly valve	gate valve	faucet	ball stop valve (ball in pipe)	to clamp a tube	to produce back pressure
5	**to generate power / load**	spring	Kurzhubmagnet	hand	weight	water pressure (pipe pressure)	engine	compressor
6	**to save water**	pipe	tube	water basin / pool	closed vessel	pressure vessel		
7	**to use the water**	raising potential energy	toilet	drinking water	water the garden	to cool something	household appliances	electrical generation

3.4. Initial Final Concepts – Presentation

We had four main methods of water extraction including an electrical system (3.4.1.), a cylindrical valve system (3.4.2.), an automatic hydraulic system (3.4.3.) and finally a manual hydraulic system (3.4.4.).

3.4.1 Electrical Concept

Our electrical system consists of a series of electromagnetic valves that control the water flow. These valves function based on the temperature of the water. We came up with this concept because using automated magnetic valves do not require a separate microcontroller. Originally our idea was to use thermocouples with electronic butterfly valves which provide the ability to accurately open and close valves when needed in a timely fashion. The difficult part of this system would be to calibrate these valves to work in a cohesive fashion, in addition to supplying the electricity to the valves. The main weakness of this design is the fact that it requires additional energy in order to function.

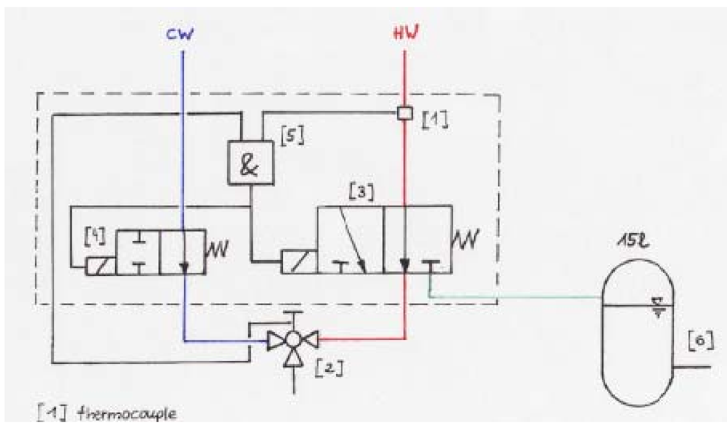

Figure 1 shows the electrical concept drawing.

3.4.2 Cylindrical Valve Concept

The cylindrical valve concept uses thermostats to control the flow of water by having valves that inversely react to temperature changes. We decided that the main drawback would be the time required to calibrate the thermostats for the temperature range we are interested in.

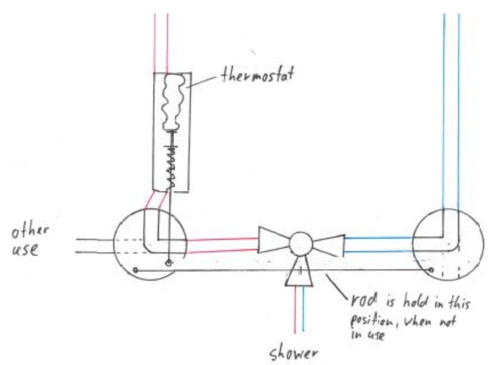

Figure2 shows the cylindrical valve concept.

3.4.3 Automated Hydraulic System

3) The automated hydraulic system uses the same principle as the manual system; however it requires additional valves that take the place of the button release. The major downfall of this system is the time it would take to run.

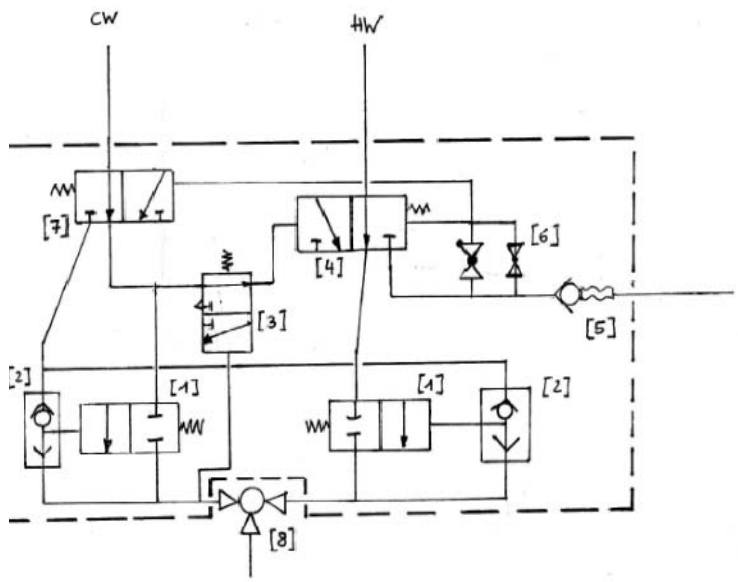

Figure 3 shows the automated hydraulic system concept.

3.4.4 Manual Hydraulic System

The following concept is a hydraulic solution. All used pressures are given by the present pressure in the waterlines. The main elements of the system are: pilot valve [1] (with a manual control button); main valve [2]; thermostat [3]; waterline to the toilet [4]; pressure valve [5]; shower faucet [6].

To start the system you have to push the button of the pilot valve [1] from starting position to working position. Because of this, the pressure of the cold waterline activates the main valve [2] from starting position to working position by using the line [a]. So the cold water from the hot waterline [HW] drains through line [b] by passing the thermostat [3]. This thermostat is supposed to be open by a water temperature below 40 °C and closed above. On account of this the water is running through line [c] to the toilet [4] or other user. In the moment water from the hot waterline [HW] reaches 40 °C the thermostat [3] will close. Pressure in line [b] rises and opens the pressure valve [5]. For this reason pressure in line [d] becomes higher and brings the main valve [2] back into the starting position. From then on the hot water is available at the faucet [6] and the user can start taking a shower.

Therefore we have chosen a separate button to start the system instead of using the shower faucet to conserve water. When using the shower faucet the water will come out immediately by reaching the temperature of 40 °C even if there is no user in the shower so water will be wasted. By separating the function of starting the system and starting the shower we avoid the problem of wasting unused water.

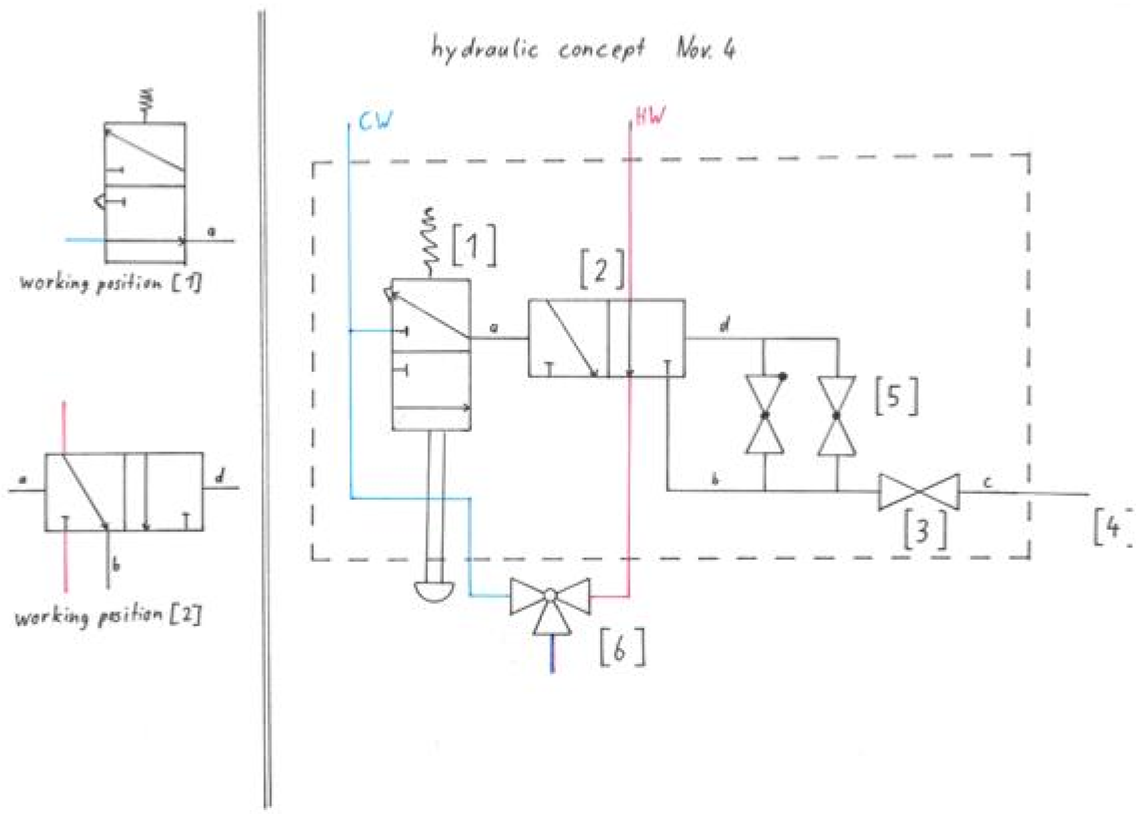

Figure 4 shows the manually operated hydraulic system concept drawing.

Maintenance and Repair – The separation device will be attached to a plate that is mounted to the shower wall using screw type fasteners. When the device fails, it can be easily replaced without using more effort than shutting off the waterline, disconnecting the separation device from the pipes, and pulling it from the wall. The device is naturally maintenance free.

Manufacture and Assembly – The body of the separation device will be casted near net shape from brass and then machined for final tolerances. All the internal components will be machined from stock stainless steel. Once those components are finished, they will slide into the brass body and sealed in using screws that fit the passages. As for the water storage system, a custom ceramic reservoir will need to be molded and kiln fired. The remaining internal components will be the same with the exception of the bobber, which will have to also be custom made to fit our design without increasing manufacturing and assembly time.

Safety Considerations – There are two main sources of failure in the water conservation system. The first is if the thermostat in the separation device gets stuck. If the thermostat is stuck closed, the conservation device needs to be replaced, though the shower will function fine without saving water. If the thermostat is stuck open, the emergency shut-off valve needs to be closed so that the system can return to starting position and the shower can be used. If the emergency shut-off valve is not closed, the system will drain water continuously into the toilet and the shower will not be operable. The other source of failure is the overflow of water in the second reservoir that collects shower water. In this case, the excess water is allowed to overflow from the second reservoir into the main reservoir, where it can then overflow into the toilet like a normal reservoir would.

3.5. Rejected Ideas

As previously mentioned we considered manufacturing electricity from the water pressure to run an electrical system. We planned to accomplish this by placing a turbine in series with the piping leading to the toilet reservoir. The rationale behind this is that the reservoir water does not need to be pressurized; therefore, all of the pressure can be absorbed out of the waterline and used for electricity before the water travels to the reservoir. The generated electricity can then be used to power the valves in the piping system, or if it generates enough power, it could potentially generate electricity that can be fed back into the power grid. Either way, the turbine-reservoir system is entirely self sufficient. However, our preliminary calculations showed that the electricity extracted from this system would not meet the requirements to make it feasible. Our calculations are shown in Appendix E.

4. Concept Evaluation

4.1 Initial Concept Analysis

In order to select our final concept we employed a decision matrix. Our Extraction Decision Matrix consists of 8 separate parts and is shown on the next page. The first criterion is **Building costs** which includes the costs of all the materials required to create the extraction of water from the hot waterline. This includes additional piping required, valves to process the flow of water, and any controllers associated with those valves. A high score in this category would equate to a more inexpensive system. The next criterion is **Running costs,** this includes any prolonged cost of running the concept, usually this comes in the form of electricity required to power the concept. Our third criterion is **Assembling,** this describes how hard and time consuming this concept would be to construct. **Handling,** is the fourth criterion and this describes the level of user interface required for each concept. Originally, we felt that complete automation was a design requirement; however, some consumers would prefer an adjustable system. Complete automation will still receive the highest score in this category, but consideration will be given to systems that allow the user limited control. **Working time,** is the next criterion and this describes how long it takes the concept to extract the cold water. **Safety,** is our sixth criterion, which relates to the reliability of the concept. We tried to anticipate how long each system would last and the likelihood each system would prematurely fail. Our seventh criterion is **Risk factor;** this addresses the difficulty faced by our team in developing a working system with this concept. A high score means that the system is simpler and we are more familiar with its components. Finally, our last criterion is **Patent uniqueness,** which analyzes how unique our idea is relative to the patents we found. We calculated each concepts' score in both a weighted and un-weighted fashion and found that the weighting factors only changed the outcome in terms of a tie in the un-weighted scores. The weighting scale we implemented was values between 0-3.

Extraction Decision Matrix:

Table 4 shows an evaluation based on rating each concept against a set list of criteria developed from the project specifications.

		1		2		3		4	
Running Costs	**weight**	**Electrical**		**Mechanical with cylindrical valves**		**Fully Hydraulic**		**Hydraulic with button**	
Building Costs	**3**	1	3	3	9	1	3	3	9
Running Costs	**2**	2	4	4	8	4	8	4	8
Cost Total		**7**		**17**		**11**		**17**	
Assembling	**1**	2	2	1	1	1	1	3	3
handling	**2**	4	8	4	8	4	8	2	4
working time	**3**	4	12	1	3	1	3	3	9
safety		3	6	2	4	2	4	4	8
Risk Factor	**3**	1	3	2	6	1	3	3	9
Patent Uniqueness	**2**	4	8	2	4	4	8	2	4
Functional Total		**39**		**26**		**27**		**37**	
Weighted Total		**46**		**43**		**38**		**54**	

The concept that won the decision matrix was the manual hydraulic system. The manual hydraulic system scored very high in terms of safety, risk factor, and working time. These are the criteria that had the greatest impact in separating it from the next closest design. At this point in the project this is the concept design that we pursued. A more detailed discussion of our reasoning for the given point values is located in Appendix F.

4.2 Approved Final Design

After meeting with our sponsor and further reviewing our manual hydraulic design we determined that this design is not feasible for production. The biggest deterrent for this design was the complex level of installation required. This design required an additional water to connect the toilet reservoir with the hot waterline entering the shower. Installing this line would require demolition of bathroom walls in any existing house. The cost and inconvenience of this installation outweigh the benefit most consumers would gain from saving water. The other major obstacle that the hydraulic system faced was the need for a custom toilet reservoir. During our research on toilet reservoirs we found hundreds of different designs each with a unique shape and dimensions. Manufacturing these custom tanks would not be feasible because there are too many styles on the market. It would require a large amount of capital to begin manufacturing our custom reservoir in multiple styles. In addition, we found that in order to store the additional water from the shower we would need to enlarge the toilet reservoir. Certain bathrooms would require this increased volume to come from increasing the depth of the tank. For our design we would need to increase the depth of the reservoir by 8 inches. After analyzing a few toilet tank and bowl systems we found that some styles could not handle this increased depth. The toilet lid would not be able to stay upright creating both a safety risk and a decrease is customer satisfaction. We looked into possibly changing the height or width of the toilet reservoir, but this brought about new problems. In many situations the toilet height or width could not change due to limited clearance with the rest of the bathroom features.

We had no doubt that this design will function properly according to the specifications initially outlined. However, some aspects of this design make marketing difficult; therefore we created a modified design. Our goal was to focus on simplifying our design. Simplifying our design decreased the cost of the system and increased our ability to market the final product. In order to do this we developed a design that is easily installed in existing systems without the need for an additional waterline. Another way to simplify the design is to decrease the amount of parts in our system. One of our trouble spots in our initial design was the custom toilet reservoir. Removing this part decreased the cost of the design and increased its simplicity. User intervention is the final area that we modified. Our goal was to make the new design fully automatic.

4.3 Analysis of Final Design

Our new design uses only a thermostat and a custom valve. This system is still connected to the toilet so that every time the toilet is flushed the reservoir fills from the hot waterline running to the shower. The initial scenario is where both hot and cold waterlines have cold water in them. In this case the water from the hot waterline is flushed into the toilet reservoir. However, if the hot waterline already contains hot water the thermostat will close and prevent flow from this line. Then the water from the cold waterline will flow into the toilet reservoir through our custom valve. The thermostat is placed in the hot waterline to prevent the reservoir from pulling hot water. Our valve functions due to a pressure gradient across a gate valve. The valve connects the hot and cold waterlines to the toilet reservoir. The cold waterline reduces in diameter to half the normal pipe diameter before it comes into contact with the gate valve. This lowers the surface area that the cold water can push on. Simultaneously, the hot waterline stays at the nominal pipe diameter. As a result there is twice the pressure pushing on the gate valve from the hot water side allowing it to flow to the toilet reservoir when the system is activated. The valve will switch positions when the thermostat shuts off the water flow in the hot waterline. This creates a void on the hot water side of the gate valve and allows the pressure from the cold waterline to swing the valve into its alternative position.

In order to theoretically test our new concept we performed two types of analysis. Initially we completed a basic cost

comparison between our new concept and the previous system. The idea was that the new system would require additional water to be heated as in most households the toilet will be used more than the shower. In this analysis we assumed a worst case scenario of 4 toilet uses per shower. Therefore, the analysis consists of comparing the cost of heating the additional water needed to be reheated against the cost of the water saved by the first system. In addition, the initial cost of both systems needs to be taken into account. Ultimately, we found out that the new system would cost the user approximately $37 for an electric heater and $26 for a gas heater per year. At the same time this device will save $5.46 equal to 584 gallons if the shower was only used once per day. This analysis also assumed that the toilet would be used 4 times per each use of the shower, based on a very conservative assumption. The lower the ratio of shower uses to toilet uses the more beneficial this system becomes. Our original system was expected to cost approximately $120-$150 for materials only. Adding the cost of production and installation approximately $400, the total cost of the hydraulic system equals $520-$550. This means that it would take 15 years before the automatic valve system was no longer more cost effective. This analysis supports our decision to proceed with the new idea as our target life span for any system as 10 years.

5. Management Plan

Our team is geographically split into two groups; one located in Munich (MUC), Germany and the other located in San Luis Obispo (SLO), CA. For the SLO group the project lead is Michael Eichermueller, and the secondary member is Mike Moren. Eichermueller handle and coordinated the communication between the SLO and Munich teams. In addition, his research focused mainly on building codes, existing solutions and fluid analysis of the system. Moren obtained patent research on ideas surrounding the project as well as keeping track of the projects progress through Microsoft Project. Our German counterparts will be working co-operatively with us on this project and will be conducting similar research as it corresponds to Germany.

5.1 Manufacturing Plan

The manufacturing analysis for the WCD at this point was conducted for both the prototype and the final factory produced product. To make the prototype, the valve device was split into 11 parts:

(3) ½”x1” Copper Pipe

(1) Control Flap

(1) Pivot Bar

(1) Square Tube

(2) Round to Square Connections

(1) Section of Contracting Curve Pipe

The total construction of this prototype device was estimated to require about 745 minutes of machining and build time. A detailed prototype plan can be found in Appendix X. Naturally, certain processes can be done simultaneously since 3 parts require a CNC 4-Axis Mill to produce, which will reduce the total prototype manufacturing time.

The final factory product made using proper jigs, tooling, and casting procedure required significantly less time to produce. There were a total of 4 parts that need to be made in this case:

(1) Control Flap
(1) Pivot Bar
(1) Valve Housing
(1) Housing Cap

The total construction time for the factory made valve system was less than 60 minutes.

Both prototype and factory manufactured parts require brazing for assembly, the only difference being that the prototype needs more brazing to assembly 11 parts as opposed to the 4 part factory manufactured valve system.

Technical Drawings are provided in Appendix K.

5.2. Proposed Test Rig

Testing was conducted separately by both teams as they deemed fit based on the budget of the project. The next phase of the project involved creating technical drawings and conducting advanced calculations on our systems. Concurrently, we designed a testing rig. This testing rig will serve two purposes for this project. First and foremost it will provide us with a

physical representation a basic plumbing system. This allowed us to size out our system and visualize how installation and operation would take place. Once our system had designed and constructed, this testing facility functioned as a working demonstration at the final Design Expo taking place May 10, 2009. The goal was to have a final design with technical drawings for manufacturing completed and approved by February 8th, 2010. For our testing facilities we had planned on building a section of wall that would commonly appear in a bathroom. Once this is complete we would install our system simulating the retro-fitting process. Water pressure was going to be provided by using either a water pump or a water column. The goal was to create a realistic representation of an average bathroom, which would most accurately allow for us to test the compatibility and efficiency of our water conservation system.

The testing rig consisted of an average bathroom following basic construction practices. It consisted of a 4' wide X 8' tall wall that has dry wall installed on both sides. This would give an accurate representation of the limited space our system can occupy. The floor of the test rig will be approximately 4' deep x 4' wide on one side. The supporting frame of the walls and flooring was to be made out of 2"x4" lumber; on this floor we installed a toilet or a reservoir simulating a toilet. In the wall we installed a faucet and shower head simulating the shower. All the piping was PEX style. We chose PEX piping because it is flexible which allowed for easier installation and it is compatible with both hot and cold water. We had two options for simulating 60 psi in our testing rig. The first option was to use multiple pumps in series. If we could not obtain enough pumps within our budget then the next idea is to use a pressurized water container that works similar to a keg. Using a pressure regulator and CO_2 cartridges we obtained the required pressure. In order to heat the water to the correct temperature we purchased a portable 2.5 gallon water heater.

Table 5 provides a cost analysis of intended test rig and estimated costs of system materials and manufacturing.

Test Rig					
Equipment	**Material**	**Amount**	**Unit**	**Cost Per Unit**	**Total Cost**
Vertical Wall Support	2x4x8	7	piece	$1.82	$12.74
Header	2x4x8	2	piece	$1.82	$3.64
Spacers	2x4x8	1	piece	$1.82	$1.82
Double Gauge Soft Drink Pressure Regulator		1	piece	$52.95	$52.95
15 lb CO2 Canister		1	piece	$88.70	$88.70
5 Gal Keg		2	piece	$25.50	$51.00
Walls	Drywall	3	sheet	$5.20	$15.60
Flooring Support	2x4x8	10	piece	$1.82	$18.20
Floor	Plywood	2	piece	$7.94	$15.88
Water Heater	Bosch	1	piece	$150.00	$150.00
Drywall Screws	Steel	1	box	$5.94	$5.94
Ball Valves	PVC	2	piece	$2.52	$5.04
Piping	PEX	4	package	$3.19	$12.76
Subtotal					**$434.27**
Tax					**$43.43**
Total					**$477.70**
System Materials					
Equipment	**Material**	**Amount**	**Unit**	**Cost Per Unit**	**Total Cost**
Fittings		5	piece	$1.00	$5.00
Thermostat		1	piece	$19.99	$19.99
Valve Housing	Copper	0.47	lbs	$3.00	$1.41
Valve	Copper	0.01	lbs	$3.00	$0.03
Valve Housing (Test Piece)	Acrylic	0.06	lbs	$5.00	$0.30
Valve (Test Piece)	Acrylic	0.01	lbs	$5.00	$0.05
Subtotal					**$26.43**
Tax					**$2.64**
Total					**$29.07**

Prototype Cost **$29.07**

Total Project Cost **$506.77**

5.3 Testing Plan

The testing of the water conservation device consisted of three parts: 1) Dynamic Testing, 2) Corrosion Testing, and 3) Fatigue testing. These three testing phases allowed the device to undergo a life time of testing in a relatively short amount of time for various environments.

