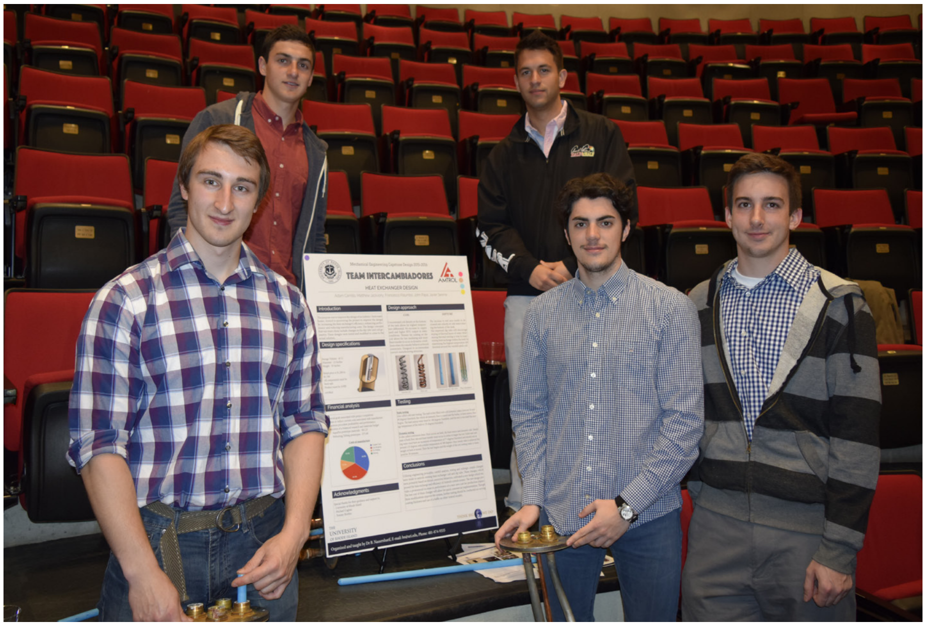
HEAT EXCHANGER DESIGN

Team Intercambiadores

May 9, 2016



Team members

Adam Camillo
Matthew Jackvony
Francesco Palumbo
John Papa
Javier Sesma

Faculty advisor
Professor Bahram Nassersharif

Representatives

Michael Cogliati
Senior R&D Engineer at Amtrol

Sponsored by

AMTROL

THE UNIVERSITY OF RHODE ISLAND

THINK BIG WE DO

Abstract

The collective goal of this project is to redesign the heat exchanger of the Amtrol Hydromax top down residential hot water heater. Although Amtrol's current model is very competitive in the marketplace it is important for businesses to maintain the competitive edge and consumer appeal. The redesign of the exchanger is governed by a number of geometric tolerances which ultimately drive many of the design choices that were made. The changes carried out must only affect the internal heat exchanging structure and cannot interfere with the external tank structure or the face plate structure. In order to further investigate the design concepts a series of models, simulations, and subsequent prototypes will be analyzed for a variety of desirable characteristics. The entire design process was carried out in a very concise and step by step linear matter. By following a certain set of guiding principles it allowed for easy correction of any potential problems. When operating in this manner, deadlines were kept, innovation proceeded, and ultimately the final proof of concept was generated and presented. The findings listed within the report helped to quantitatively and qualitatively display sound product generational concepts, which ultimately will lead to product implementation in the marketplace. By aligning our goals with, customer satisfaction, reliability, uniqueness, and keeping mark with the all important quality, Amtrol will be sure to be presented with a concept that will not only meet, but exceed their expectations. The new concept involves modification to the coil and the dip tube in the heat exchanger. A new coil structure, moving from the constant pitch to the variable pitch, is expected to introduce a gain in 10 percent thermal output. By introducing a new dip tube design there will be a reduction in the turbulence in the tank thereby reducing stochastic losses and allowing for a more predictable performance.

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Nomenclature

A - Total surface area (m^2)

A_f - Area of fins (m^2)

A_c - Area of Coil (without fins) (m^2)

h - Convective heat transfer coefficient ($\frac{Watts}{m^2 Kelvin}$)

k - Conduction heat transfer coefficient ($\frac{Watts}{m\ Kelvin}$)

L - Length of the coil (m)

Nu - Nusselt Number (unitless)

q - Thermal power (Watts)

m - Mass flow rate (kg/s)

T - Temperature (F) or (K)

P - Pressure (psi)

psi - Pounds per square inch

in/s - Inches per second

F - Degrees Fahrenheit

kg/s - Kilograms per second

kg^3/s - Cubic kilograms per second

BTU/hr - British Thermal Unit per hour

α - Unitless CDF function defining number of coils per height

Γ - Unitless function defining the temperature of the potable water as a function of coil height throughout the tank

List of Acronyms

CDF- Cumulative Distribution Function

HDPE - High density polyethylene

HVAC - Heating, Ventilation, and Air Conditioning

ISO - International organization for standardization

LP - Liquid propane

PEX - Cross-linked Polyethylene

ROI - Return on Investment

USD- United States Dollar

QFD - Quality function deployment

AHRI – Air Conditioning, Heating and Refrigeration Institute

GPM – Gallons Per Minute

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1. Introduction

Amtrol was founded in 1946 and since then has been a world leader in the operation and design of heating and potable water storage systems. Throughout their 75 plus years, Amtrol has revolutionized the HVAC industry with products such as, the first pre-pressurized well tank, refrigerant gas cylinders, indirect fired water heaters, and, as of recently, the composite metal LP gas tank. Along with their constant innovation, Amtrol has stringent standards to ensure that their products have exceptional quality. Amtrol currently holds an ISO 9001:2008 certification.

Mission Statement

AMTROL IS AN INTERNATIONAL COMPANY COMMITTED TO ENHANCING CUSTOMER AND SHAREHOLDER VALUE BY PROVIDING RELIABLE PRODUCTS WITH OUTSTANDING SERVICE.

THE VALUE WE CREATE WILL BE ACCOMPLISHED BY WORKING AS A TEAM TO BUILD CUSTOMER LOYALTY WHILE SURPASSING CUSTOMER EXPECTATIONS VIA INNOVATIVE SOLUTIONS.

FIGURE 1: AMTROL'S MISSION STATEMENT

Today Amtrol employs over 1700 people. Their corporate headquarters is located in West Warwick, Rhode Island and they have sales offices in the United States, Canada, South America and Europe. Their products are manufactured in Rhode Island, Maryland, Kentucky and internationally in Portugal.

Amtrol has presented Team Intercambiadores with the problem of improving upon the current design for their Hydromax® 41 gallon Indirect-fired water heater. Indirect-fired water heaters use a closed loop of hot water, pumped from a boiler to a heat exchanger within a potable water tank, to increase the temperature of water. The workings of the example indirect hot water heater can be seen in figure 2. Compared to direct fired water heaters, where the heat is added directly into the potable water, indirect water heaters have much higher efficiency, performance, product life and reduced heat loss.

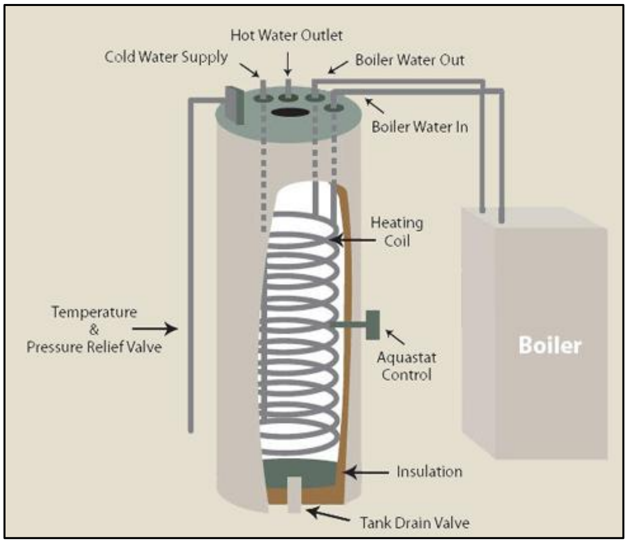

FIGURE 2: INDIRECT HEAT WATER HEATER SCHEMATIC [1]

Amtrol's Hydromax® 41 gallon Indirect-fired water heater is made up of internal and external components. The internal components are the heat exchanger coil and dip tube. The external components of the system are the top plate and potable water storage tank. Team Intercambiadores is restricted when improving the indirect-fired water heater to only the internal components of the Hydromax® 41 gallon Indirect-fired water heater; therefore the potable water storage tank and top plate cannot be changed in any way.