1. Dynamic Testing
    - With an acrylic valve model, the test was to see if the device will function with no control flap. The cold waterline was colored with a dye such that if mixing were to occur it can be readily seen.
    - If a flap is needed, the acrylic model will be used again to check the function of the valve to ensure there is a complete water seal. Dye was used again to check for any discrepancies in flow
    - With either case, the flow rate was measured at the outlet to determine the maximum amount of losses that occur through the valve and make sure they are not too high.
2. Corrosion Testing
    - The thermostat and valve will be checked against hazardous environments by tainting the water with calcium, iron, chlorine, and other minerals/chemicals that can be found in high quantities in tap water.
3. Fatigue Testing
    - The function of the thermostat and valve was checked with as many cycles as possible between now and June 2010 to ensure long lasting durability.

The fatigue and corrosion testing phase can be conducted simultaneously to shorten the amount of testing time. As a worst case scenario, the valve and thermostat will be used about 5 times per day, yielding 18,250 uses in a lifetime of 10 years. With the current water heater set-up on the test rig, it takes about 20 minutes to reheat 2 gallons of water that we are using to simulate the system. At this rate, it would take about 250 days of continuous testing to simulate a life-time worth of use, which is unattainable for a June 2010 deadline. Aside from that, we can test the valve with purely cold water using a ball valve to simulate the opening and closing of the thermostat.   This will cycle the system every 5-10 seconds as opposed to 20 minutes, giving us the capability to test a lifetime worth of use in 50 hours. The water heater can be kept for final demonstration to show the functionality of the entire device

6. Manufacturing Process

During the manufacturing phase of the prototype, the work was split into two parts; the Cal Poly students manufactured the valve body and flap, while the Munich students built the thermostat. Each part was responsible for building two working prototypes of their respective designs. The goal was to build to exact models and then transport one version to the other groups of students. Then each part of the team would create two identical test rigs, one in San Luis Obispo, California and the other in Munich, Germany allowing for simultaneous experimenting to take place.

6.1 Valve Body Prototype

The valve prototype was manufactured from a clear acrylic, seen in Figure 5 which enabled the teams to see the valve functioning. This allowed us to visually analyze the flow through the valve and spot areas that needed to be improved.

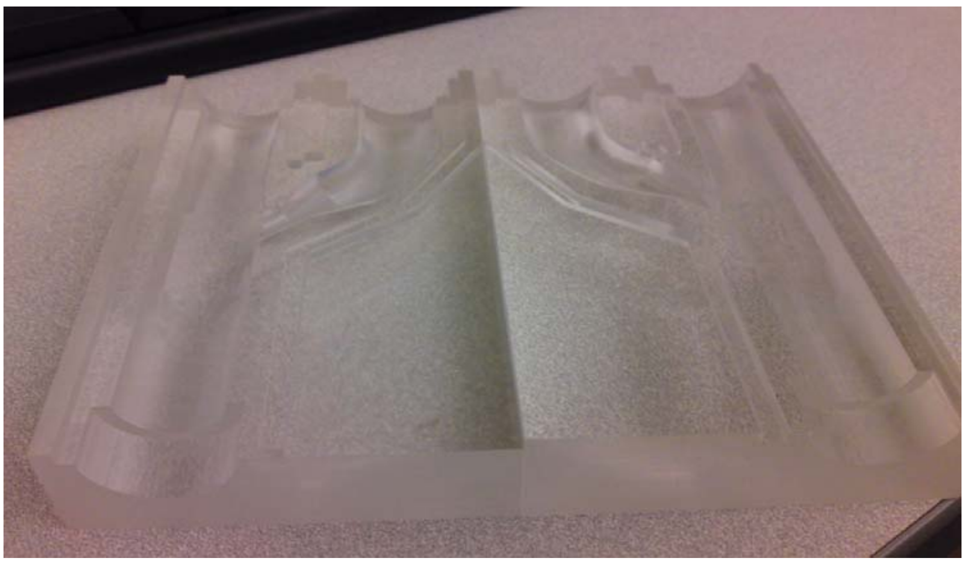

Figure 5 shows the two halves of the acrylic valve prototype.

Acrylic was used as prototype material for the valve instead of brass, which would be used for production. Acrylic was a cheaper and transparent substitute which we believed to be more beneficial than using brass for this stage of the development.

The final manufacturing method will be to cast this part; however, creating a casting mold for a prototype would have been expensive and would not have been feasible until the system is ready for final production. Thus, the easiest method available was to use the Computer Numerical Control machine, CNC, available to the Cal Poly students. The part was manufactured in two halves, top and bottom, with the split plane bisecting the pipe bores. The milling procedure required the use of multiple square endmills, a round ball endmill and a surface planar. The final prototype version required a total of three hours to produce including setup and cleanup time. Through the multiple iterations of production, modifications were made to how the Valve was designed, including the addition of channels to locate the two halves for alignment purposes. The final version has smooth contours and optimized dimensions with tolerances less than ±0.003 inch. Complete CAD drawing can be found in Appendix K.

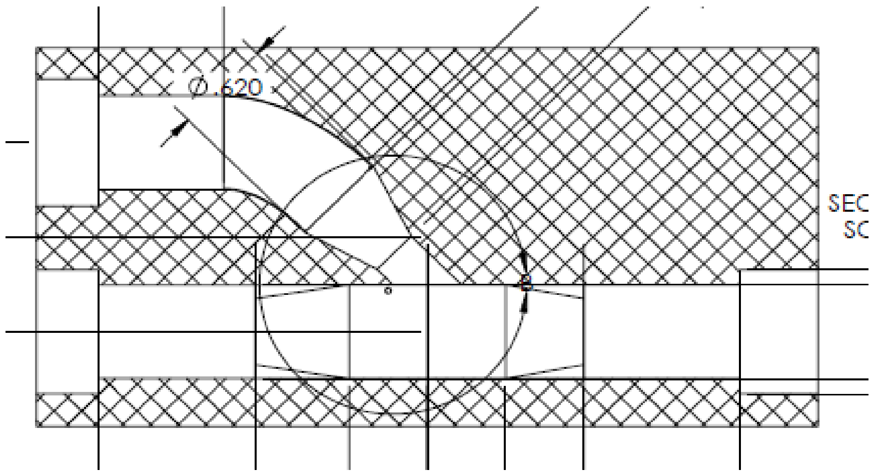

Figure 6 shows a drawing of one half of the valve prototype.

6.2 Thermostat Prototype

Unlike the valve, the thermostat prototype was manufactured out of the final design material, brass.

The manufacturing method for the thermostat had to be changed to facilitate the lathe and mill equipment that was available to the Munich students. Wanting to produce the thermostat prototype quickly, additional time to to optimize the dimensions was not used, resulting in an increase in prototype weight and thickness. Future iterations to the thermostat are planned in order to optimize its performance and size.

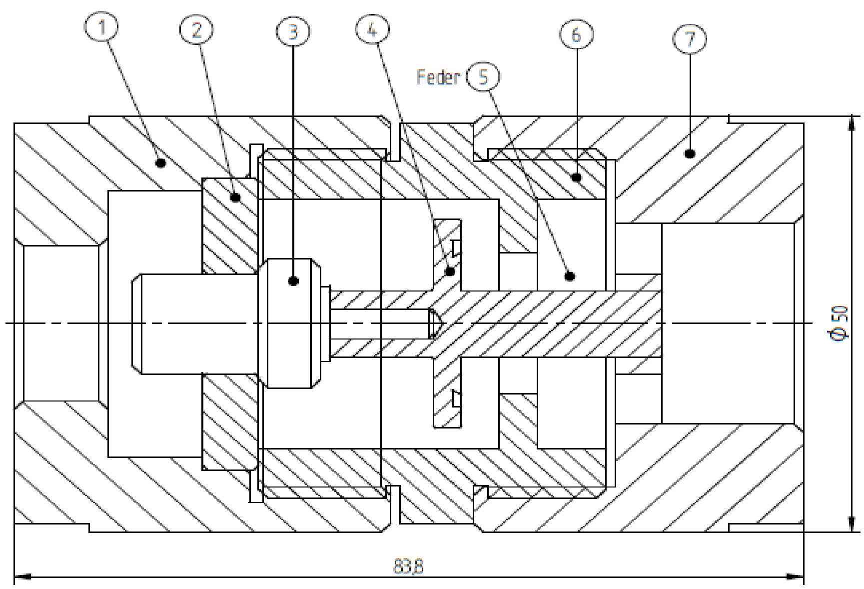

Figure 7 shows the basic layout of the thermostat prototype. A complete schematic of the thermostat can be seen in Appendix K.

The threads that enable the three separately machined parts are sealed with Teflon tape. For the testing phase a rubber gasket was adhered to (4) decreasing the leakage through the valve and softening the closing of the valve in order to prevent water hammer. The stroke of the valve element (4) can be set up with lining discs between (2) and the (6) in order to achieve different closing temperatures and times.

While the Munich students manufactured the thermostat body and main components, they purchased the thermostat spring (5) and the wax element (3) from manufacturers. The wax element was purchased from the company *ACS GmbH*

and the spring was purchased from the company *FedertechnikKnörzer GmbH*. The wax element starts to expand at a temperature of 30°C with a maximum stroke of 4mm, exerting a force of 5.0 N/mm. The spring was selected to be compatible with this wax element, with a spring constant of 4.58 N/mm. For complete specifications for these purchased components, please refer to Appendix I and J.

7. Testing Phase

7.1 MUC Testing Rig

The complete system for the thermostat and valve can be seen below in Figure 8. The core portion of the system is outlined with a dashed red box and contains the main components labeled with bracketed red numbers (the thermostat and valve). The thermostat [1] has a 3/4” outlet pipe that is stepped down to 3/8"in order to connect to the valve [2]. All pipes leading into and out of the valve are 3/8” pipe, while all remaining tubing and piping is 1/2".

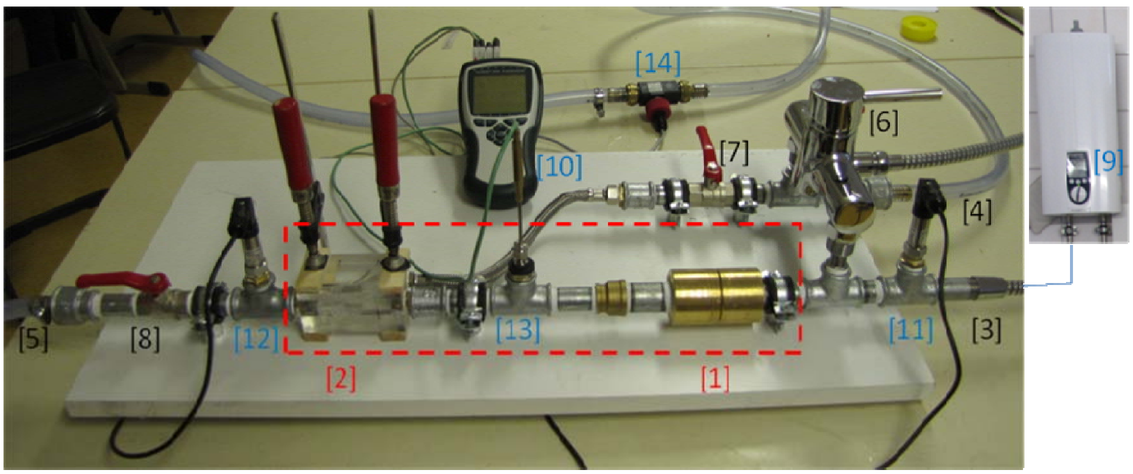

Figure 8 shows the final MUC testing setup complete with measuring devices.

The control valves and connections are labeled in Figure 1 with bracketed black numbers. The shower hot waterline [3] is connected to the same line as the thermostat and upper valve input, while the cold waterline [4] is attached to the lower input of the valve. The output line [5] runs between the system and the toilet reservoir.

The system contains a shower faucet [6] prior to the thermostat and simulates an actual shower faucet. There is also a ball valve [7] to regulate the flow rate of the cold waterline. Similarly, there is a ball valve [8] to simulate the closing of the toilet tank.

The measuring components are labeled with bracketed blue numbers in the figure above. The electrical boiler [9] has a digital display that enables variable hot water temperature and displays the water temperature and the flow rate. The data-measuring device [10] collects, displays, and saves the data from the pressure taps [11] and [12], the thermometer [13], and the flow rate-measuring element [14] on the cold waterline.

The valve is made up of two separate halves and a special flap that pivots around a small axis pin. C-clamps were used to keep the two halves tight and the flap in place.

Some of the pipes are fastened to a board by small clamping supports in order to make the test rig rigid and portable. This was important because the available waterlines were not present in the workshop. Flexible tubing was also used in order to alleviate the trouble of connecting and disconnecting the testing rig to water supply lines.

7.2 Cal Poly Testing Rig

The Cal Poly testing rig followed the same principle as the MUC testing rig. The testing rig was connected to the hot and cold waterlines from a sink in the Fluids Laboratory. Dial pressures gauges were installed before and after the thermostat, in the cold waterline, and at the outlet of the system. The outlet of the system was connected to a toilet fill valve that was installed in a bucket in order to simulate the toilet reservoir.

7.3 Testing Rig Comparison

The thermostat and valve in the Cal Poly test rig was joined together with PVC and galvanized steel piping. Dial indicators were used for the pressure gauges and flow rate was measured through a bucket and scale system. The test rig in Munich useda combination of flexible tubing, pipes, and digital readouts. The layouts can be seen in Figure 9 and Figure 10.

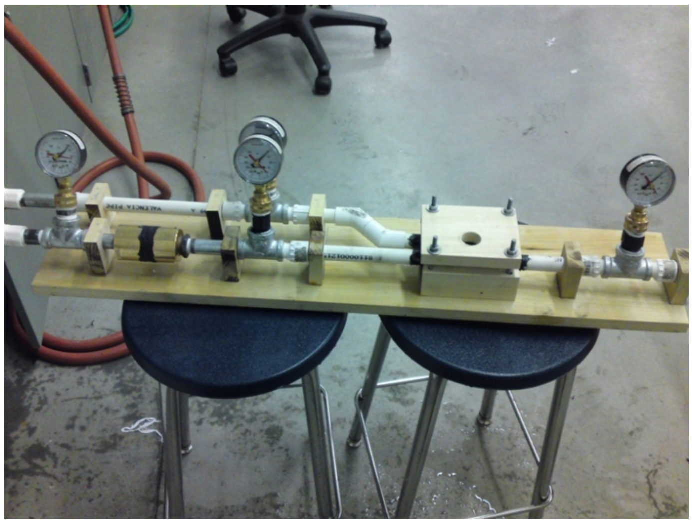

Figure 9 shows the Cal Poly testing rig with dial pressure gauges.

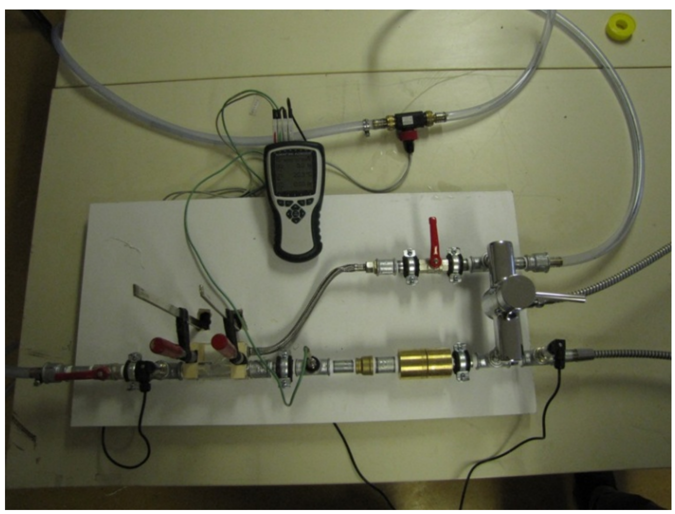

Figure 10 shows the MUC testing rig with digital readouts.

Having two testing rigs was very advantageous to the development of the system. The MUC team was able to more accurately determine the pressure drops throughout the system as a result of better testing equipment. The other significant difference in testing conditions was the available flow rate. The MUC students had access to a shower enclosure at their campus which limited the flow rate in the lines to approximately 2.5 gpm. This shower enclosure also

allowed variable hot water temperatures. The Cal Poly students were able to connect their testing rig to the Fluids laboratory which allowed for flow rates of up to 6 gpm in each waterline, however the hot water line remained at one temperature. Therefore a variety of situations were able to be tested and analyzed with enough overlap so that testing resulted could be compared for a range of conditions.

7.4 Testing Procedures

7.4.1 Thermostat Procedure

To test the thermostat, we connected directly to the hot waterline with two outflow channels controlled by two separate ball valves, as seen below in Figure 11. The goal of these tests was to compare the time that the wax element inside the thermostat took to close the valve and record the amount of warm water that was wasted.

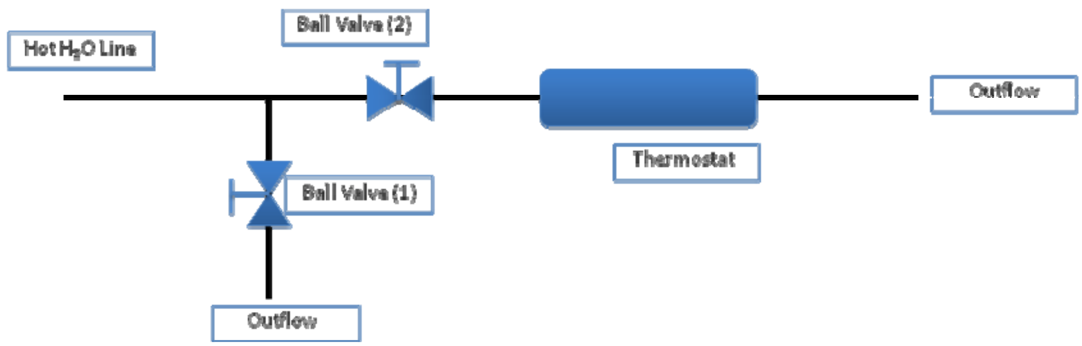

Figure 11 shows the thermostat testing configuration. The main information obtained was the amount of time before the thermostat closed.

Valves (1) and (2) were initially closed at the beginning of the thermostat testing. Valve (1) was then opened and hot water ran through the system until the desired water temperature was reached. The temperature was recorded using the electronic thermostat and Valve (1) was closed causing the tubing in front of the thermostat to be filled with hot water of known temperature. Valve (2) was opened and the water flow was timed until the wax element inside the thermostat closed causing the flow of hot water to stop. The time and amount of water dispensed was recorded and the flow rate was calculated in an excel spreadsheet and is posted in the *Results* section of this report. This test was run with two different wax elements to see if the amount of stroke or the wax element itself contributed to the closing time and how much hot water was wasted.

The Cal Poly students did not have variable temperature capabilities so their testing rig did not have Valve (1). In addition the Cal Poly students measured the water temperature after the water left the thermostat, however in comparing with original hot waterline testing the temperature did not significantly drop through the thermostat.

7.4.2 MUC Valve Testing Procedure

To visually test the function of the valve, it was connected to the shower waterline and the cold waterline. Each line is controlled by a ball valve and coloring was added to the cold waterline. The testing setup can be seen below in Figure 12. The goal of this test was to visually be able to see if the valve flap was closing completely when the thermostat was still open, or if it was leaking to what extent.

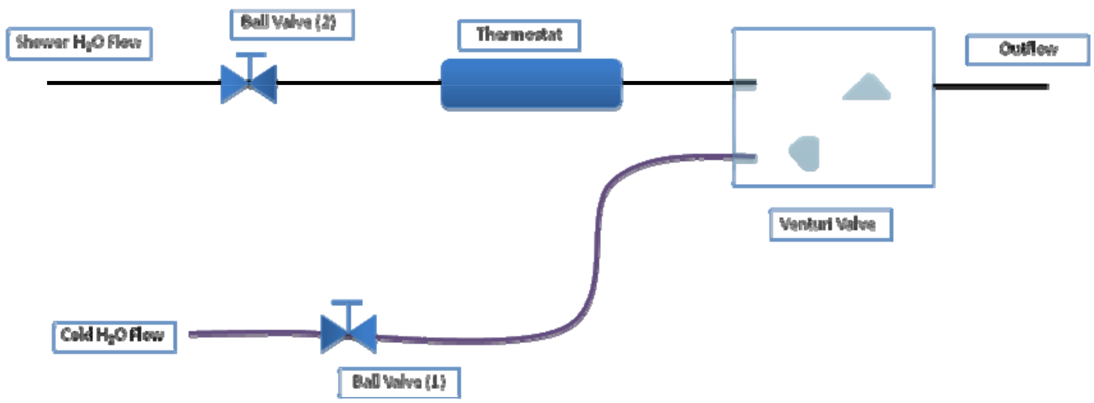

Figure 12 shows the MUC valve body testing configuration. The main testing concern was cold water leakage while the thermostat was open.

In order to test the valve and its function there needed to be a way to distinguish the water coming from the shower and the water coming from the cold line. Purple coloring was added to the cold waterline prior to the start of the test. Valve (1) and (2) were initially closed, allowing cold water to fill the tubing. Valve (2) was then opened and cold water ran through the thermostat and the upper half of the valve. Valve (1) was then opened slightly and the dyed cold water ran up to fill the valve. If the valve flap were not completely closed, the dyed water would leak through to the outflow and would be visible. Video documentation was recorded.

7.4.3 Cal Poly Valve Testing Procedure

The schematic for the Cal Poly students testing configuration was the same, however the method of calculating cold waterline leakage was different. Using the overall change in temperature from the hot waterline to the final temperature of the water through the valve allows for the amount of cold water leakage to be calculated. The procedure included running the system for a small amount of time allowing hot water to pass into the collection bucket. Assuming no leakage this water would be at the same temperature as the hot water line, however the temperature would be lower depending on the amount of leakage that occurs.

Equation 1

$$T_{finalexpected} = \frac{mass_{cold} \cdot T_{cold} + mass_{hot} \cdot T_{hot}}{mass_{hot} + mass_{cold}}$$

Equation 1 shows the equation we derived in order to approximate how much cold water was leaking through the flap. This was developed with an energy balance between the cold and hot water. By solving for the expected final temperature the mass of cold water entering the outlet bucket can be found. These results combined with the fluid injection testing that the MUC students conducted allowed for an accurate analysis of the flap’s effectiveness.

7.4.4 Complete Testing Procedure

The setup for testing both components in a system as a whole can be seen below in Figure 13. These tests are to demonstrate that both components are able to function when integrated together in the same system.