FIGURE 3: AMTROL'S HYDROMAX INDIRECT WATER HEATER [2]

The components of the Indirect-fired water heater that are to be improved are the heat exchanger and dip tube. The heat exchanger currently is a helical coil of copper tubing wound uniformly. The dip tube is used to bring water, from a domestic source, into the potable water tank to be heated. The dip tube currently is a long straight tube made of PEX that runs from the top plate of the water heater to the bottom of the heat exchanger.

When improving these components Amtrol has set a goal to increase the efficiency of the system while maintaining or reducing the price. Amtrol has also set a requirement of researching the competition, providing CAD drawings, fluid and thermal analysis, providing a cost analysis and finally creating a number of working prototypes by the completion of the project.

To complete Amtrol's requirements Team Intercambiadores will start by conducting research. The first area of research will be into competitors. This will allow our team to understand how other companies have made effective indirect hot water heaters and understand the direction of the HVAC market. The second area of research will be into patent searching. This will give our team an advantage in understanding what has already been done and what restrictions we have on improving the product. The final area of research will be, understanding the design specifications of Amtrol's product and the competitors products. This entails understanding the physical attributes the system possesses and the restrictions in alteration. Design specifications are the values our team will be basing improvement from. From a reduction in weight to increased efficiency, Amtrol's current design specifications will be the initial values that the improvements will be compared to. To better position Amtrol's product in the marketplace, the competitors design specifications will also be understood. Values will be compared using tools such as a QFD.

After gaining enough understanding of the current market and competition, our team will begin concept generation. This stage will allow for each member of Team Intercambiadores to approach the engineering design problem in their unique manner. Thirty concepts per member will be generated. Concepts will be distinct to one another but may overlap from person to person.

The concepts will then be discussed as a group and with Michael Cogliati and Dr. Nassersharif. Through discussion viable options will be discovered from the full list and set aside. The viable options will then be further refined into a group of the concepts deemed to have the most potential for success in improving the indirect water heater. This will be the designs chosen to further pursue.

The designs chosen to further pursue will then analyzed mathematically, modeled using Solidworks and run through thermal and fluid flow analysis. This step of analysis will prove that our concept will improve Amtrol's current system. During this, a price and market comparison will be conducted to prove that our redesigned system will be of the same or lesser in price to produce and be a more competitive product in the market.

After the designs are analyzed, the designs that mathematically prove to improve heat transfer, efficiency, cost and manufacturability will be constructed as prototypes. Industry standard testing will then be done on these prototypes in Amtrol's facility to confirm the mathematical theory.

When positive prototype testing results coincide with theory, the data will be collected and presented to Amtrol, as well as a final model will be constructed. Team Intercambidores plans on accomplishing this plan and these goals by the completion of the spring semester.

2. Project Planning

At the start of this project, the team had to ensure that there was a clear problem definition to plan out the steps necessary to complete it in time. A meeting with Amtrol allowed for a clear understanding of their demands. These demands were then analyzed by the team in which we planned weekly meetings and deadlines to assure that all tasks were completed in time. The team designated a weekly meeting time with Amtrol to keep up with their expectations and ask any questions. Also, the team met frequently outside of class time to discuss plans and tasks that needed to be completed. Team roles were designated to allow tasks to be divided up.

The first step in completing this project was to do research on everything relevant to indirect hot water heaters and Amtrol's competitors. Amtrol also gave the team some direction to optimize the heat exchanger, including a potential change of material, or use of a coating. Once the research was complete, the team began to devise concepts based on prospective designs. Many of these concepts were not feasible to Amtrol, therefore they were narrowed down. Once selecting the best concepts more theoretical research and analysis was done to make sure they were practical. This theoretical investigation includes material testing, CAD analysis, and geometrical tests. Prototypes are to be built and tested based on the selected concepts. The theoretical analysis is the basis for the prototyping to be completed next semester. Once the prototypes are optimized, and all of Amtrol's expectations are met, the product can be finalized.

In order to stay on track with this project through the testing and re-design phase of the project we were very conscious of the scheduled testing time and were diligent in planning and carrying out individual and meaningful tests. By keeping up with these tests and being both thorough and expedient in both analysis and redesign we were able to navigate around or through any unexpected difficulties faced during the closing testing phase of this project.

2.1 Research

Initially, it was difficult to understand the restrictions the group had in changing the overall design of the heat exchanger. The team thus met with Amtrol to understand their expectations and limitations. After discovering the performance of Amtrol's current design, the team began to research how to optimize this. This research looked into three different categories to optimize. These being; overall coil geometry, cross-sectional coil geometry, and dip-tube geometry. Also, on top of these categories, coatings were to be researched to potentially provide better heat exchange. The actual analysis of heat exchange needed to be researched and understood in order to optimize heat exchanger performance.

In order to get a full understanding of the heat exchange process and the heat exchanger itself research was done. Preliminary research involved looking into the current market environment for residential heat exchangers to get an understanding of their price range, function, and application. The product we are looking to modify is an indirect water heater which helped in narrowing the search. The price range for standard residential indirect water heaters is currently as low as 959 dollars to 2199 dollars [3]. Most exchangers have a thermal output, which is highly dependent on the boiler used in the system. The boiler varies house to house, of about 40,000 to 220,000BTU/hr. After this initial layer of research the product in question (Amtrol's Hydromax 41 gallon) was explored.

2.2 Concept Generation

At the start of this project it was difficult to decide which of the characteristics would be more relevant to the project. There are a lot of issues that are important in heat transfer.

At the beginning we were thinking about a lot of possibilities to improve as the shape of the dip-tube, the coatings, the shape of the coil, the different dispositions for all the parts that compose the internal part of the heat exchanger.

After our second meeting with the Professor Bahram Nassersharif we realized that working with all of those characteristics would be difficult to reach a good solution that increases the efficiency and reduces the costs of manufacturing. Thus, we tried to narrow the scope of study and to develop a new dip-tube that would be a nice solution and provide a 10% increase in the efficiency of the current heat exchanger.

2.3 Preliminary Design

After the concepts were generated it was vital to narrow down the list of ideas and develop a preliminary design. This process was done by first discussing the concepts with Dr. Nassersharif, Michael Cogliati from Amtrol and together as a group. Through this, Team Intercambiadores refined the large list of concepts down to four or five. Next, was to explore the effectiveness of our solutions through engineering analysis. This included the use of Solidworks FloXpress, publications, and mathematical analysis. Once the concepts were theoretically proven to enhance the performance of the Hydromax®41 gallon Indirect-fired water heater, a list of components and cost analysis was conducted to determine if the preliminary design would be cost effective as well. The components currently are in the process of being accumulated and a working prototype is well within Team Intercambiadores sights.