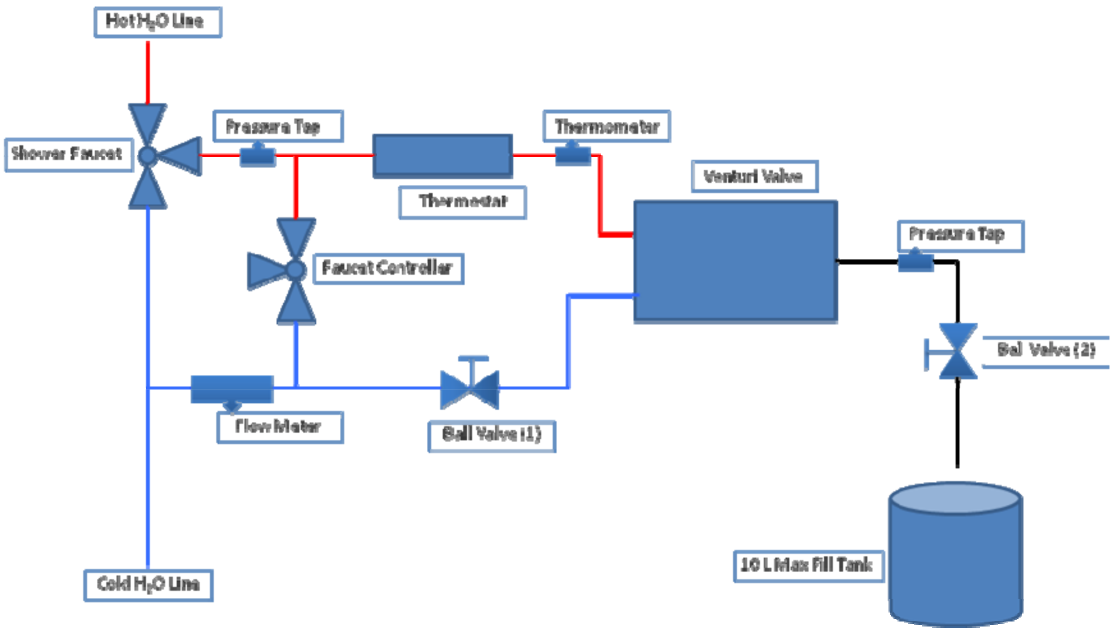

Figure 13 shows the MUC complete testing schematic. The Cal Poly testing configuration was very similar minus the flow meter and shower faucet. The Cal Poly flow rate was calculated by weighing the final weight of water flowing out of the system. The shower faucet was not added to the Cal Poly system as their goal was to test at higher flow rates. A toilet fill valve was added at the entrance to the fill tank in order to simulate a flow into the toilet reservoir.

Prior to testing the system's functionality, the initial temperature of the thermostat was recorded. With the shower faucet shut off, Valve (1) was opened allowing cold water to flow through the valve with a measured flow rate reading from the flow meter. The boiler temperature was then set and the shower faucet turned on while simultaneously beginning to time. The time at which the thermostat close was recorded, as well as the time it took to fill the outlet bucket. The flow rate from the boiler, the pressure in the hot waterline, and the temperature at which the thermostat closed were all noted during the test. The recorded information can be seen in the *Results* portion of this report.

The Cal Poly testing followed the same basic principles. Starting both the hot and cold water lines at a fixed flow rate the test would run until the toilet valve shut off the system simulating a full toilet reservoir. During the test the time was noted at which the thermostat shut off giving allowing for the calculation of thermostat waste to be conducted. In addition because the overall water output could be measured the amount of cold water flowing through the system could also be calculated. These tests were important to analyze and record because they showed areas of improvement in the systems interaction as a whole. The previous experiments had tested each component; however it is important to consider how each component can affect functionality of surrounding components. These ideas will be further addressed in the *Analysis* portion of the report.

8. Results

8.1 MUC Testing Results

Table 6 below is a quick overview of the different tests that were run and the date that the data was collected. Three wax elements were obtained from the manufacturer so the MUC students were able to test two different wax elements for comparison while the Cal Poly students tested with the same wax element for all the tests. Multiple tests with each element helped determine if the element component affected the performance overall. The stroke length was also a variable that was changed and therefore is also noted in Table 6.

Table 6 shows the testing purpose, date and wax element used for the MUC testing.

Number	Date	Purpose	Wax element	Stroke
1	20.05.10	Functionality of the whole system	1	1 mm
2	26.05.10	Thermostat reaction time	1	1 mm
3	27.05.10	Thermostat reaction time	2	1 mm
4	27.05.10	Thermostat reaction time	2	2 mm
5	27.05.10	Visual test of venture valve	1	1 mm

8.1.1 Complete System Testing Results

Table 7 is the collection of data from the entire system obtained from the installed flow meters, thermometers, boiler display, and pressure taps. Using the values from Table 7 for flow rate and time that it took for the thermostat to close along with conversion factors, the amount of water dissipated from the hot waterline was calculated in columns 3, 4 and 5 of Table 8.

Table 7 shows test data that was collected while testing the entire systems functionality (with thermostat and valve).

Test Nr.	Thermo. StartingTemp (°C)	Boiler Output Temp (°C)	Cold H_2O Flow Rate (L/min)	Time Until Thermo Close (sec)	Time Until 10L Total Output (sec)	Flow Rate with Both Lines Open (L/min)	Boiler Flow Rate (L/min)	Hot H_2OPressure (BAR)	Temp. when Thermo. Closed (°C)
1	14,20	42,00	8,40	14,10	53,10	7,70	8,10	4,65	
2	12,00	42,00	10,10	16,00	42,40	9,00	8,10	4,65	33,00
3	12,40	42,00	16,70*	17,00	26,00	14,10	8,20	4,23	
4	13,20	50,00	8,20	15,00	56,90	7,70	7,20	4,75	33,30
5	13,50	60,00*	8,90	15,00	51,40	8,20	5,50	4,50	31,40
6	14,10	42,00	8,60	12,00			8,10		32,70
7	13,80	42,00	8,70	14,88	50,04		8,20		
8	12,40	60,00	8,20	16,03			5,80		

9**	12,50	50,00	8,70	4,05			6,20		31,20

* Maximum Value
** Test run with hot water backfilled in the shower line, before the thermostat.
***Missing data was not recorded, as it was not needed to calculate the values in Table 8.

Table 8 shows values for the hot water line from the values in Table 7

Test Nr.	Time Until Thermo. Closed (sec.)	Water Dissipated (Lbs.)	Water Dissipated (Gal.)	Water Dissipated (L)	Hot H_2O Line Flow Rate (gpm)	Hot H_2O Line Flow Rate (lpm)
1	14,10	4,19	0,50	1,90	2,14	8,10
2	16,00	4,75	0,57	2,16	2,14	8,10
3	17,00	5,11	0,61	2,32	2,17	8,20
4	15,00	3,96	0,48	1,80	1,90	7,20
5	15,00	3,03	0,36	1,38	1,46	5,50
6	12,00	3,56	0,43	1,62	2,14	8,10
7	14,88	4,47	0,54	2,03	2,17	8,20
8	16,03	3,41	0,41	1,55	1,53	5,80
9	4,05	0,92	0,11	0,42	1,64	6,20

8.1.2 Thermostat Component Test 1

The initial test run on the thermostat component was with wax element #1 and a stroke of 1mm. The line temperature and flow rate seen in Table 9 were recorded from the boiler display while the time that it took for the thermostat to close was recorded using a stopwatch. The calculated volume values in columns 3 and 4 were achieved using the recorded time and displayed flow rate.

Table 9 shows collected thermostat data while connected to the shower as an individual component.

T [°C]	t [s]	V [L]	V [gal]	Flow Rate [lpm]
35,3	12,5	1,85	0,489	8,9
35,0	11,9	1,90	0,502	9,6
40,2	6,0	0,90	0,238	9,0
40,2	5,8	0,90	0,238	9,3
45,1	4,1	0,68	0,180	10,0
45,3	4,3	0,65	0,172	9,1
50,1	2,8	0,49	0,129	10,5
55,2*	2,3	0,40	0,106	10,4
60,5*	2,0	0,36	0,095	10,8

*Testing temperature was so high, response time of the thermostat was too low to allow the system to reach steady state; therefore, data is referenced, not exact

Figure 14 and Figure 15 give a visual perspective of how the thermostat responds to temperature and as a result how much water is going to be wasted from the hot waterline before the thermostat shuts off.

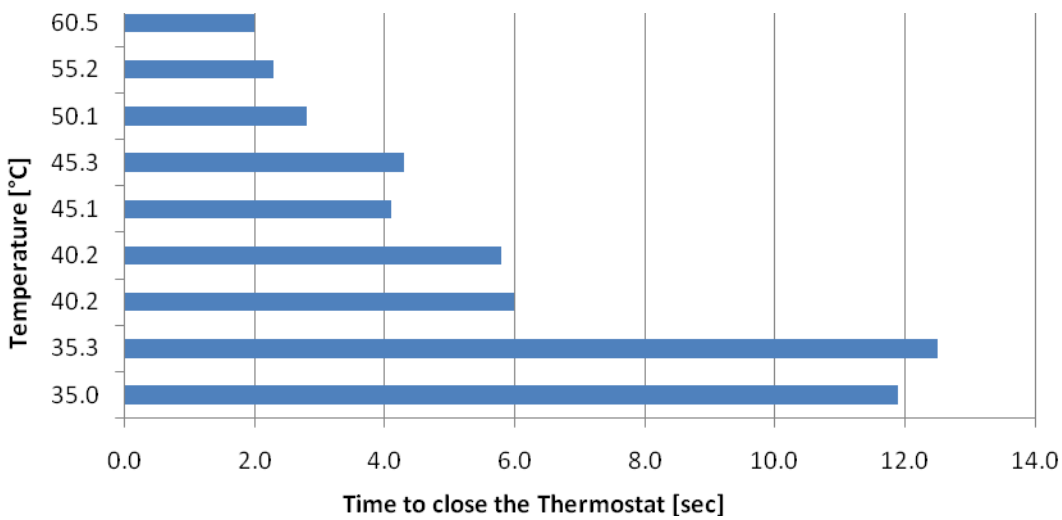

Figure 14 shows a graphical display of how the shower temperature affects the time it takes the thermostat to close.

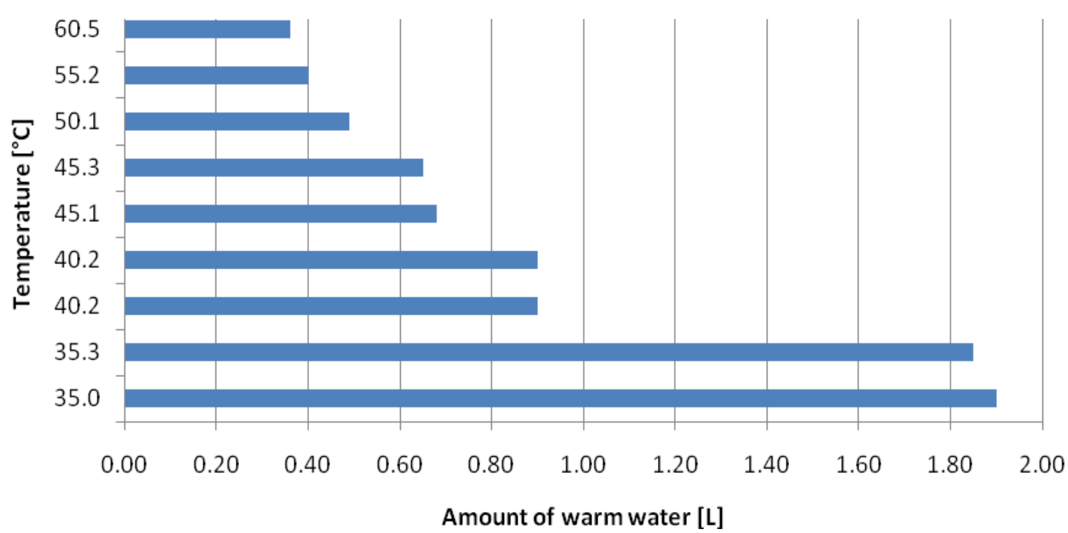

Figure 15 shows how the water temperature affects the amount of wasted water from the hot water line before the thermostat responds.

8.1.3 Thermostat Component Test 2

The second test was with wax element #2 and a stroke of 1mm.The design of this experiment was to see if the manufacturing of the wax element affects the response time of the thermostat. The same data was collected from the boiler in the first test was also collected in this test; enabling, us to, again, calculate the amount of water that was dispensed from the hot waterline prior to the thermostat responding and shutting off.

Table 10 shows the collected data with the second wax element.

T [°C]	t [s]	V [l]	V [gal]	Flow Rate [l/min]
35,10	16,98	2,40	0,63	8,48
35,40	16,33	2,11	0,56	7,75
40,00	9,40	1,40	0,37	8,94
40,00	9,95	1,50	0,40	9,05
45,00	5,60	0,90	0,24	9,64
45,00	5,95	0,80	0,21	8,07

Figure 16 and Figure 17 display how the thermostat responds with a new wax element installed and how much hot water was dispensed before the wax element inside the thermostat responds and shuts off.

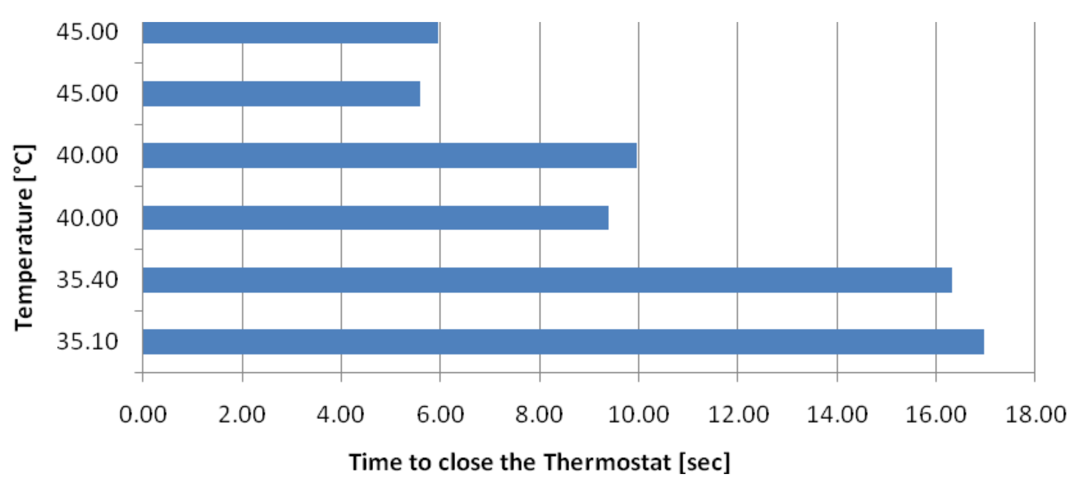

Figure 16 displays the response time of the thermostat with a new wax element installed.

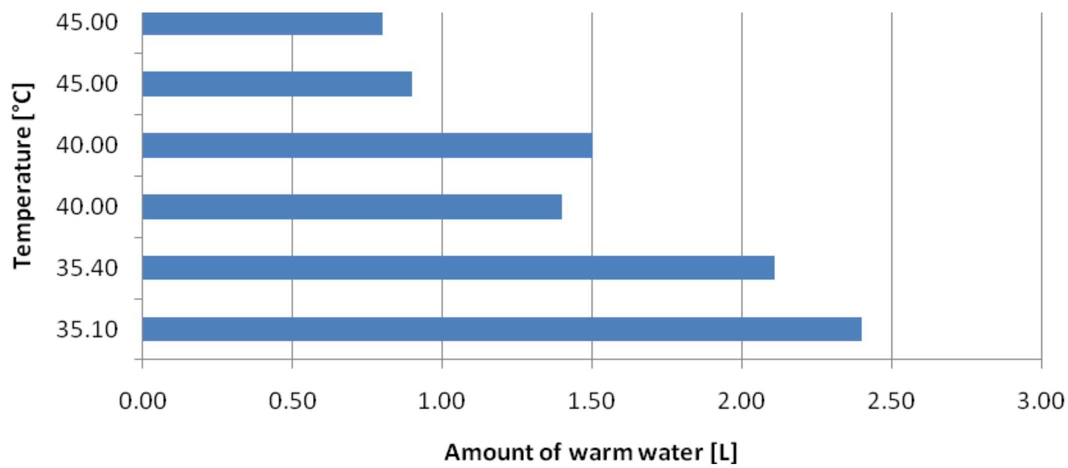

Figure 17 illustrates the affect of water temperature on the new wax element and how much water is wasted before it responds.

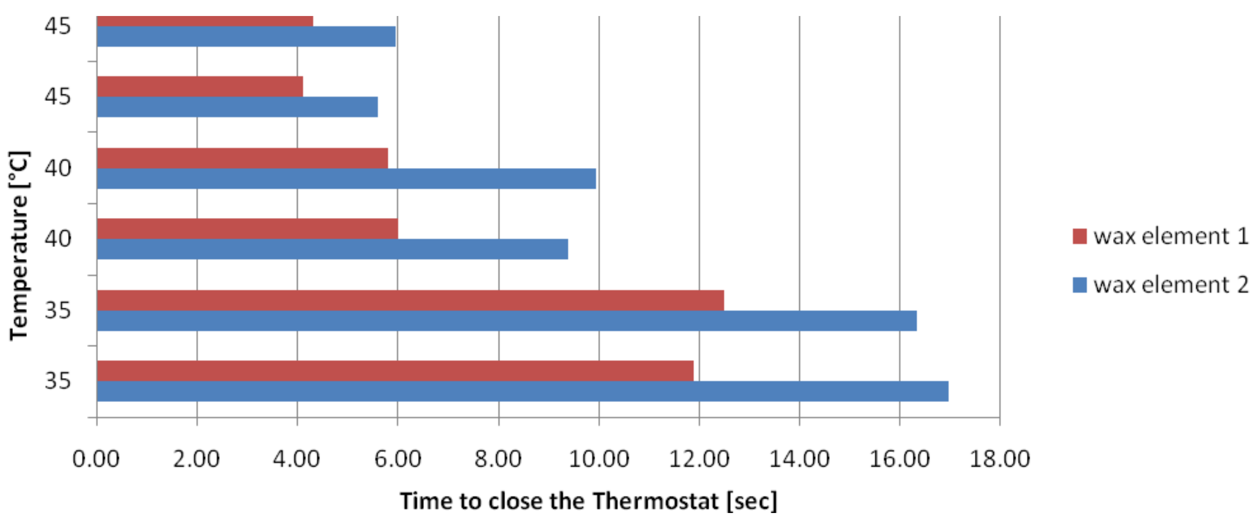

Figure 18 shows the differences in the response times for each temperature between wax element 1 and 2.

8.1.4 Thermostat Component Test 3

The final test performed on the thermostat was with wax element 1 with a stroke of 2mm. The function of this experiment was to compare the affects of stroke length on the closing time and ultimately the amount of wasted water.

Table 11 shows data collected from thermostat testing with a stroke of 2mm.

T [°C]	t [s]	V [l]	V [gal]	Flow Rate [l/min]
35,00	24,96	3,60	0,95	8,65
35,40	22,30	3,30	0,87	8,88
40,30	14,70	2,10	0,55	8,57
40,20	14,60	2,10	0,55	8,63
45,20	13,00	1,80	0,48	8,31
45,10	12,70	1,95	0,52	9,21
60,30	4,70	0,80	0,21	10,21

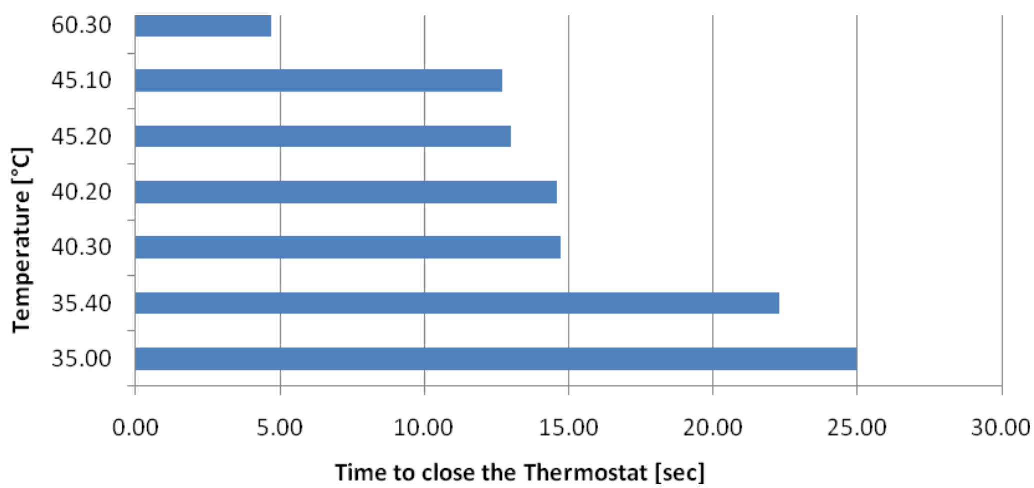

Figure 19 shows the effect that water temperature had on the reaction time it took for a thermostat to close with a 2mm stroke.

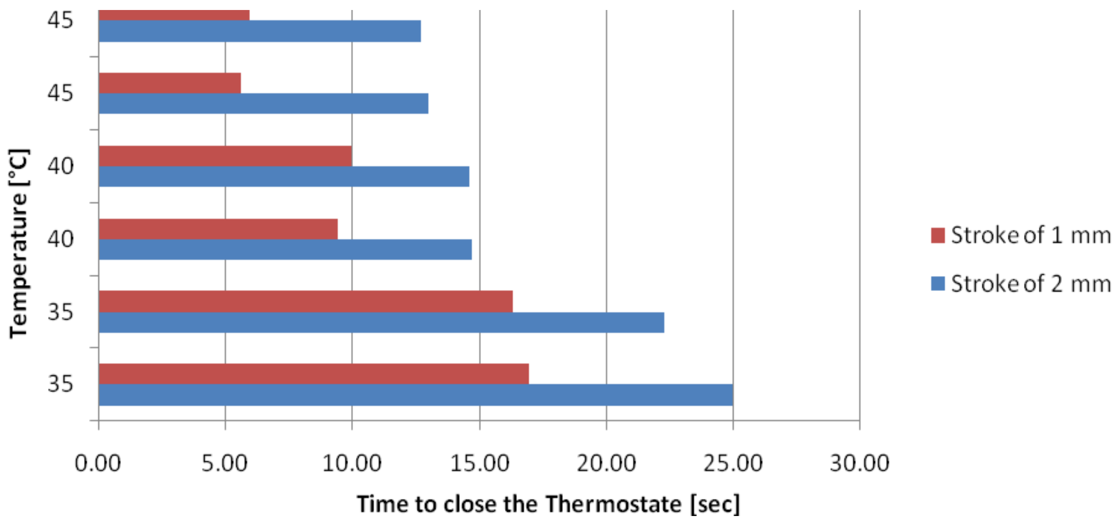

Figure 20 shows the comparison between different stroke lengths with the same wax element. According to this data it seems that the stroke length of the thermostat is very important as it has a direct correlation to the time before the thermostat will close.

8.2 Cal Poly Testing Results

The test results from Cal Poly highlighted a major design flaw in the thermostat component that is detrimental to the use of the entire device, water hammer. The results show that at high flow rates water hammer occurs which can destroy pipes, see section 8.3 for further information. The data collected gives insight on areas of improvement for further iterations.

Table 12 shows the final testing data from the Cal Poly testing rig.

Test #	Seconds to Close	Pin/Gasket Offset (mm)	Water Dissipated (lb)	Water Dissipated (Gal)	Water Dissipated (L)	Flow Rate (GPM)	Flow Rate (L/min)	Notes
1	24.51	4.50	19.18	2.31	8.72	5.65	21.34	Extreme Water Hammer
2	27.10	5.75	22.74	2.73	10.34	6.05	22.88	Extreme Water Hammer (See Video)
3	26.00	5.75	21.38	2.57	9.72	5.93	22.43	Extreme Water Hammer (See Video)
4	29.00	8.00	23.00	2.77	10.45	5.72	21.63	Extreme Water Hammer (See Video)
5	67.00	8.00	29.26	3.52	13.30	3.15	11.91	Valve Never Closed
6	41.00	6.00	26.56	3.19	12.07	4.67	17.67	Water Hammer
7	-	2.00	-	-	-	-	-	Added Gasket From this point on. Valve Never Closed
8	-	4.00	-	-	-	-	-	Valve Never Closed. Persistent Hammer
9	7.74	6.00	1.77	0.21	0.80	1.65	6.24	Closed with 3 Hammers
10	14.70	6.00	7.90	0.95	3.59	3.88	14.66	Closed with 3 Hammers
11	16.27	6.00	4.74	0.57	2.15	2.10	7.95	Hammer on close
12	14.90	6.00	5.31	0.64	2.42	2.57	9.73	Hammer on close
13	27.28	6.00	13.22	1.59	6.01	3.50	13.22	Closed with two hammers
14	35.80	6.00	7.45	0.90	3.39	1.50	5.68	hammer on close
15	45.90	6.00	11.28	1.36	5.13	1.77	6.70	Soft Close
16	22.90	6.00	9.62	1.16	4.37	3.03	11.46	Normal (Hammer on close); 43 ^{o}C
17	34.70	6.00	14.04	1.69	6.38	2.92	11.03	Normal (Hammer on close); 41 ^{o}C
18	28.90	6.00	13.24	1.59	6.02	3.31	12.49	Closed with 3 Hammers; 41 ^{o}C
19	35.80	6.00	11.56	1.39	5.25	2.33	8.81	Normal; 42 ^{o}C
20	23.80	6.00	9.26	1.11	4.21	2.81	10.61	Normal; 42 ^{o}C
21	33.50	6.00	11.98	1.44	5.45	2.58	9.75	Normal; 42 ^{o}C
22	25.60	6.00	12.04	1.45	5.47	3.39	12.83	Closed with persistent hammering; 43 ^{o}C
23	14.50	6.50	10.00	1.20	4.55	4.98	18.81	Hard Stop; 45C inside, 44 C Surface
24	24.60	6.50	15.96	1.92	7.25	4.68	17.69	Persistent Hammer, 44 C
25	25.50	6.50	15.16	1.82	6.89	4.29	16.21	Persistent hammer, 44.6 C
26	26.20	6.50	14.90	1.79	6.77	4.10	15.51	Persistent Hammer, 44.3
27	26.90	6.50	15.16	1.82	6.89	4.07	15.37	Persistent hammer, 44.6 C
28	27.60	6.50	14.90	1.79	6.77	3.90	14.72	Persistent Hammer, 44.4
29	28.20	6.50	12.86	1.55	5.85	3.29	12.44	2 hammers, 43.7 C

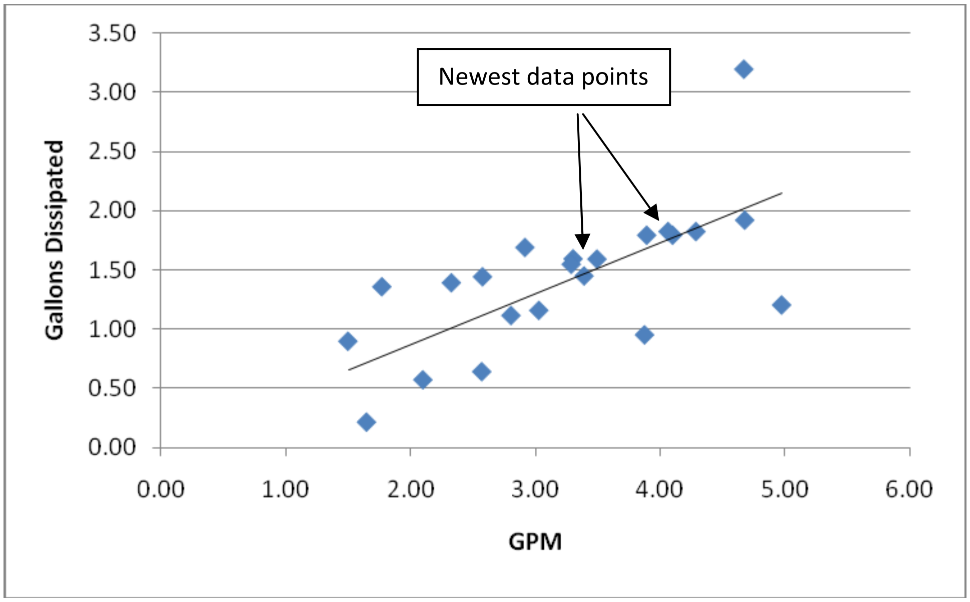

Figure 21 shows the gallons dissipated versus the flow rate from the hot water line. The arrows point to the newest data points and appear to correlate very well with a linear trend.

8.3 Water Hammer

A major obstacle in this project has been the ability to overcome water hammer. Our data shows that with the current set-up the thermostat is water hammer free only in a small region over the possible working conditions. The upper limit of 3.31 GPM presents a problem since waterlines in the U.S. can have up to 10 GPM of water flow and that of a toilet even after restriction can be at about 6 GPM. The next step in the design process is to determine methods to eliminate water hammer at flow rates of up to 10 GPM to at least get a factor of safety of one with house line inputs. This would require a more in-depth analysis to determine the forces acting on the internal components as to slow the movement of the shut-off plate and prevent water hammer.

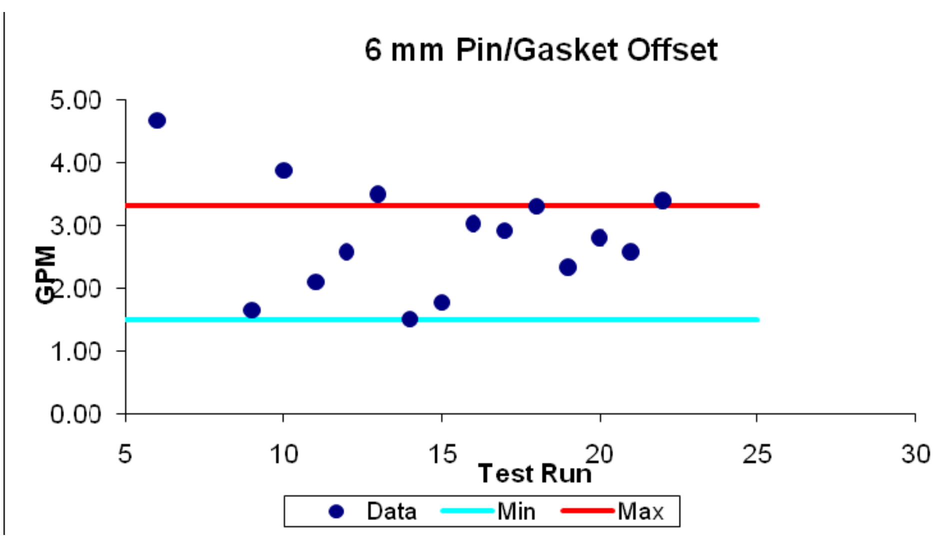

Figure 22 shows the working region of the thermostat at which no water hammer is experienced. The exact limitation found during experimentation was at 3.31 GPM.

9. Analysis

9.1 Thermostat Velocity Flow Field

Solutions to improving the design would be to improve the fluid dynamics of the flow within the thermostat. This would allow for there to be less drag acting on the shut-off plate on the thermostat, which in turn lets the spring counteract only the force of the wax element. Calculations would be simplified, noise reduced and the functionality of the thermostat will become independent of flow speed.

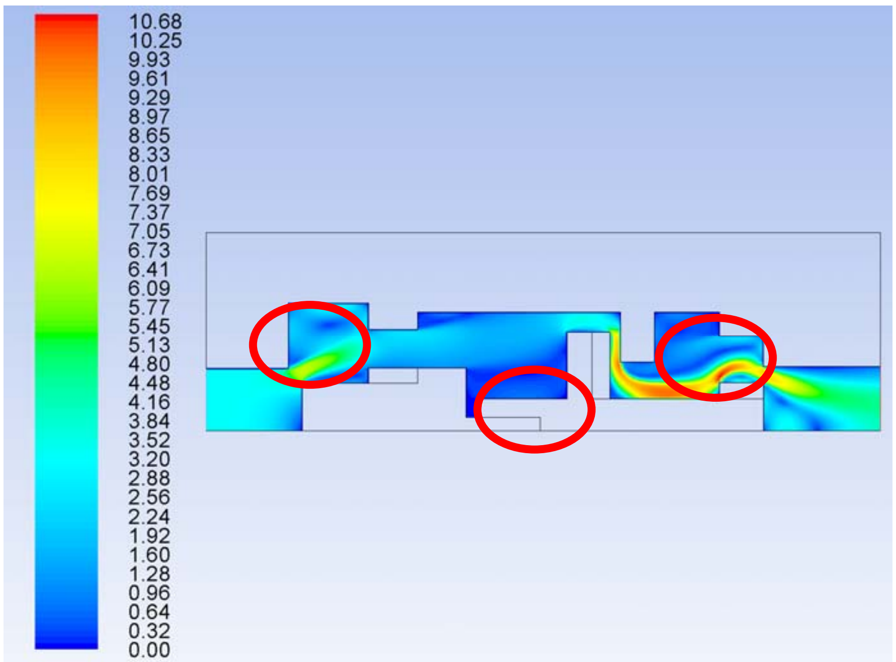

Figure 23 shows a CFD analysis of the velocity flow field with units of m/s at a flow rate of approximately 10 gallons per minute. Circled in red are areas where the design of the thermostat can be improved to prevent dead zones and excessive drag in the flow through the thermostat. Improvements in flow can help prevent water hammer from occurring in during the shutting process of the thermostat. The CFD model has been validating using experimental values in pressure drop.

9.2 Theoretical Valve, Flap, and Thermostat Configurations

After testing our system we realized that the overall effectiveness was influenced by parameters inherent in each customer's home. As a result we created a model that allows us to calculate the respective effectiveness of three configurations. The first configuration is the system that we manufactured ourselves with the assumption of an ideally functioning flap. The ideal case is where the flap allows no cold water to slip through when the hot waterline is activated in the valve body. This analysis will allow us to gauge the effectiveness of perfectly functioning valve body. The second configuration removes the thermostat from the system altogether, allowing us to examine the effect of the thermostat on the overall system. The final configuration includes the thermostat; however the flap has been removed from the valve body. Our early hypothesis was that the flap itself may have been limiting the effectiveness of the system.

The model was developed around the assumption that water flow rate would be equal in both the hot and cold waterlines. Our model takes into account three variables; water pipe diameter, gallons per flush and thermostat waste. During our research we discovered that although the normal water pipe diameter is 0.5 in this is not always the case. Our

model allows us to input any size waterline and analyze the results. The gallons per flush is determined based on the size of the toilet and is normally between 1 and 2 gallons. This value is important because it determines the amount of water that needs to enter the toilet reservoir in-between flushes. Thermostat waste is the amount of hot water that passes through the thermostat before it closes. We will analyze our model with an average thermostat waste value from our current thermostat and we will run the analysis with our future projected thermostat waste value.

Another important aspect of our model is the distance between the shower and the hot water heater. These values have been normalized in our model based on the footage of pipe required to fill half of the toilet reservoir (Equation 2). The theory behind this is that no matter which pipe is filling the reservoir at no point will it be required to fill more than 2 times the normalized value. At this point one line would have sufficient footage to fill the toilet reservoir by itself as 2 multiplied by the footage required to fill half the reservoir equals a full reservoir. For this reason our model only consists of normalized pipe footage values from 0 to 2.

Equation 2

$$\textit{footage of pipe for half flush} = \textit{gallons per flush}\left(\frac{1\ ft^3}{7.48\ gal}\right)(0.25\pi(\textit{pipe diameter}))\left(\frac{1\ ft^2}{144\ in^2}\right)\left(\frac{1}{2}\textit{flush}\right)$$

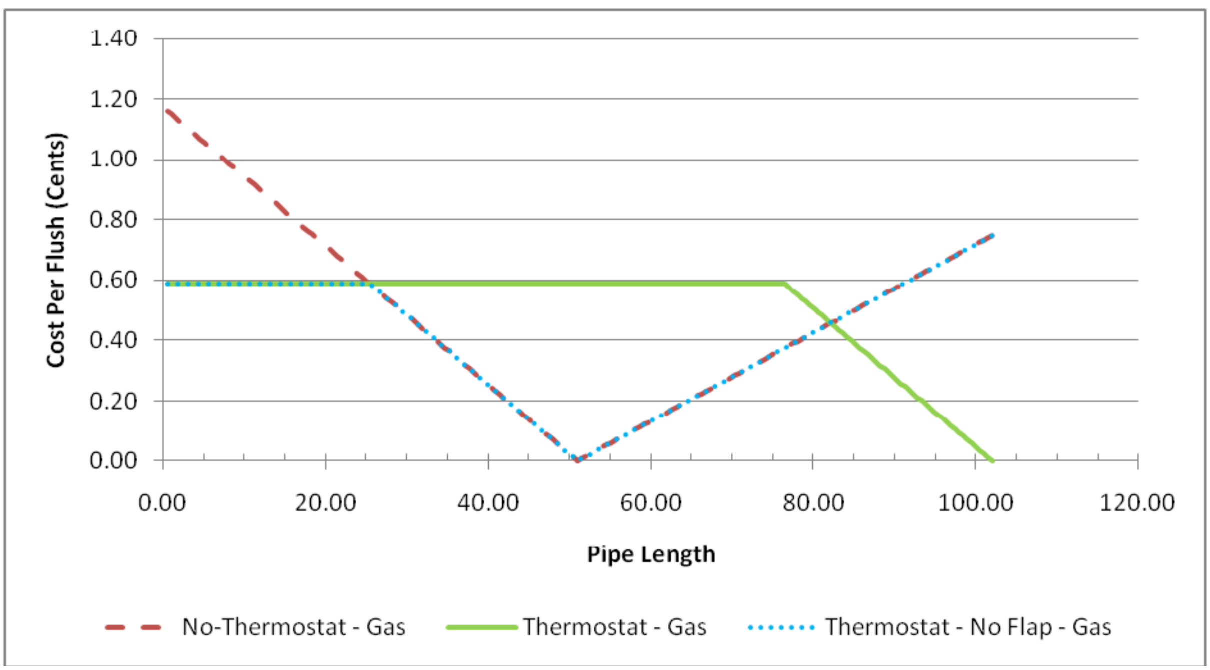

Figure 24 shows the cost per flush for each of the 3 configurations present in the model. The gallons per flush value was held constant at 1.6 gallons for all three cases, pipe diameter is 0.5 in, and the thermostat waste is 0.4 gallons. The thermostat waste value represents the lower end of the thermostat waste values that we found during testing. Cold water cost was developed based on $7.00/unit of water[6] and hot water cost was developed based on 1.47 cents to heat 1 gallon of water.

For this setup of parameters the system bereft of the flap appears to be the most cost effective. The thermostat and flap system only has higher cost effectiveness when there is more than 81 ft between the shower and the water heater. This value correlates to 1.6 gallons of water in the pipe.

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[6]Information taken from http://www.ci.san-luis-obispo.ca.us/utilities/billing.asp

Without a flap in the system, lengths of pipe larger than the footage required for half a flush do not maximize the cold water drawn out of the hot waterline. As a result some water is wasted when the shower is turned on.

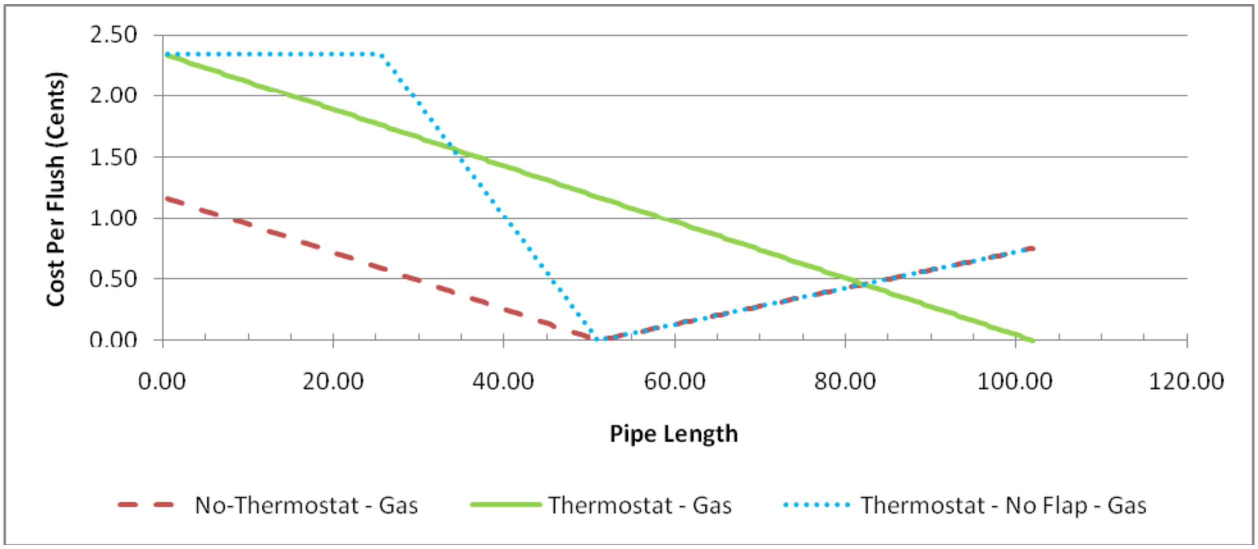


Figure 25 shows another cost per flush analysis with different parameters. In this situation the only difference is that the thermostat waste value has been increased to 1.6 gallons.

A thermostat waste value of 1.6 gallons is extremely high. At this performance the system is not very feasible as seen in Figure 25. However, this graph does illustrate the effect that a higher thermostat waste value has on the system operation.

An important note to consider is that this analysis only pertains to single flush circumstances. We felt that this analysis was important to understand the importance of each piece of the device. In addition, the single flush case is most common. A double flush scenario is defined as a new flush of the toilet before the hot water in line has had time to cool down. This scenario poses multiple new variables and with it a degree of difficulty. Before this analysis can be done an accurate assessment of the temperature change over time in both the thermostat entrance cavity and the hot waterline must be completed. Most likely, this assessment will vary depending on the amount of insulation acting on the pipe, which in turn will vary greatly between houses.

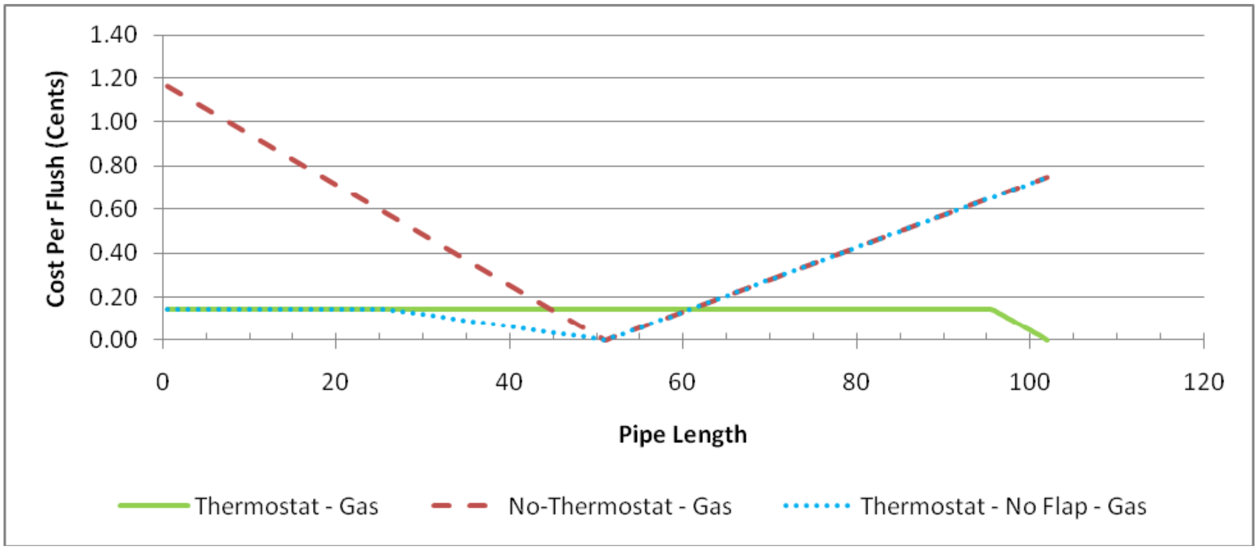


Figure 26 shows the same cost effectiveness analysis however this analysis was completed with thermostat waste value of 0.1 gallons.

Figure 26 illustrates the main finding from our theoretical analysis. The ultimate determining factor in our system's effectiveness is the speed at which the thermostat can react. The faster that we can get the thermostat to react, less and less hot water will be wasted into the toilet reservoir and our device becomes increasingly cost efficient. As we have previously mentioned there is a correlation between a fast acting thermostat and water hammer. Therefore it is important to balance the system's need for a quick response in order to insure that it remains feasible, with the overall safety of our system on the clients piping system.

Table 13 shows the Failure Mode and Effects Analysis[6] (FMEA) analysis developed after the parts were manufactured and tested.

Function	Potential Failure Mode	Effects	S (Severity Rating)[2]	Causes	O (Occurrence Rating)[2]	Current Controls • Prevention • Detection	D (Detection Rating)[7]	RPN (Risk Priority Number)[8]	Recommended Actions
Thermostat Wax Element	Element breaks	Warm H_2O fills up tank reservoir	3	Temperature higher than design rating	3	Can see toilet and hear the tank fill up faster because H_2O comes from both lines	4	36	Install thermometer in tank, alert owner
	Abrasion causes deterioration	H_2O leaks from the thermostat, loss in H_2O pressure	2	Self-lubricating design is not sufficient	4	Visually see toilet fill up slower. See parts of thermostat in the toilet when it is flushed	3	24	Change of material may be needed
	Dirt/Random particles introduced into system	Wax element seal does not close completely	3	Work done on pipeline, corrosion in pipeline	4	Can see toilet and hear the tank fill up faster because H_2O comes from both lines. Hot water will enter the tank	4	48	Redesign the first plate in the thermostat with smaller holes to create a filter effect.
Thermostat Spring	Spring breaks	Wax element remains closed	2	Reached fatigue limit, corrosion	2	Purchase corrosion resistant springs. Cold H_2O	1	4	
Valve Flap	Flap sticks in the open position	Excess cold H_2O from the hot H_2O line is not used to fill tank	2	Fatigue from the flap opening/closing continuously, Dirt/Random particles introduced	2	Cold H_2O might come out of shower when it is first turned on because the hot water line would not be completely emptied	3	12	Install thermometer in tank, alert owner
	Flap sticks in the closed position	H_2O from the hot line is only used	4	Fatigue from the flap opening/closing continuously, Dirt/Random particles introduced	2	No water fills up the tank. Would not be able to flush toilet multiple times in a row	1	8	Install thermometer in tank, alert owner
	Flap never closes completely	Mixture of cold and hot H_2O	1	Pressure difference is not enough to close it completely, flap design	4	May get some cold water in the shower if not all of the cold H_2O in the hot line is emptied.	5	20	Flap assistant spring, flap redesign, install thermometer in tank to alert owner on tank temp.
	Flap breaks off completely	Gets stuck in the pipe	4	Flap pin fatigue/corrodes	1	No water in the tank	1	4	

[7] Grading scale 1-5 (1=No influence on the system/Easily detected, 5=Great influence on the system/hard to detect)
[8] RPN = S*O*D

10.Conclusions

10.1 Valve Body Observations

During the experiments both teams experienced problems with properly sealing the two halves of the valve. The two teams agreed that by permanently gluing the valve together and clamping it tight, the little amount of water coming out through the crack of the halves was negligible. The test in which the Munich students used coloring in the cold waterline proved that the valve flap was not completely closed, resulting in a mixture between water from both the cold and hot waterlines. A screenshot showing this test can be seen in Figure 27.