2.4 Gantt Chart

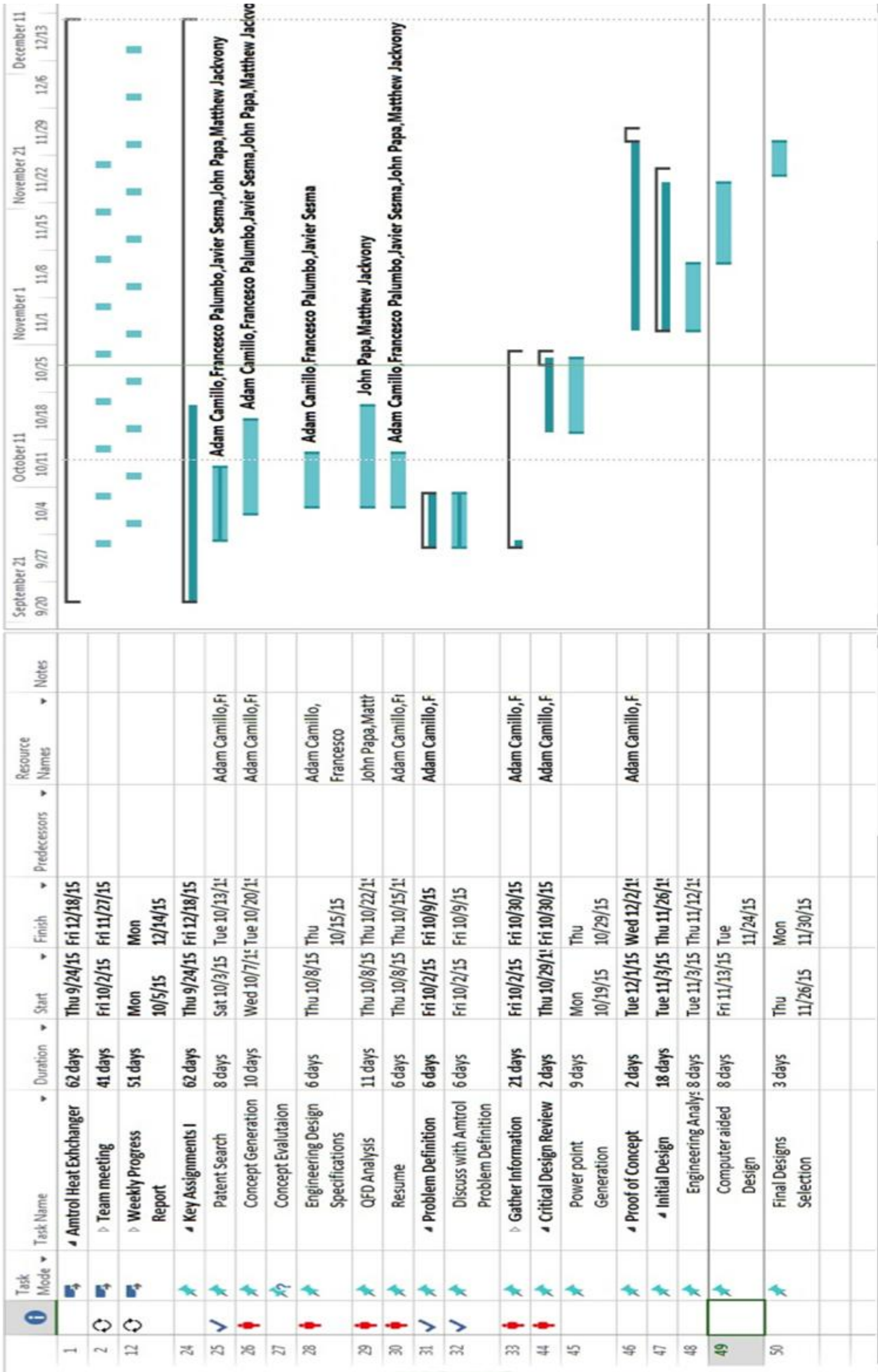

FIGURE 4: FIRST GANTT CHART

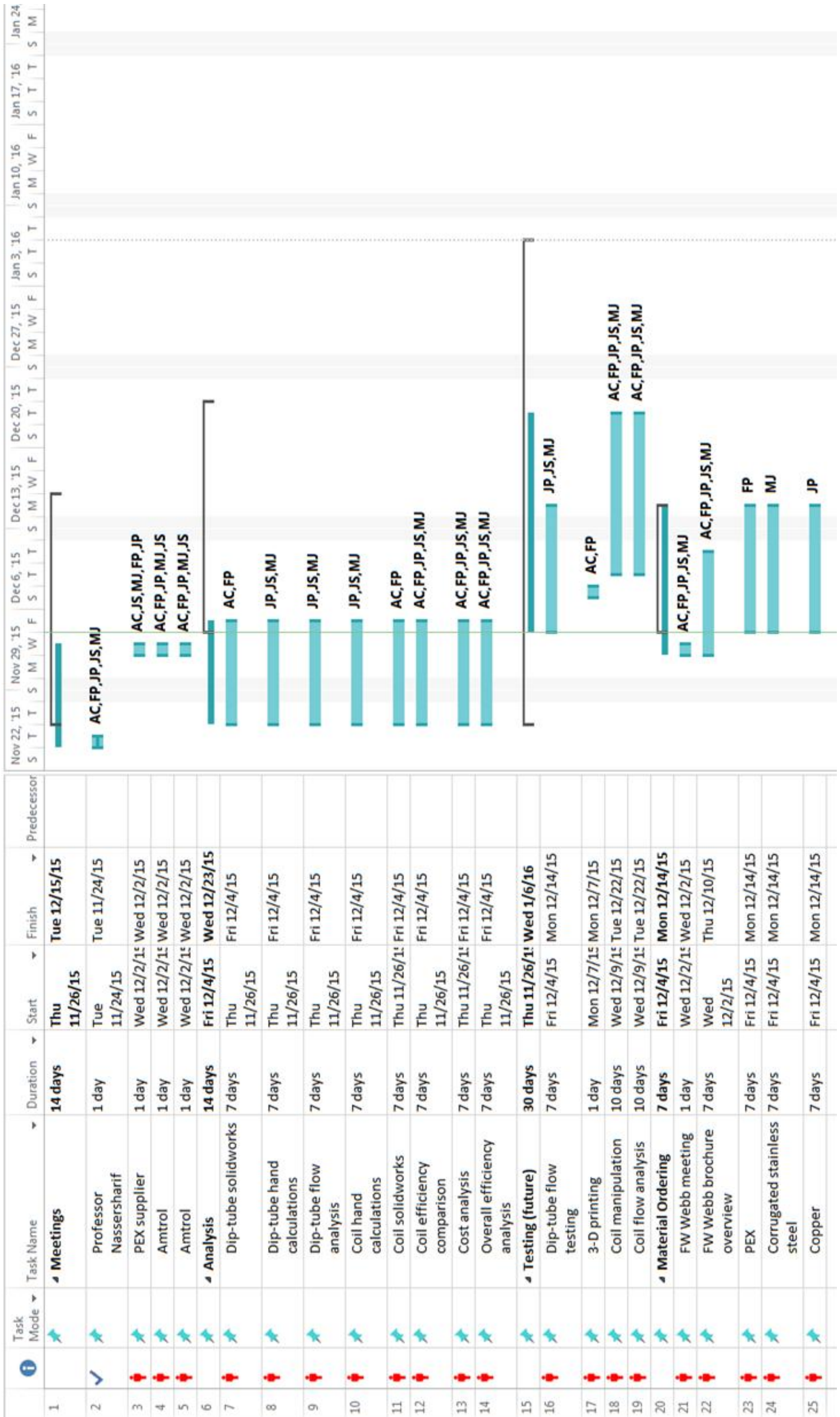

FIGURE 5: SECOND GANTT CHART

3. Financial Analysis

The preliminary cost analysis can be approached from a number of angles. The existing heat exchanger and the proof of concept design are unique in the way that they share many similar properties such as; material of choice (copper), plating material (tin), and fin structure. Amtrol has kindly provided their current suppliers and manufacturers and without being overly specific have also provided corresponding pricing scopes which will help in determining the competitiveness of a particular supplier and alternative manufacturing methods. Additionally due to the fact that the proof of concept does not require an additional volume of material, raw material cost calculations are significantly simplified. Since the driving material of the entire heat exchanger is copper piping, the cost analysis can begin there. Since the finished coils are produced in a four-step process, the cost analysis will follow the processes in order. First we begin with unprocessed copper piping. Due to the fact that Amtrol has been using many of the same suppliers and manufacturers for years and have received extremely competitive pricing for many of the processes. For sake of simplicity we will maintain the pricing from many of these trusted contractors.