Figure 27 shows the injected dye testing that the MUC students performed. The screen shot shows that the valve is not fully closing off the flow from the cold water line.

10.2 Wax Element Observations

From the results of the wax element experiments we can deduce that the individual wax element does factor into the closing time of the thermostat. In addition the temperature of the hot water also determines how fast the thermostat will shut. With hotter water the heat can be transferred to the wax element faster making it expand rapidly. If the wax element responds too slowly then there is too much hot water wasted into the toilet reservoir for the system to be practical. The speed at which the thermostat valve closes needs to be balanced against the potential for water hammer. The faster that the thermostat closes risk for water hammer increases. The other contributing factor to water hammer is the flow rate in the pipeline. During the testing of this project we have come to realize that the wax element is a key element. In order to create an efficient device the wax element will need to be manufactured with tight tolerances.

The wax element closing stroke length also factors into the amount of water wasted. The longer the stroke length, the longer it takes for the wax element to affect the system; resulting in more wasted hot water.

10.3 System Conclusion

Overall, the project produced two working prototypes that function properly. The next stage in development of this device is to optimize the designs. At this point it clear that one device will not be able to meet the needs of all consumers. However, with using the analysis provided in the report further optimization can yield a device that will work for the majority of consumers. The following section will address our team’s suggestions about further optimization.

11. Future Recommendations

11.1 Thermostat

The thermostat prototype component proved that the function and concept works. The original design was for the thermometer to have a 4mm stroke; however, after testing with different stroke lengths it is suggested that the wax element be limited to traveling a stroke length of 1mm. The element proved to be more efficient with a shorter stroke.

The closing velocity of the thermostat wax element is something that needs to be taken into account. This is proportional to the flow rate; meaning, with high flow rates the thermostat is going to start to experience intense water hammer that will most likely be detrimental to the thermostat element and waterlines, over time. The Cal Poly students experienced water hammer at flow rates above 3.31 gpm. In order for the device to improve the water hammer must be resolved. Based on the velocity contours that can be seen Figure 23 the internal shape of the thermostat can be optimized. In order to prevent water hammer the pressure acting on the shut-off plate must be decreased. Optimizing the flow of water through the thermostat is the first step in changing the water hammer threshold. Once this is accomplished then the wax element and spring must be optimized to give a rapid reaction to hot water, yet does not provide an excessive pressure gradient forcing water hammer.

Another approach to the violent water hammer situation is to change the shape of the shutting element. By having a cone-shaped shutting element, instead of the current flat broad-shape, might be able to offset higher tank refill rates (higher flow rates) and minimize the amount of water hammer. This is a design method that would need to be tested and proven.

If heat loss starts to become an issue, the thermostat material (brass) might need to be addressed. Brass is a very thermally conductive material that, in some extreme cases, might pose a problem of conducting too much heat and causing the wax element to trigger incorrectly. The possible problems include the brass drawing too much heat away from the thermostat wax not allowing it to operate. The second potential problem lies in the brass retaining heat for too long and not allowing the thermostat valve to open when the water in the line has cooled again. Neither of these issues developed during the testing phase; however they are points of concern for a prolonged testing cycle.

11.2 Valve

Overall, the valve initial design demonstrated its ability to control what pipe is sending water to the toilet reservoir. The key issue regarding the valve is making sure that the internal flap is completely shut and not allowing water from the cold waterline to escape when it is not supposed to. The Cal Poly Team ran a few tests on different valve coverings, and due to time restrictions and money it was decided that a flat flap with a spoiler would be sufficient enough to prove that the valve would serve its purpose.

After a couple of full system tests it was seen that the flat spoiler flap was allowing cold water to escape while it was 'closed'. Some design approaches were discussed amongst the Munich Team and had there been more time with the project, the flap needed to be redesigned. It was noted that despite helping keep the flap down, the spoiler might be counterproductive as it created an area of lower pressure behind it. Perhaps having a flap that possess a spoiler that extends past the cold water entrance might achieve complete closure; or maybe, eliminate the spoiler on the flap and design it so that the flap is closing at an angle into the flow, rather than parallel with flow. A second solution would be to include a torsional spring to aid the flap in shutting, but this would add more parts that would complicate assembly during production and be another source of failure. A final and more thorough solution would be to install a reed valve in place of the flap, which would provide a constant amount of force to keep the cold line closed when not needed, but weak enough to open when the thermostat shuts the hot waterline. Nevertheless, the valve prototype design also proved that

its function and concept works well. Another aspect of the valve that can be optimized is the flow restriction of the cold waterline. By increasing the proportion of hot line to cold line flow the amount of cold water pulled out of the hot water line will also increase. Adding new flow restrictions to the valve will require the cost analysis to be redone. The model projecting the cost per flush was developed assuming an equal flow rate between the hot and cold waterlines. Changing the proportion between these flow rates will change the way in which the toilet reservoir is filled.

The last considerable option is to eliminate the flap completely. The analysis conducted at Cal Poly discovered that with less effective thermostats, it is more efficient to have a flap-less valve as opposed to a fully functioning flap. When a thermostat is inefficient and allows hot water to pass by before closing off water flow, money and energy is wasted by filling the toilet with warm water where it is not needed. It was found that if a home-owner had less than 53 feet of 1/2 inch pipe between the water boiler and shower that it was more effective to have no flap in the valve body at any level of thermostat efficiency. Since most homes have approximately that amount or less of piping, it is the recommendation of the Cal Poly team that a flap-less design is used. Further analysis should be conducted for other in home scenarios such as larger diameter pipe.

The ultimate goal of the water conservation project is to be able to manufacture a device that contains both the thermostat component and the valve component as one single component.

11.3 System Integration

Another area for improvement to consider is to integrate both the thermostat and the valve body into one piece. This would simplify the system and make the installation process easier. Conversely, this would also make the manufacturing process more difficult. In order to do this the body of the device would have to be made with slots allowing for the insertion of the thermostat internal components. An alternative option would be to make the bore holes large enough to allow for the insertion of the internal components and then holding pieces can be screwed into the system body to lock the pieces into place.

Figure 28 shows the internal components of the thermostat. Starting from the left side of the picture the components are, wax element retention plate, wax element, stopper plate, and spring.

The most feasible idea for system integration at this point would be to place the thermostat inside the valve body. This would eliminate the outer shell of the thermostat and would require only the internal pieces to be manufactured. By

placing the thermostat closer to the junction point between the hot and cold lines an important aspect would be the flow around the thermostat pieces. As previously mentioned this flow would need to be optimized to make sure it did not have any adverse effects on the junction. Things in particular to look for would be eddies, areas of dead flow and excessive drag.

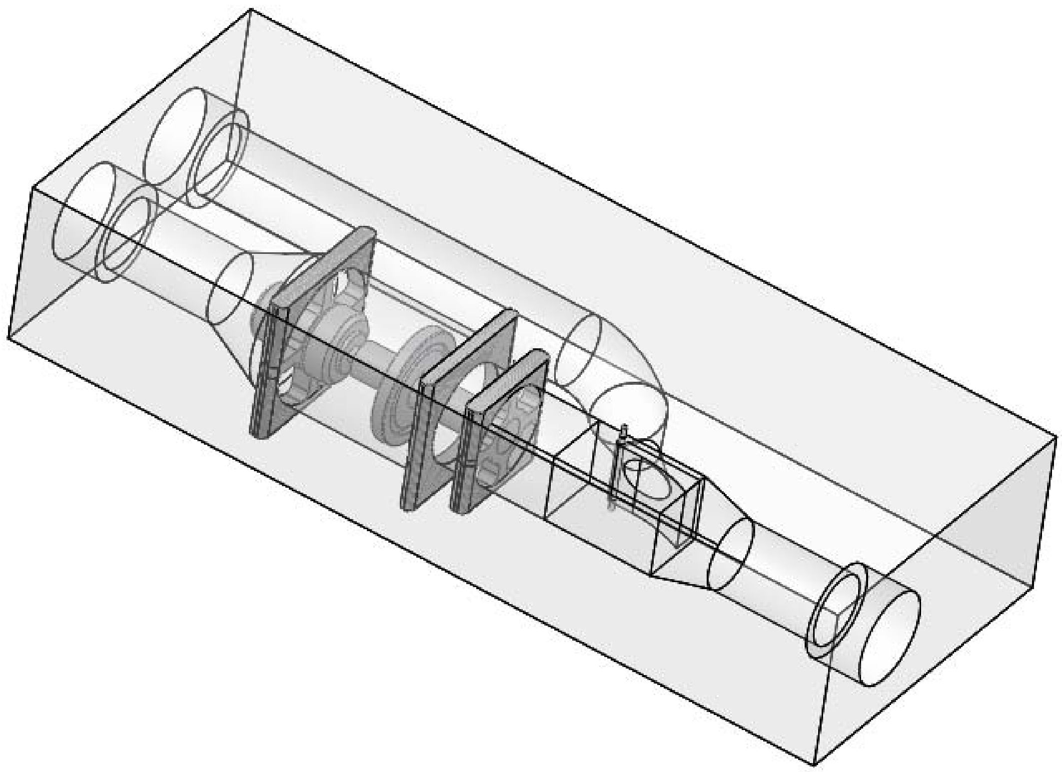


Figure 29 shows a drawing of a possible integrated system placing the thermostat in-line with the hot water line of the original valve body.

Appendix

I. Appendix A – Requirement List

Table 14 shows the requirement list developed in the initial brainstorming stage.

Abbreviations: R: requirement W: wish

N: no requirement P: possible

No.		requirement	Require-ment type	numerical values (incl. tolerance) and data		
			(R,W,N,P)	min	max	Dimension unit
1	**Geometry**	required space	R		0.039	m^3
2		expansion / re-fitting	W			
3	**Kinematics**	transaction type (valves: ball valve)	N			
4	**Forces**	weight	N			
5	**Energy**	power	W	0		Watt
6		necessary water temperature	R	40		°C
7		storage	P	7	10	liter
8		electrical power supply of the system (**no**)	W			
9		pressure in the pipes (working pressure)	P	3.5	7	bar
10	**Material**	used material	N			
11	**Signal**	Indicator for operating state (stand by)	N			
12		visual signal	N			
13	**Security**	using a protection system (e.g. temperature sensor to avoid scalding)	N			
14	**Ergonomics**	new / different operating agents for user	W			
15	**Production**	fabrication method (e.g. milling, ...)	N			
16		manufacturing equipment, machinery	N			
17		quality and tolerances	R			
18	**Control**	special regulations (buildings, USA - GER)	R			
19		backflow	R		0	
20	**Assembly**	fitting (by installer)	R			
21		inner wall fastening	P			
22		outer wall fastening	P			
23		accessibility	R			
24	**Application**	noise level	R			
25		humid conditions	R			
26	**Maintenance**	number of services	R	0	0	
27		options for change of similar assemblies	P			
28	**Costs**	acceptable (allowed) fabrication costs	R		15	$
29		running costs	W		18	$
30	**time-limit**	termination of engineering	W			
31		assembly time	R		24	hours
32		production time / time of delivery	no specif.			
33	**Recycling**	recycling	N			

II. Appendix B - Description of Compliance Abbreviations

	Similarity to Existing Designs	S
* based on preliminary analysis and 10 year life span	Analysis	A
	Test	T
Installation refers to placing into a new home	Inspection	I
Replacing includes retrofitting older homes		

Figure 30 provides a description of abbreviations from Table 1 on page 9.

III. Appendix C – Engineering Requirements

Table 15 portrays the Quality Function Deployment correlating engineering requirements to the customer's requirements.

Customer Requirements	#	Water Accumulation Gadget	Weight (out of 100)	Must Reach Hot Temperature	Size	Weight	Cost	Water Flow	No Energy	Time to Reach 90% of Hot Temperature	No Backflow	Time to Install	Steps to Replace	Corrosion	Chili Pepper	Heating Coils	Irrigation	Recirculation
	1	**Automatic**	13	9			3			9					1	5	3	5
	2	**Supply Hot Water**	15	9				3		3					4	4	4	4
	3	**Little Maintenance**	11											9	3	3	2	4
	4	**Cost Efficient**	6		3		9		3	1		1			3	1	2	1
	5	**No Energy Usage**	6	1				3	9		1				1	1	3	1
	6	**Supply Water Quickly**	13	9				9	1	9					1	3	1	4
	7	**Easy to Install**	5		3	3	1					9	9		3	1	1	1
	8	**Follow Code**	10		1			3			9			3	1	4	4	4
	9	**Small**	13		9	1	1					1			4	3	2	4
	10	**Interchangable**	8		3							3	3		3	1	3	3

		Must Reach Hot Temperature	Size	Weight	Cost	Water Flow	No Energy	Time to Reach 90% of Hot Temperature	No Backflow	Time to Install	Steps to Replace	Corrosion
Units		°C	m^3	kg	$	Pa	J	min	-	hour	hour	
Targets		awaiting response of sponsor for final values										
Benchmark #1		research is still underway for final specificiations										
Benchmark #2												
Benchmark #3												
Benchmark #4												

Table 16 continues the Quality Function Deployment.

	Must Reach Hot Temperature	Size	Weight	Cost	Water Flow	No Energy	Time for System to Work	No Backflow	Steps to Install	Steps to Replace	Corrosion
Must Reach Hot Temperature					3	1	9				
Size				1					3	3	
Weight				1					3	3	
Cost		1	1		1	9	9		3	3	
Water Flow	3			1			3	9			
No Energy	1			9							
Time for System to Work	9										
No Backflow											
Steps to Install		3	3	3						1	
Steps to Replace		3	3	3					1		1
Corrosion										1	

IV. Appendix D – Brainstorming

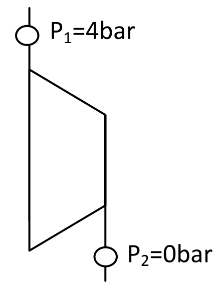
Table 17 provides brainstorming ideas for various uses of the extracted cold water.

	Fitting for project	Need additional energy	Required space	Costs
Conserve	+	+	-	o
Cold Shower	-			
Watering the garden	+	+	+	+
Toilet flush	+	+	+	o
To drink	-			
Raise the potential energy	+	o	-	-
Heat	+	-	-	-
Make steam	-			
Make ice	+	-	o	-
Aquarium, pool, mini lake	+	+	+	+
Car wash	o			
Wash the hands or feet	-			
Give it to the pets for drinking	-			
Wash pets	-			
Actuator, e.g. water wheel	-			
Climatic of a room	o	-	-	-
To cool something	+	+	-	o
Cooking	-			
Washing machine	+	+	+	+

The result of the Brainstorming is that the ideas best fitting to the project and not using additional energy are these, in which the water is separated from the primary water pipe.

V. Appendix E – Turbine Generator Calculations

Generator:



$E_{12} = V * \Delta p_{12}$

$E_{12} = V(p_2 - p_1)$

$E_{12} = 8 * 10^{-3} m^3 * (0 - 4) 10^5 \frac{N}{m^2}$

$E_{12} = -3200J = -3{,}2kJ$

$E_{12} = -8{,}89 * 10^{-7} kWh$

$J = Ws = 10^{-3} kWs * \frac{h}{3600s}$

$J = \frac{1}{3{,}6} * 10^{-6} kWh$

Shower per year:

USA: $1{,}5 \times 2{,}6 \times 365 = 1423{,}5$

GER: $\frac{300}{365} \times 2{,}1 \times 365 = 630$

Energy:

USA: $1423{,}5 \times 8{,}89 \times 10^{-7}$ kWh = 1,265Wh

GER: $630 \times 8{,}89 \times 10^{-7} kWh = 0{,}56Wh$

Saved money:

USA: $2 \times 10^{-4} \frac{€}{year}$

GER: $0{,}2 \times 0{,}56 \times 10^{-3} \frac{€}{year}$

Price[8]: $Price = 9{,}5cent$

Valve:

Power for one valve: P=15VA[6]

Working time: t=80sec[7]

Energy for one shower:

$E = P \times t = 15VA \times 80sec = 1200J$

For 1423 showers/a:

$E_{total} = 1708kJ = 0{,}4745kWh$

[6] Origin: Firma Burkhardt

[7] Self made test

[8] 20cent/kWh

VI. Appendix F – Evaluation of Concepts

Building costs: This criterion was given a weight of 3 given its importance to the project. In order for the concept to be feasible it needs to remain relatively inexpensive so that the economic cost does not outweigh the economic and environmental savings created by the water conservation. In this scenario the hydraulic system and cylindrical valve system scored the highest. Using common valves and controllers allow these concepts to remain relatively inexpensive. The electrical system contains either electro-magnetic valves which are very expensive, approximately $45-60 a piece, or require thermocouples and micro-controllers which are also expensive.

Running cost: This criterion was given a weight of 2. Only the electrical concept did not receive the highest score of 4 because it is the only concept that would require additional electricity in order to run. We did consider a concept that used a turbine to create energy from the water flow through the pipes and thus providing power for the conservation system. Preliminary analysis showed that we would not be able to develop enough power to run the electrical system so the idea was not accepted.

Assembling: This criterion was given a weight of 1 because we felt that this factor should not be one of the driving aspects of our design. Our manual hydraulic system scored the highest because of its relatively simple nature, followed by the electrical system in which the difficulty would lie in initial calibration. The automatic hydraulic system would require a multitude of valves and piping, and calibration would also be fairly difficult.

Handling: This criterion received a weight of 2. The only concept that did not receive the highest score was the manual hydraulic system. This system does require user interaction to release the hot water flow once the cold water has been extracted. Additional inquiries will determine how desired this feature would be to customers.

Working time: This criterion also received a high score of 3 because it is an integral aspect of this project. The electrical system received the highest score largely due to the speed in which the valves would be able to operate. Coming in second with a score of 3 was the manual hydraulic concept because its simpler nature allowed for a quick response. The automated hydraulic concept was deemed slow relative to other concepts.

Safety: This criterion received a weight of 2. Our team decided that generally the more basic the design the more reliable it would tend to be. Thus the automated hydraulic design received the lowest score due to its complex nature. The electrical and cylindrical valve concepts scored 3 because they present only a few means of failure. The manual hydraulic concept received the highest score due to its simple and robust nature.

Risk factor: This criterion received a weight of 3 as it is very important to the project. The electrical and automatic hydraulic systems both received a score of 1 due to the automated systems complexity and our unfamiliarity with some of the components in the electrical system. The highest score was given to the manual hydraulic because members of our team have experience with basic hydraulics and we have created a simple concept.

Patent uniqueness: This criterion received a weight of 2. Our team decided that this was an important factor; however we did not want it to be a determining factor in the weighted system. The automatic hydraulic system and the electrical system received high scores of 4 because we have not found many patents resembling these systems. The cylindrical valve system received a 1 because it was very similar to already existing patents and the manual hydraulic system shared similar components to patents, however still offered some unique aspects.

VII. Appendix G – Concept Sketches

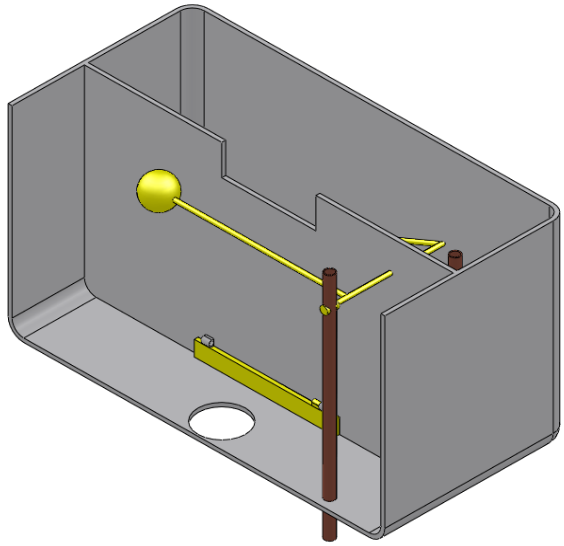


Figure 31. Custom reservoir concept with an auxiliary tank in the back for collecting shower water

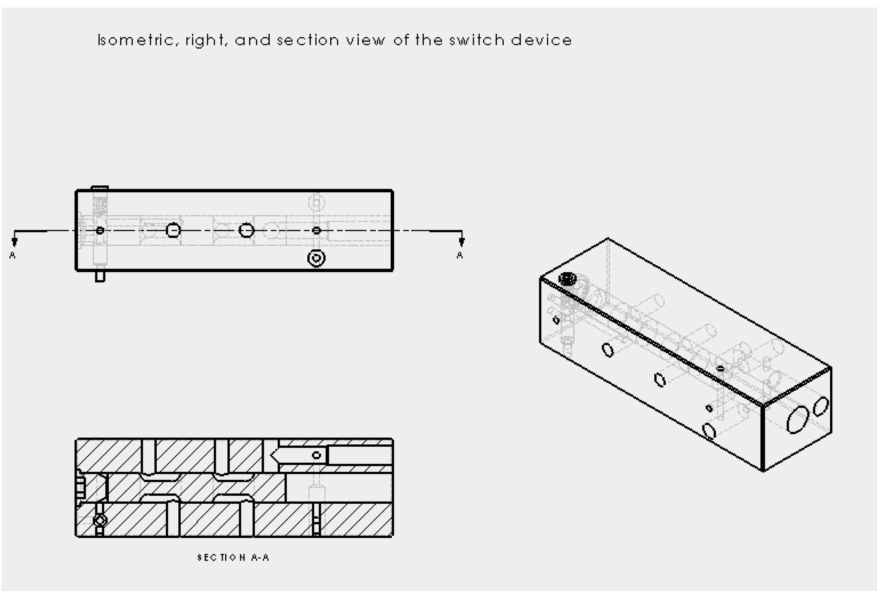


Figure 32 shows the hydraulic switch concept with multiple views.