Outside radius of Copper Piping 0.435”

Inner radius of Copper Piping 0.35”

Cross sectional area of the copper piping = Area of outer - Area of inner

Cross sectional area $= \pi {R_o}^2 - \pi {R_i}^2$

Cross sectional area = $\left(\pi(0.435^2)\right) - \left(\pi(0.35^2)\right)$

Cross sectional area = (0.594 - 0.384) = $0.21in^2$

Volume of material = $Cross\ section\ area * Length$

Volume = $\left(0.21in^2 * 12ft * \frac{12in}{1ft}\right) = 30.24in^3$

Density of copper is 0.324$\frac{lb}{in^3}$

Mass of the material = $(Density * Volume) = 30.24in^3 * 0.324\frac{lb}{in^3} = 9.79lbs$

Current cost of copper = $2.05\frac{USD}{lb}$

Cost per mass used in heat exchanger = $9.79 * 2.05\frac{USD}{lb} = \$20.38$

The second step involved with production of the heat exchanger involves the movement of material with the use of a finning machine. This process is what produces the fins on the exchanger. These, as previously described, are important to the convective heat transfer of the overall system. The cost to produce finning on a residential Hydromax 41 gallon system is $1 per foot. The Hydromax's exchanger has 12 feet of piping but only approximately 10 feet of the exchanger requires coiling.

Cost to fin Hydromax 41 = (Number of ft required to be coiled) * (1 USD/ FT)

Cost to fin Hydromax 41 = $\left(10ft * 1\frac{USD}{ft}\right) = 10\ USD = \$10$

The following step after finning is the process of shaping the coil into the overall geometry that will be acceptable to fit within the dimensional tolerances provided for the tank itself. The current cost to shape the material is set at a fixed rate of $20 per coil. This process is carried out by a machine similar to the MS32 by Sistemi Meccanici industrial of Italy. We will refer back to this machine later on in the financial analysis section.

The final step involved with the production of the exchanger is the tin plating of the coil. The current cost of Sn (tin) as of writing this is $6.88 per pound. The current contract negotiated with the tin plating company has an arrangement of $6.00 per coil.

As a whole, after all four steps have been completed the total cost per coil sits at around $56.00. This cost excludes fittings for attachment and additional labor costs that incur due to installation and assembly.

Due to commodity pricing and its fluctuations within the market it is important to assess the long term volatility of the materials. Accordingly we will assess the correlations between material cost and its percent composition within the exchanger. The two highest percentage holders for exchanger involvement are the volume of copper and the cost to shape the coil. Copper historically has fluctuated in price from as low as $0.60 per pound to a high of nearly $4.50 per pound in 2010-2011. Amtrol is currently paying nearly half of the cost it was during the 2010-2011 years. Although this does not sound like much on a small scale, it has significant impact when the volume of material purchased is in the scale of hundreds of tons of material. This has huge impacts on the Amtrol's bottom line. Its nearly an $800,000 difference in annual cost savings. Since the warranty associated with the product is 7 years, we will only consider volatility within the past 7 years.

It's important to note the forth moving concept exhibits a performance output increase of over 10 percent. Since the proof of concept presented in this paper has a near net zero cost change in comparison to the existing design it would be good to explore the possibility of purchasing equipment which would in turn lower the overall cost to manufacture the coil. This is especially evident with the cost associated with the shaping of the coil. This second section carries a weight of 35.71 percent of the total cost to produce the coil. Since Amtrol already in house manufactures many of their items, it would only be wise to consider the cost of purchasing a machine whose work volume will help reduce the bottom line of the product. According to initial financial review, it appears that the purchase of an MS32 finned coiling machine would conservatively have a return of investment of less than one year. Since the sponsor company already sets aside $700,000 annually to shape the coil, this initial value will be considered for analysis. The analysis can be viewed below;

- MS32 finned coiling machine - $450,000 - cost per unit new.
- Preventative Maintenance & general upkeep - 25% of initial purchase price per year = $112,500
- 2 Shifts of operators - $126,000 annually for labor costs

$$\$700{,}000 - Purchase\ Price - Preventative\ maintenance - labor\ costs = Cash\ flow\ positive$$

$700,000 – $450,000 – $112,000 – $126,000 = $11,500

Having a return of investment of less than one year on an industrial piece of machinery while maintaining generous overestimates on purchase price, labor costs, and preventative maintenance is something many companies would consider highly desireable.

The third highest cost percentage portion of the exchanger is the process of finning the raw copper piping. The contractor requests a price of one dollar per foot of finned copper. Approximately 10 of the 12 total feet of the copper pipe is finned, this carries a cost of $10 dollars. Systemi Meccanici also offers a finning machine and the company has proposed the possibility of competitively pricing both machines for sale.