VIII. Appendix H – Maximum Pressure Loss Calculations

Assumption	all pressures are in comparison to the environment
	lines are ideal
	shower is located higher than water inflow
	all lines are 0.5inch in diameter

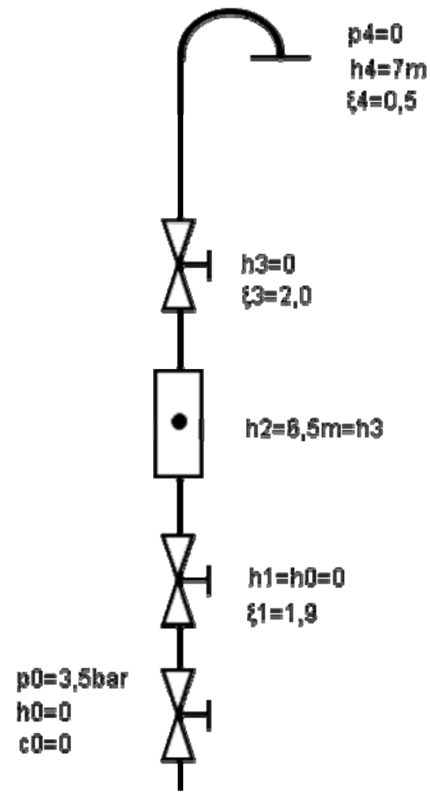


Figure 33 illustrates a flow schematic for a shower and valve system

Bernoulli from 0 --> 4

$$p_0 + h_0 \cdot g \cdot \rho + \frac{\rho}{2} \cdot c_0^{\ 2} = p_4 + h_4 \cdot g \cdot \rho + \frac{\rho}{2} \cdot c_4^{\ 2} + p_v$$

$$\dot{m} = \rho \cdot \dot{V} = \rho \cdot c \cdot A$$

$$c_1 = c_2 = c_3 = c_4 = \frac{\dot{V}}{A}$$

$$p_v = c^2 \cdot \frac{\rho}{2} \cdot (\zeta_1 + \zeta_2 + \zeta_3 + \zeta_4)$$

$$\zeta_{2zul} = \frac{p_v \cdot 2}{c^2 \cdot \rho} - (\zeta_1 + \zeta_2 + \zeta_3)$$

V=	2.5	GPM
r=	0.00635	m
A=	0.00012668	m²
c4=	1.24496551	m/s
p0=	350000	Pa
h4=	7	m
g=	9.81	m/s²
ρ=	1000	kg/m³
pv=	280555	Pa
ξ1=	1.9	
ξ3=	2	
ξ4=	0.5	
ξ2zul=	357.620712	

IX. Appendix I - Cost analysis to determine return of investment time for original device.

To heat 1 g of H2O 1 degree C

$h = 4.18$ [J]

$v_{us} = 1.6$ [Gal]

Reservoir Volume in cc

$v_m = v_{us} \cdot 3.78 \cdot 1000$

$T = 40$ [C]

Total Heat Needed [J]

$Heat = T \cdot v_m \cdot h$

$Heat_{total} = Heat \cdot 3$

Total Heat in Therm per day

$$Heat_{therm} = \frac{Heat_{total}}{1.05506 \times 10^{8}}$$

For gas Heater with 0.6 efficiency

$$Heat_{gasyear} = Heat_{therm} \cdot \frac{365}{0.6}$$

Cost per year using gas

$Cost_{gas} = Heat_{gasyear} \cdot 1.47$

Water Savings

$W_{saved} = 1.6 \cdot 365$

$$Cost_{water} = 7 \cdot \frac{W_{saved}}{748}$$

For Electric Heater with 0.9 efficiency

$Heat_{electricyear} = Heat_{total} \cdot 365 \cdot 2.777778 \times 10^{-7}$

$Cost_{electric} = 36.91$	$Cost_{gas} = 25.71$	$Cost_{water} = 5.465$	$h = 4.18$ [J]	$Heat = 1.011E+06$
$Heat_{electricyear} = 307.6$	$Heat_{gasyear} = 17.49$	$Heat_{therm} = 0.02875$	$Heat_{total} = 3.034E+06$	$T = 40$ [C]
$v_m = 6048$	$v_{us} = 1.6$ [Gal]	$W_{saved} = 584$		

X. Appendix J - Simulink Model of System

The following model was developed in order to test potential failure points in the devices operating range. For example, what would theoretically happen if someone opened the shower faucet while the toilet was flushing? These were failure modes that we tried to analyze before constructing the system in order to gain insight into potential fixes. The model allows for different line pressures to be set in the hot and cold waterlines in case of discrepancy in the lines.

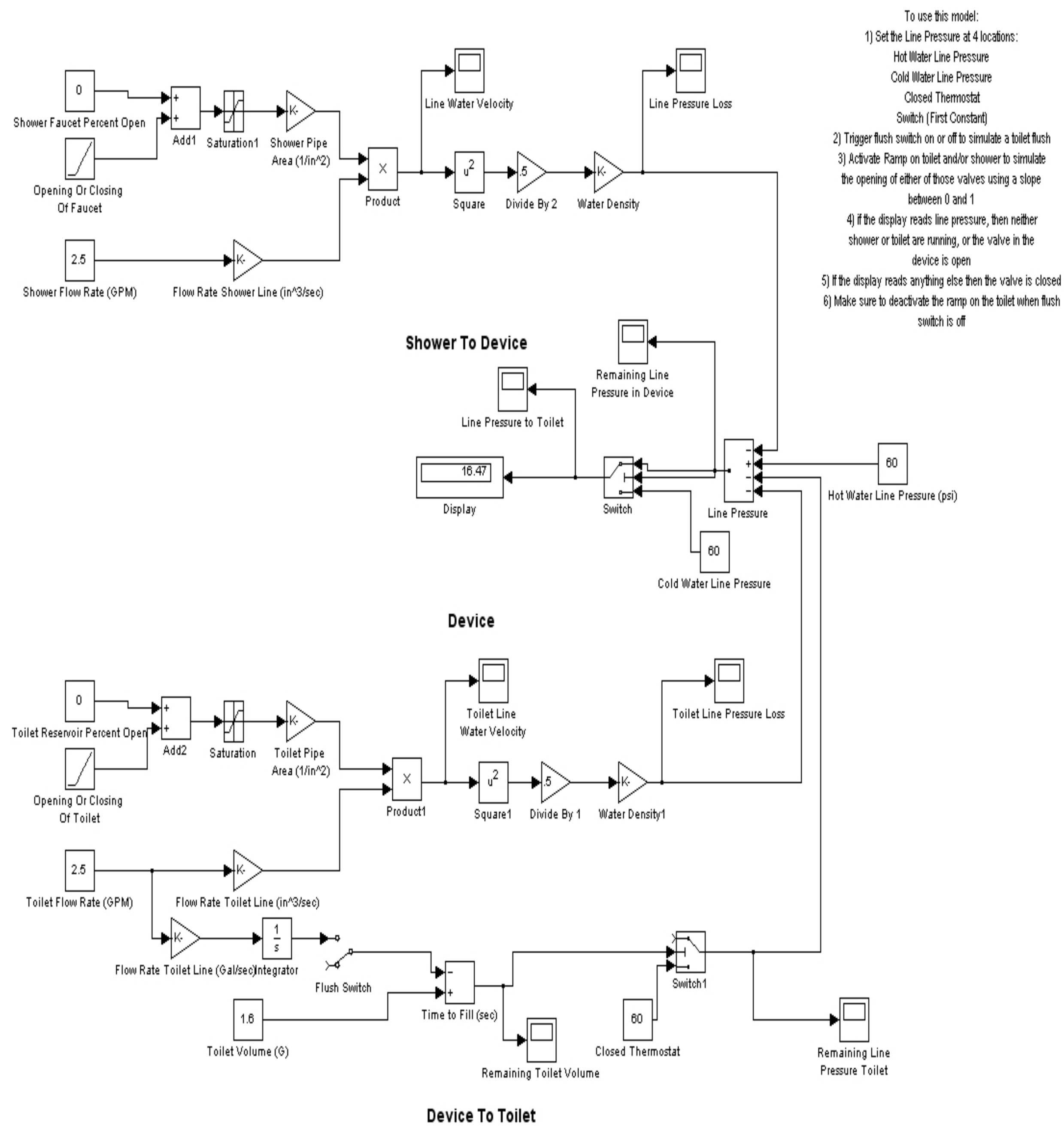
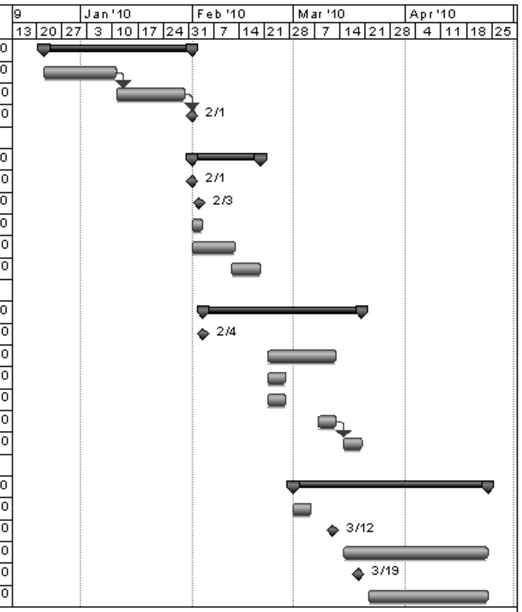


Figure 34 shows the Simulink flow model developed in order to test a variety of situations. The model shows the pressure level at various points of interest in the system.

XI. Appendix K - Proposed Manufacturing Plan

ID		Task Name	Duration	Start	Finish
1		Design	29 days?	Tue 12/22/09	Mon 2/1/10
2		Generate New Design	14 days?	Tue 12/22/09	Sun 1/10/10
3		Finalize New Design	15 days?	Mon 1/11/10	Fri 1/29/10
4		Final Design Report	0 days	Mon 2/1/10	Mon 2/1/10
5					
6		Test Rig	15 days?	Mon 2/1/10	Fri 2/19/10
7		Consultant Meeting with CM	0 days	Mon 2/1/10	Mon 2/1/10
8		Meeting with Eric for space alotment in Bonderson	0 days	Wed 2/3/10	Wed 2/3/10
9		Test Rig Design	3 days?	Mon 2/1/10	Wed 2/3/10
10		Material Procurement	10 days?	Mon 2/1/10	Fri 2/12/10
11		Test Rig Construction	6 days?	Fri 2/12/10	Fri 2/19/10
12					
13		Prototype	32 days?	Thu 2/4/10	Fri 3/19/10
14		Meeting with Chem Dept. on Acrylic Wax	0 days	Thu 2/4/10	Thu 2/4/10
15		Potential Fabrication of a Thermostat	15 days?	Mon 2/22/10	Fri 3/12/10
16		Fabrication of an Acrylic Prototype Version 1	5 days?	Mon 2/22/10	Fri 2/26/10
17		Fabrication of an Acrylic Prototype Version 2	5 days?	Mon 2/22/10	Fri 2/26/10
18		Fabrication of a Copper Prototype	5 days?	Mon 3/8/10	Fri 3/12/10
19		Fabrication of a PVC Prototype	5 days?	Mon 3/15/10	Fri 3/19/10
20					
21		Testing	40 days?	Mon 3/1/10	Fri 4/23/10
22		Test Acrylic Prototype Version 1 and 2	5 days?	Mon 3/1/10	Fri 3/5/10
23		Install Copper Prototype to determine install time	0 days	Fri 3/12/10	Fri 3/12/10
24		Test Copper Prototype	30 days?	Mon 3/15/10	Fri 4/23/10
25		Install PVC Prototype	0 days	Fri 3/19/10	Fri 3/19/10
26		Test PVC Prototype	25 days?	Mon 3/22/10	Fri 4/23/10



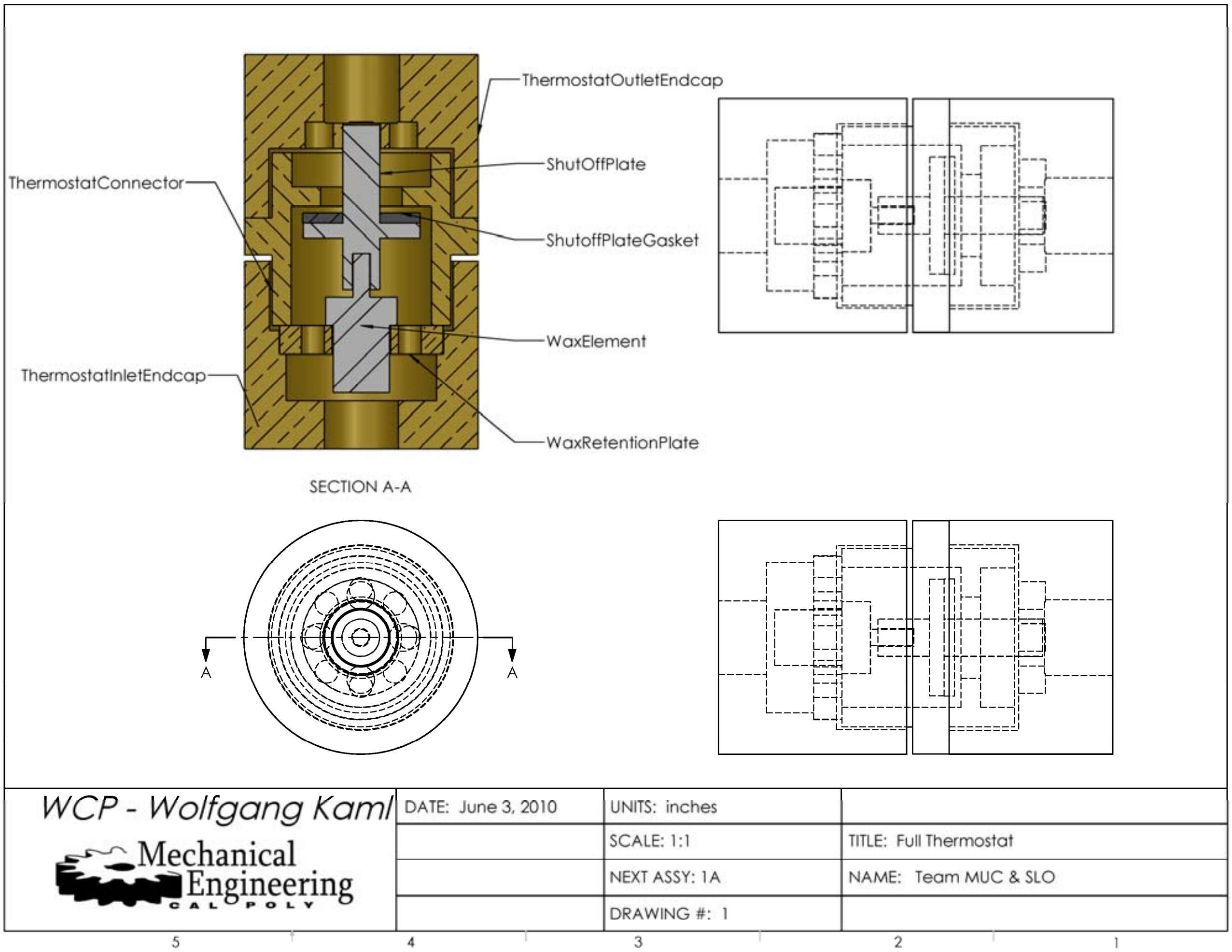
Project: Fabrication Plan
Date: Thu 6/3/10

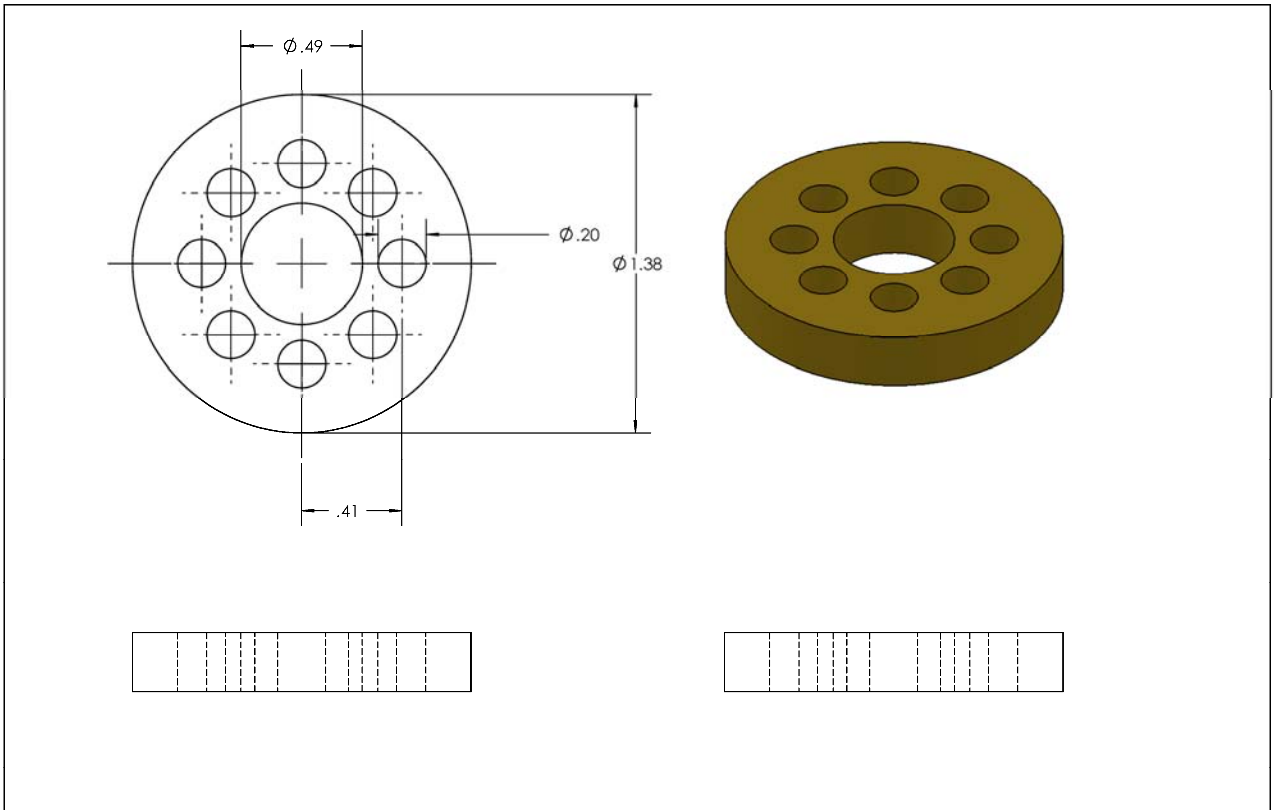
Task		Milestone	◆	External Tasks	
Split	....	Summary		External Milestone	◇
Progress		Project Summary		Deadline	⇩

Page 1

Figure 35 illustrates the proposed manufacturing timeline created during the design stage.

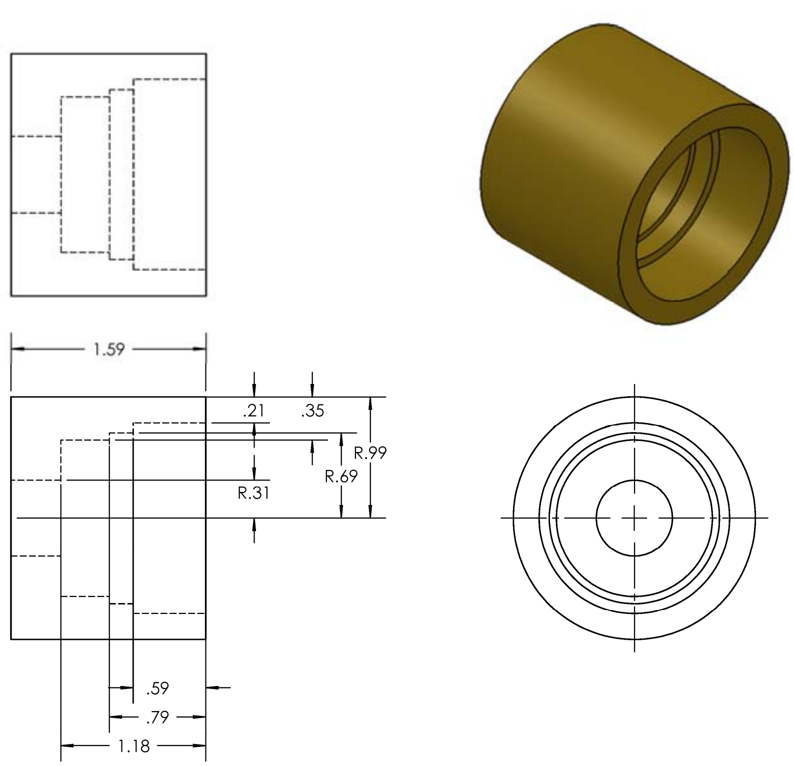
XII. Appendix L - CAD Drawings





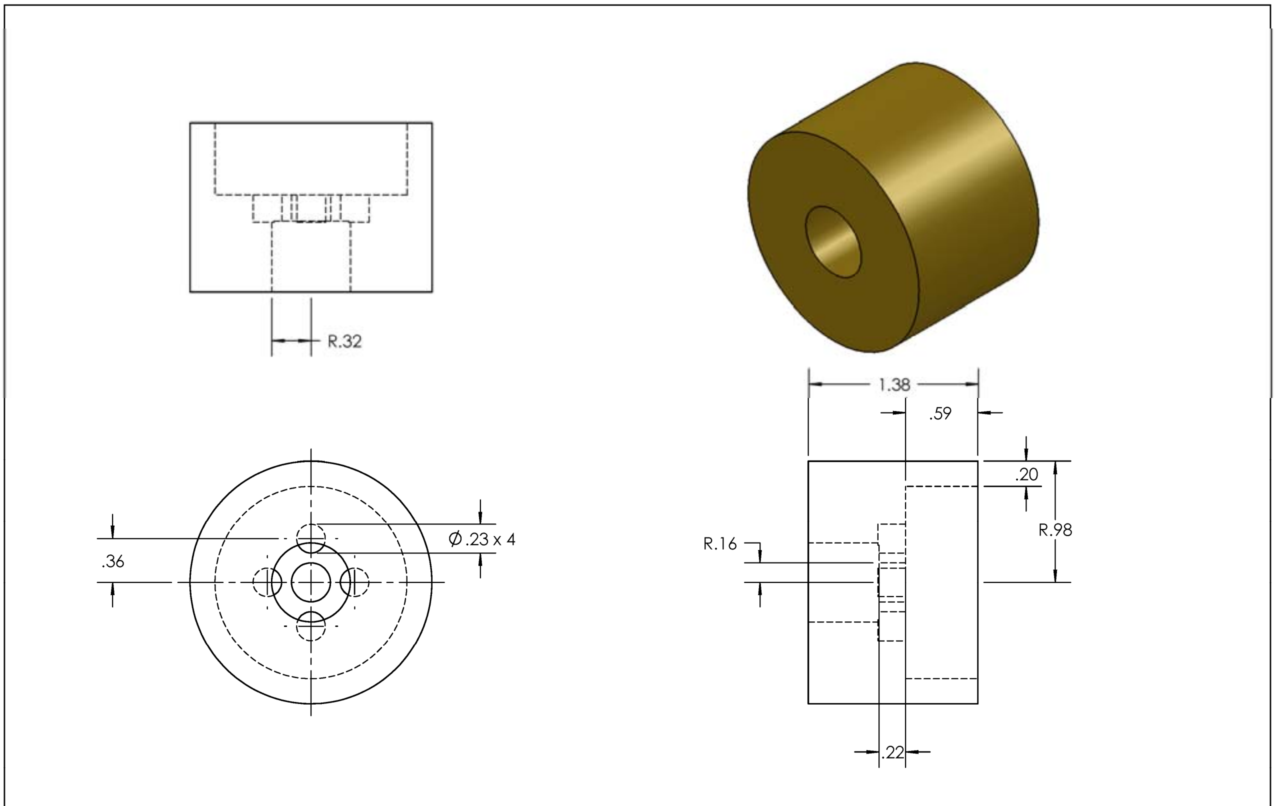
WCP - Wolfgang Kaml	DATE: June 3, 2010	UNITS: inches	MATERIAL: Brass
Mechanical Engineering CAL POLY	TOLERANCE: ±0.005	SCALE: 2:1	TITLE: Wax Retention Plate
		NEXT ASSY: 1B	NAME: Team MUC & SLO
		DRAWING #: 1A	

5 4 3 2 1

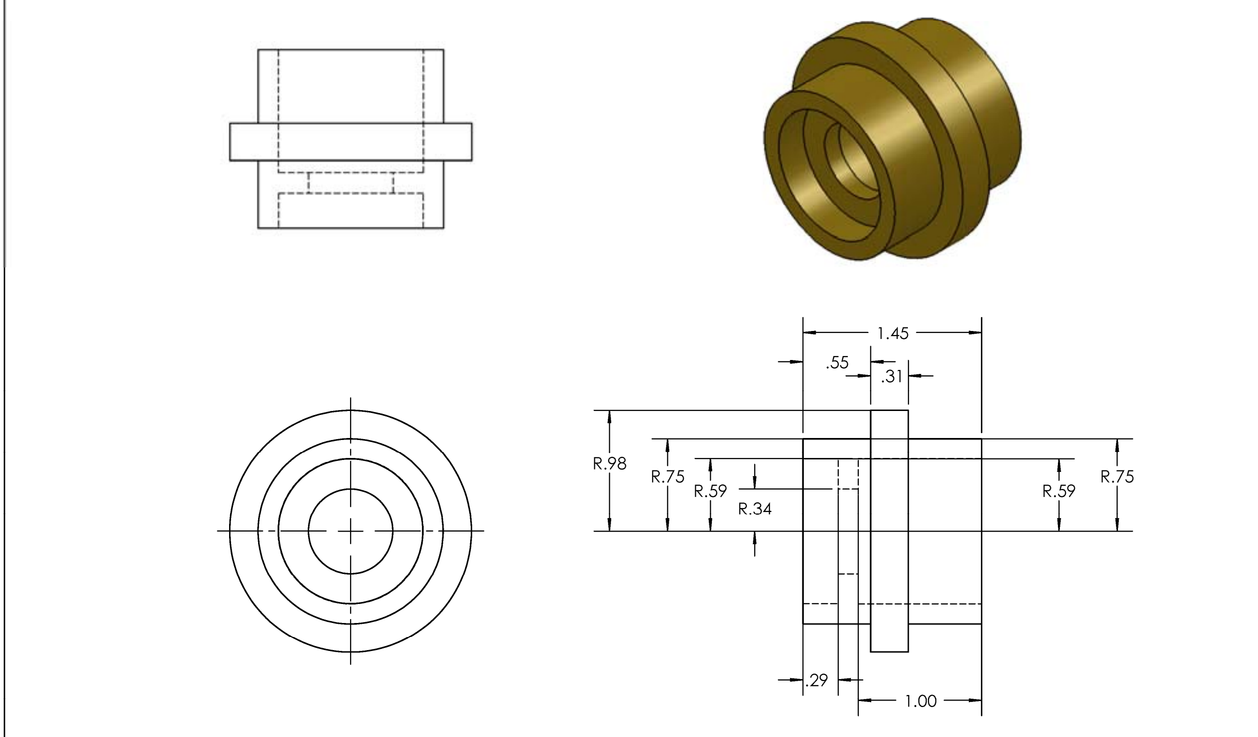


WCP - Wolfgang Kaml	DATE: June 3, 2010	UNITS: inches	MATERIAL: Brass
Mechanical Engineering CAL POLY	TOLERANCE: ±0.005	SCALE: 1:1	TITLE: Thermostat Inlet Endcap
		NEXT ASSY: 1C	NAME: Team MUC & SLO
		DRAWING #: 1B	

5 4 3 2 1

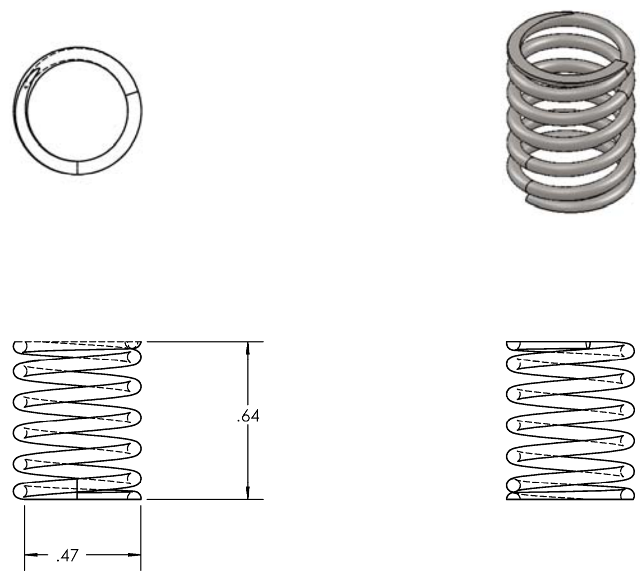


WCP - Wolfgang Kaml	DATE: June 3, 2010	UNITS: inches	MATERIAL: Brass
Mechanical Engineering CAL POLY	TOLERANCE: ±0.005	SCALE: 1:1	TITLE: Thermostat Outlet Endcap
		NEXT ASSY: 1D	NAME: Team MUC & SLO
		DRAWING #: 1C	



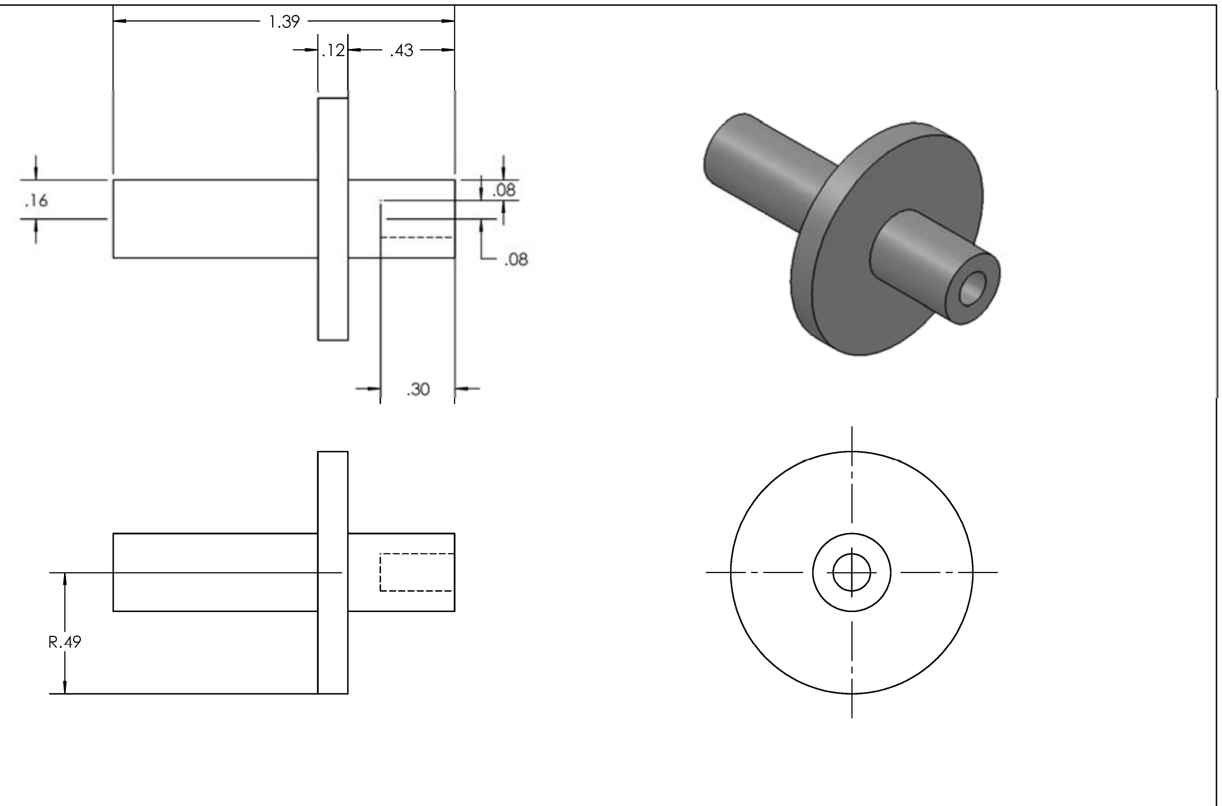
WCP - Wolfgang Kaml	DATE: June 3, 2010	UNITS: inches	MATERIAL: Brass
Mechanical Engineering CAL POLY	TOLERANCE: ±0.005	SCALE: 1:1	TITLE: Thermostat Connector
		NEXT ASSY: 1E	NAME: Team MUC & SLO
		DRAWING #: 1D	

5 4 3 2 1

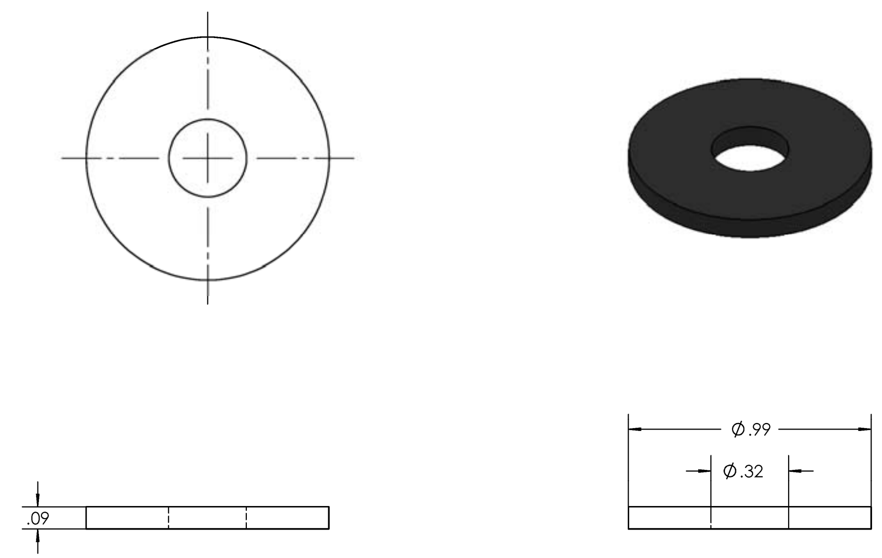


WCP - Wolfgang Kaml	DATE: June 3, 2010	UNITS: Inches	MATERIAL: Steel
Mechanical Engineering CAL POLY		SCALE: 2:1	TITLE: Spring
		NEXT ASSY: 1F	NAME: Team MUC & SLO
		DRAWING #: 1E	

5 4 3 2 1

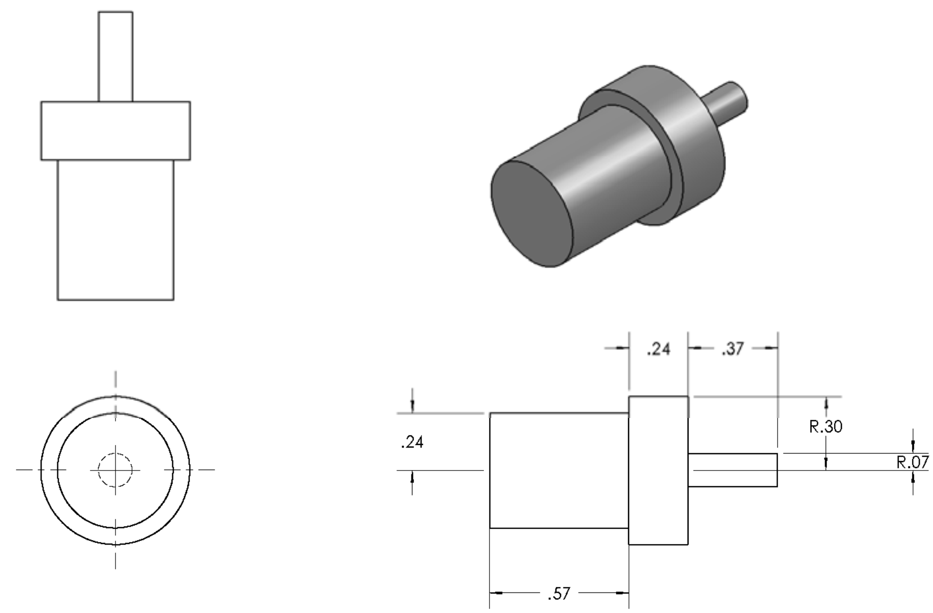


WCP - Wolfgang Kaml	DATE: June 3, 2010	UNITS: inches	MATERIAL: Stainless Steel
Mechanical Engineering CAL POLY	TOLERANCE: ±0.005	SCALE: 2:1	TITLE: Shutoff Plate
		NEXT ASSY: 1G	NAME: Team MUC & SLO
		DRAWING #: 1F	

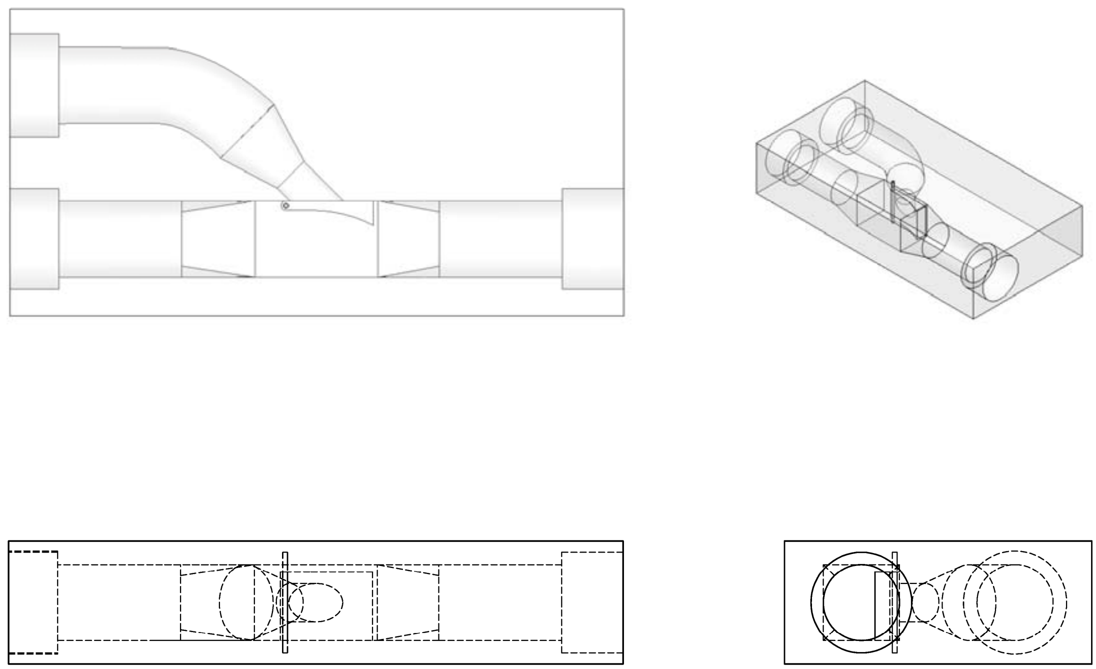


WCP - Wolfgang Kaml	DATE: June 3, 2010	UNITS: inches	MATERIAL: Rubber
Mechanical Engineering CAL POLY	TOLERANCE: ±0.005	SCALE: 2:1	TITLE: Shutoff Plate Gasket
		NEXT ASSY: 1H	NAME: Team MUC & SLO
		DRAWING #: 1G	

5 4 3 2 1

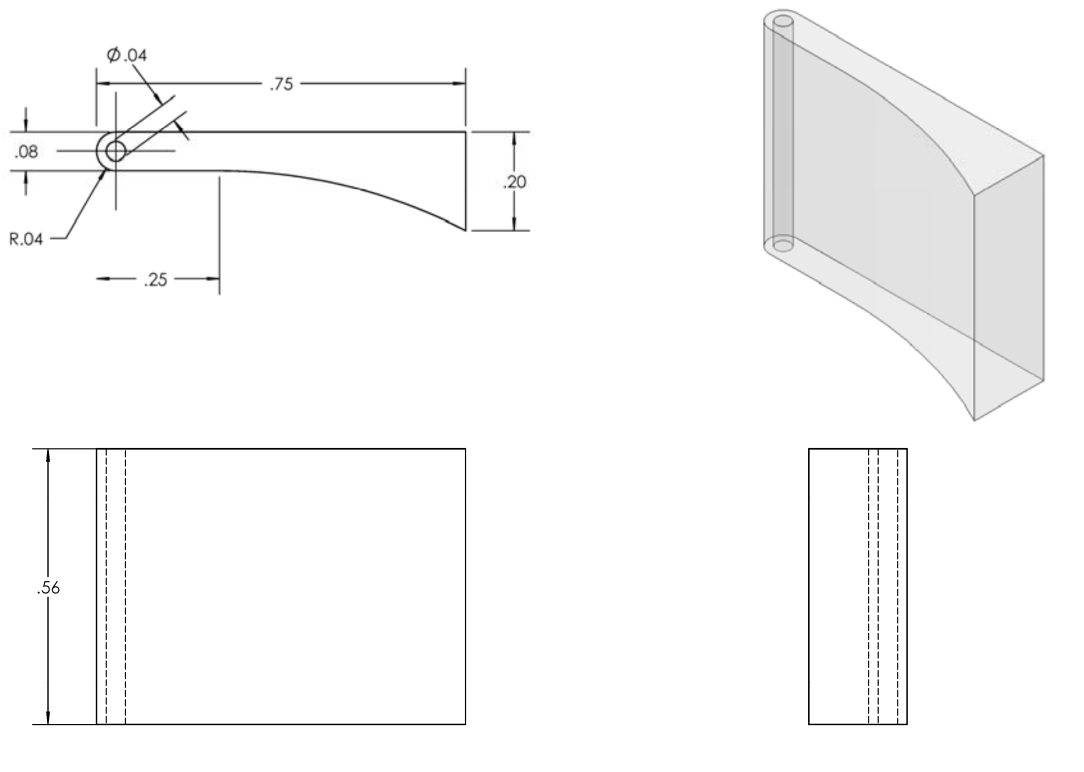


WCP - Wolfgang Kaml	DATE: June 3, 2010	UNITS: inches	MATERIAL: Mixed
	TOLERANCE: ±0.005	SCALE: 2:1	TITLE: Wax Element
		NEXT ASSY: 2	NAME: Team MUC & SLO
		DRAWING #: 1H	



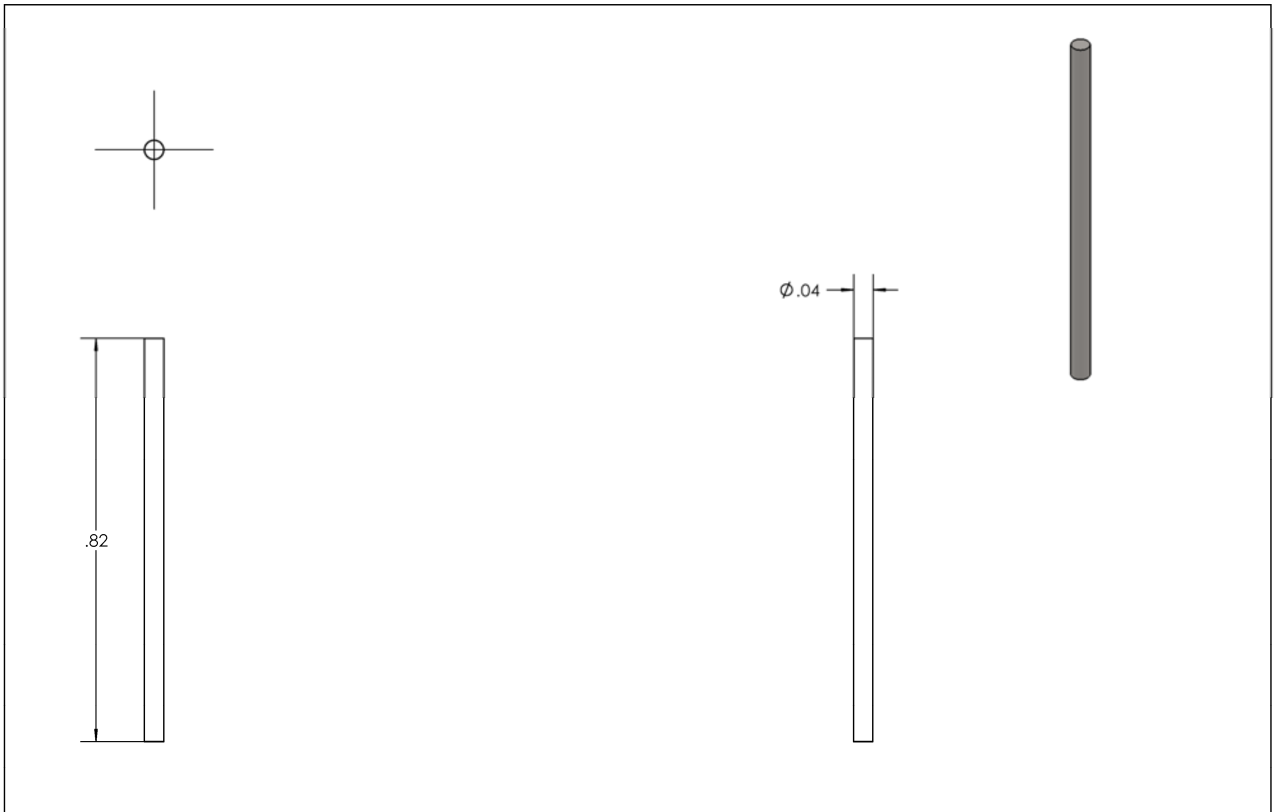
WCP - Wolfgang Kaml	DATE: June 3, 2010		
Mechanical Engineering CAL POLY		SCALE: 1:1	TITLE: Venturi Valve Mk IV
		NEXT ASSY: 2A	NAME: Team MUC & SLO
		DRAWING #: 2	

5 4 3 2 1

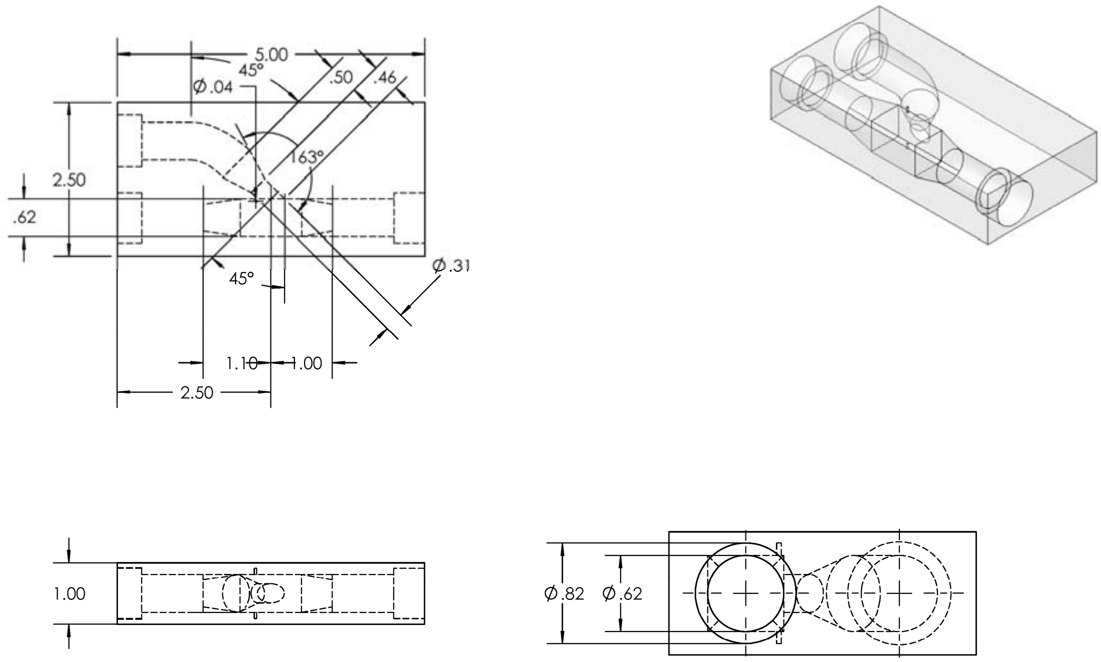


WCP - Wolfgang Kaml	DATE: June 3, 2010	UNITS: inches	MATERIAL: Acrylic
Mechanical Engineering CAL POLY	TOLERANCE: ±0.005	SCALE: 4:1	TITLE: FlapMk IV
		NEXT ASSY: 2B	NAME: Team MUC & SLO
		DRAWING #: 2A	

5 4 3 2 1

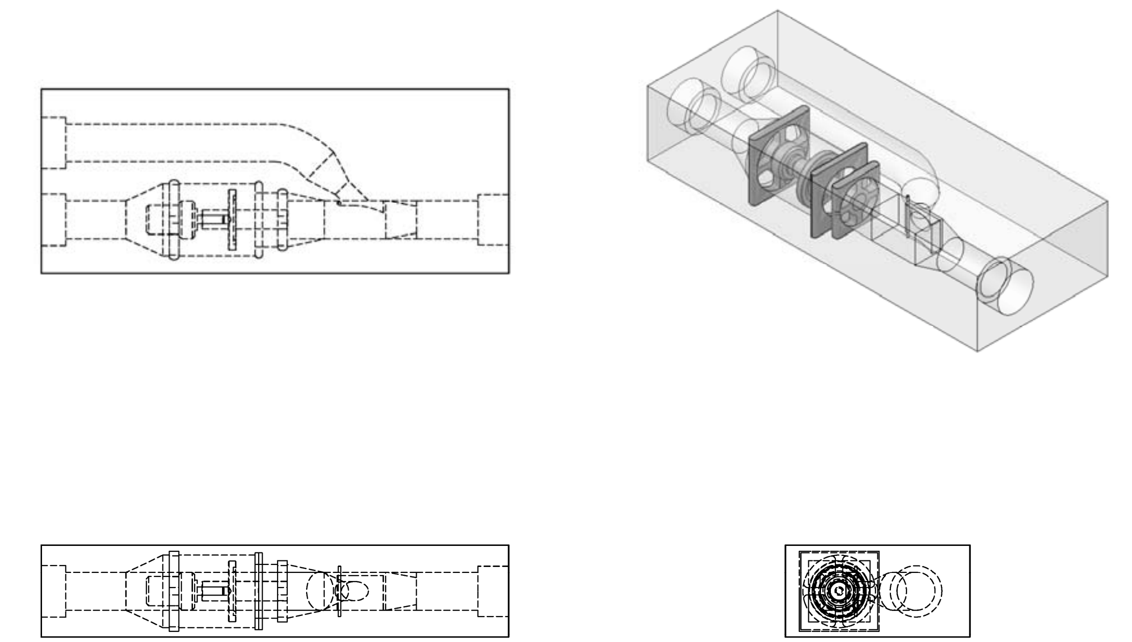


WCP - Wolfgang Kaml	DATE: June 3, 2010	UNITS: inches	MATERIAL: Stainless Steel
Mechanical Engineering CAL POLY	TOLERANCE: ±0.005	SCALE: 4:1	TITLE: Flap Pin
		NEXT ASSY: 2C	NAME: Team MUC & SLO
		DRAWING #: 2B	

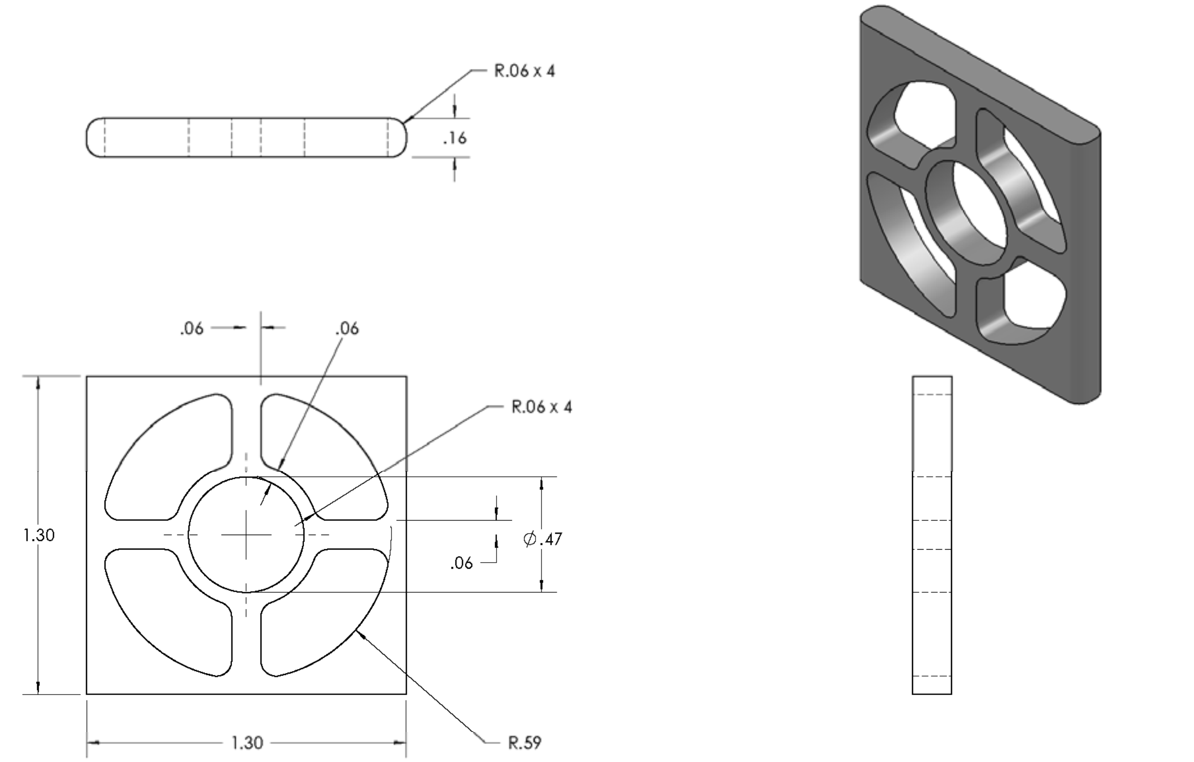


WCP - Wolfgang Kaml	DATE: June 3, 2010	UNITS: inches	MATERIAL: Acrylic
Mechanical Engineering CAL POLY	TOLERANCE: ±0.005	SCALE: 1:1	TITLE: Venturi body
		NEXT ASSY: 3	NAME: Team MUC & SLO
		DRAWING #: 2C	

5 4 3 2 1

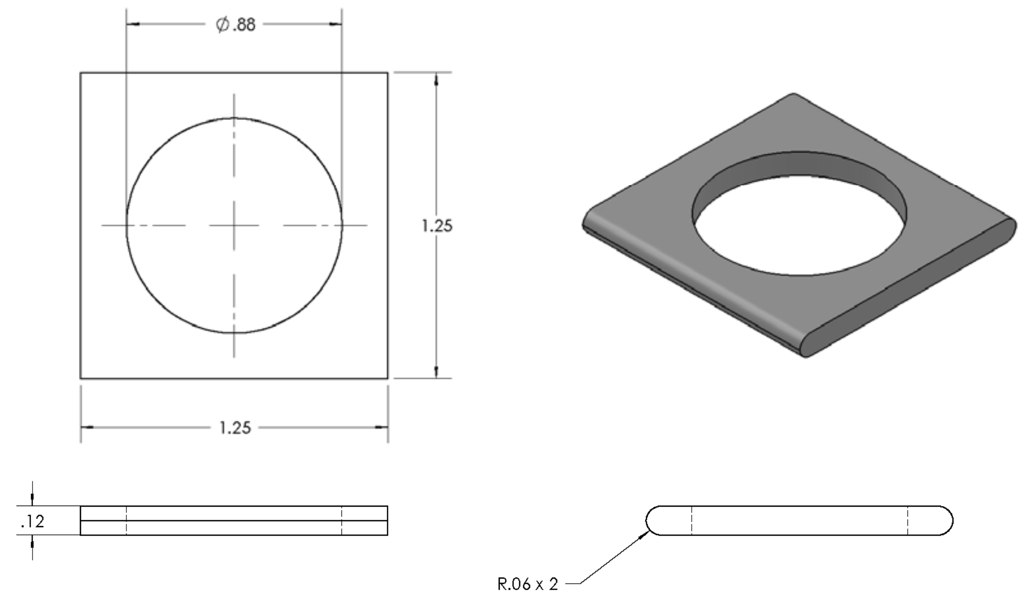


WCP - Wolfgang Kaml	DATE: June 3, 2010		
Mechanical Engineering CAL POLY		SCALE: 1:2	TITLE: Integrated Body
		NEXT ASSY: 3A	NAME: Team MUC & SLO
		DRAWING #: 3	

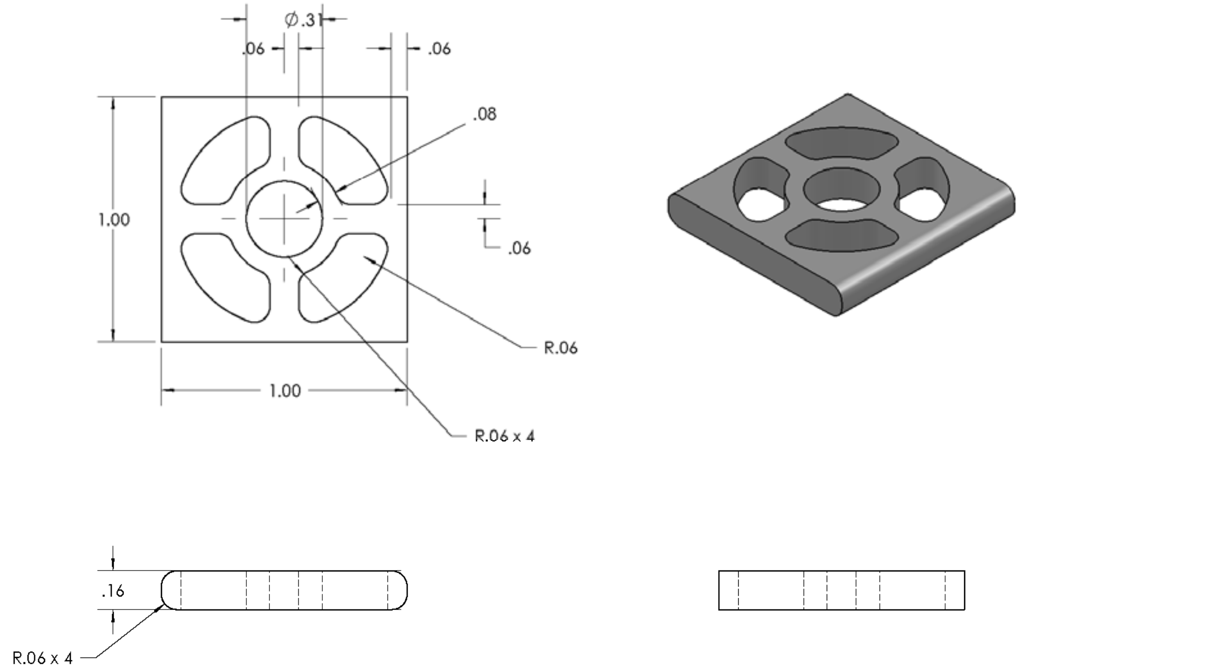


WCP - Wolfgang Kaml	DATE: June 3, 2010	UNITS: inches	MATERIAL: Stainless Steel
	TOLERANCE: ±0.005	SCALE: 2:1	TITLE: Wax Retention Plate Integrated
		NEXT ASSY: 3B	NAME: Team MUC & SLO
		DRAWING #: 3A	

5 4 3 2 1

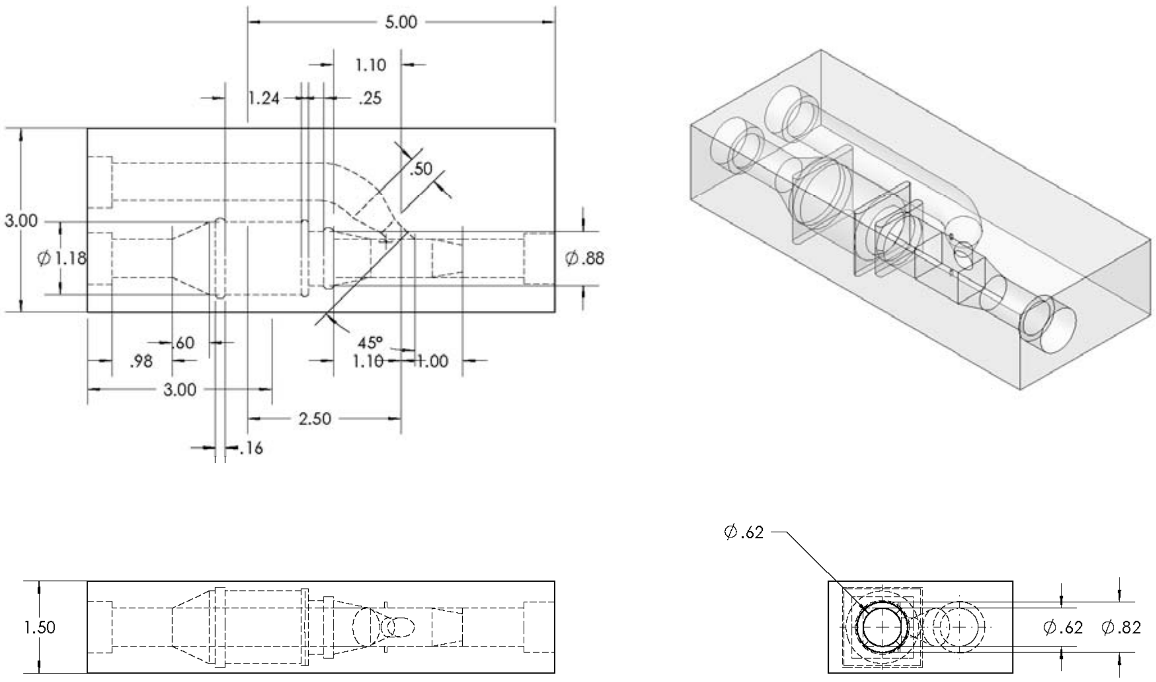


WCP - Wolfgang Kaml	DATE: June 3, 2010	UNITS: inches	MATERIAL: Stainless Steel
	TOLERANCE: ±0.005	SCALE: 2:1	TITLE: Shut0ff Plate Integrated
		NEXT ASSY: 3C	NAME: Team MUC & SLO
		DRAWING #: 3B	



WCP - Wolfgang Kaml	DATE: June 3, 2010	UNITS: inches	MATERIAL: Steel
	TOLERANCE: ±0.005	SCALE: 2:1	TITLE: Stop Plate Retention Integrated
		NEXT ASSY: 3D	NAME: Team MUC & SLO
		DRAWING #: 3C	

5 4 3 2 1



WCP - Wolfgang Kaml	DATE: June 3, 2010	UNITS: inches	MATERIAL: Acrylic
	TOLERANCE: ±0.005	SCALE: 1:2	TITLE: Integrated Valve Body
			NAME: Team MUC & SLO
		DRAWING #: 3D	

5 4 3 2 1

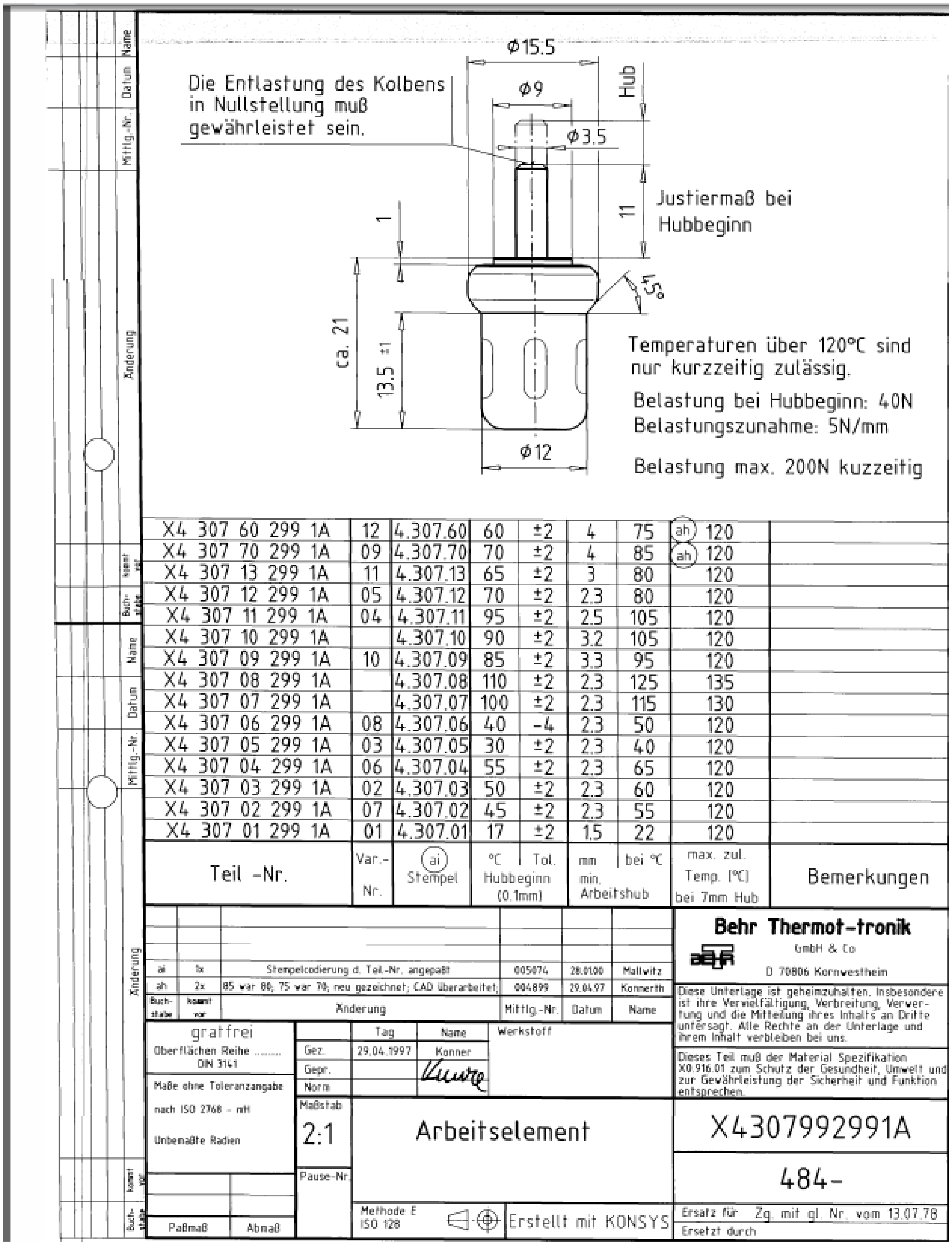
XIII. Appendix M - Spring Information

Datenblatt für Artikel: 59/35/1

Artikelnummer:	59/35/1
Bezeichnung:	Druckfeder
Werkstoff:	1.4310
d - Drahtstärke (mm):	1.4
De - äußerer Windungs Ø (mm):	13.2
D - mittlerer Windungs Ø (mm):	11.8
Di - innerer Windungs Ø (mm):	10.4
Lo - ungespannte Länge (mm):	25.3
n - federnde Windungen:	4.3
m - Steigung:	5.56
sn - max. zul. Federweg (mm):	15.58
Ln - max- gedrückte Länge (mm):	9.72
Fn - max. Kraft bei Ln (N):	75.62
R - Federrate (N/mm):	4.85
Dd - Dorndurchmesser (mm):	10.09
Dh - Hülsendurchmesser (mm):	13.71
G - Geschliffen:	ja
K - Knicksicher:	ja
m - Masse (g):	2.86
Beschichtung:	

Figure 36 shows the spring information sheet obtained from the manufacturer in Germany.

XIV. Appendix N - Wax Element Data Sheet



Teil -Nr.	Var.-Nr.	(ai) Stempel	°C Hubbeginn	Tol. (0.1mm)	mm min. Arbeitshub	bei °C	max. zul. Temp. [°C] bei 7mm Hub	Bemerkungen
X4 307 60 299 1A	12	4.307.60	60	±2	4	75	(ah) 120	
X4 307 70 299 1A	09	4.307.70	70	±2	4	85	(ah) 120	
X4 307 13 299 1A	11	4.307.13	65	±2	3	80	120	
X4 307 12 299 1A	05	4.307.12	70	±2	2.3	80	120	
X4 307 11 299 1A	04	4.307.11	95	±2	2.5	105	120	
X4 307 10 299 1A		4.307.10	90	±2	3.2	105	120	
X4 307 09 299 1A	10	4.307.09	85	±2	3.3	95	120	
X4 307 08 299 1A		4.307.08	110	±2	2.3	125	135	
X4 307 07 299 1A		4.307.07	100	±2	2.3	115	130	
X4 307 06 299 1A	08	4.307.06	40	-4	2.3	50	120	
X4 307 05 299 1A	03	4.307.05	30	±2	2.3	40	120	
X4 307 04 299 1A	06	4.307.04	55	±2	2.3	65	120	
X4 307 03 299 1A	02	4.307.03	50	±2	2.3	60	120	
X4 307 02 299 1A	07	4.307.02	45	±2	2.3	55	120	
X4 307 01 299 1A	01	4.307.01	17	±2	1.5	22	120	

Buch-stabe	kommt vor	Änderung	Mittlg.-Nr.	Datum	Name
ai	1x	Stempelcodierung d. Teil.-Nr. angepaßt	005074	28.01.00	Mallvitz
ah	2x	85 war 80; 75 war 70; neu gezeichnet; CAD überarbeitet;	004899	29.04.97	Konnerth

Behr Thermot-tronik GmbH & Co
D 70806 Kornwestheim

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Dieses Teil muß der Material Spezifikation X0.916.01 zum Schutz der Gesundheit, Umwelt und zur Gewährleistung der Sicherheit und Funktion entsprechen.

gratfrei
Oberflächen Reihe .... DIN 3141
Maße ohne Toleranzangabe nach ISO 2768 - mH
Unbemaßte Radien

	Tag	Name
Gez.	29.04.1997	Konner
Gepr.		Kunz
Norm		

Werkstoff

Maßstab 2:1

Arbeitselement

X4307992991A

484-

Pause-Nr.

Methode E ISO 128

Erstellt mit KONSYS

Ersatz für Zg. mit gl. Nr. vom 13.07.78
Ersetzt durch

Paßmaß Abmaß

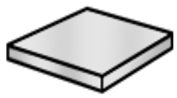
Figure 37 shows the thermostat wax element data sheet obtained from the manufacturer in Germany.

XV. Appendix O - Acrylic Material Data Sheet

Material > Shape > Thickness > Length

Plastics

This product matches all of your selections.



Part Number: 8560K321 — $41.62 Each

Material	Acrylic
Acrylic Material	Cast Acrylic
Backing	Plain Back
Finish	Smooth
Shape	Sheets, Bars, Strips, and Cubes
Sheets, Bars, Strips, and Cubes Type	Square Sheet
Sheet Style	Standard
Thickness	1"
Thickness Tolerance	+.023", -.087"
Length	12"
Length Tolerance	±1/4"
Width	12"
Width Tolerance	±1/4"
Clear	Clear with No Tint
Operating Temperature Range	-20° to +170° F
Softening Point	+196° to +239° F
Performance Characteristic	Weather Resistant
Tensile Strength	Good
Impact Strength	Poor
Tolerance	Standard
Hardness	Rockwell M90-M103
Specifications Met	Not Rated

Figure 38 shows the material data sheet for the acrylic from which the valve and flap prototypes were manufactured.

Info obtained from: http://www.mcmaster.com/#acrylic/=7d3gid