The final portion of the manufacturing process is the tin plating. This step carries just above 10 percent of the of the total cost to produce, however Tin has significantly higher volatility than copper. The same company that shapes the overall coil geometry is also responsible for the plating. The cost per plate is fixed at a constant $6 per coil. Although this process currently carries the lowest percentage weight, due to its volatility it was a wise decision to explore the potential behind alternative, less volatile coatings.

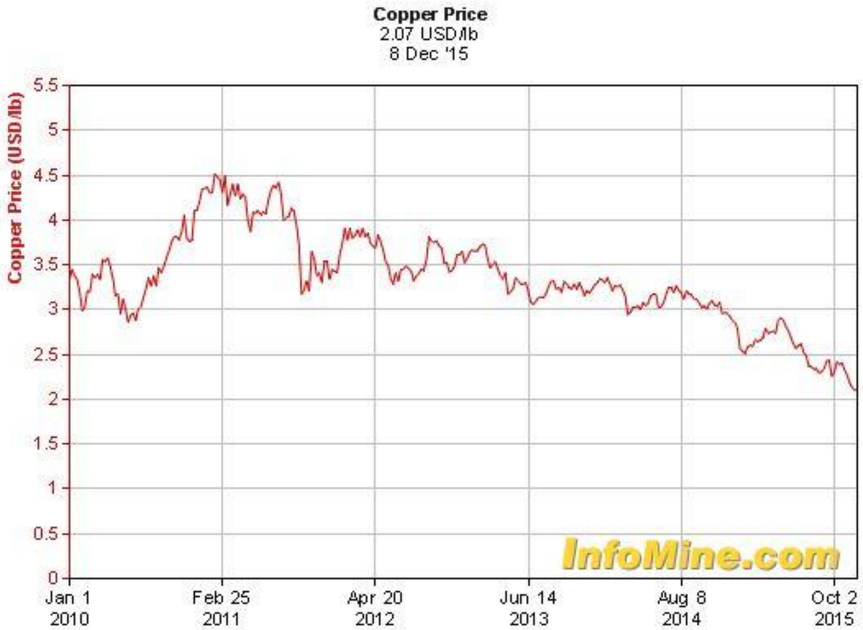

FIGURE 6: 5 YEAR VOLATILITY OF COPPER – USD [6]

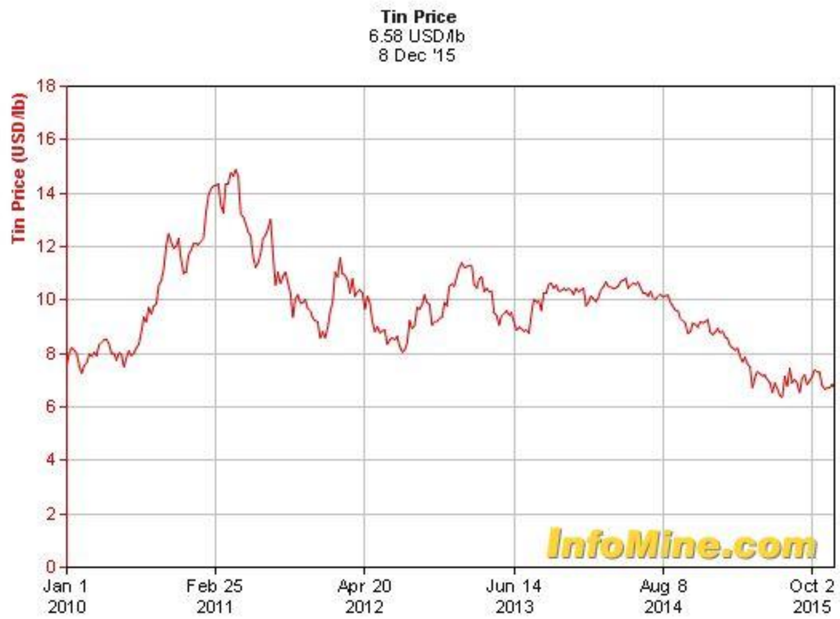

FIGURE 7: 5 YEAR VOLATILITY OF TIN (Sn) – USD [7]

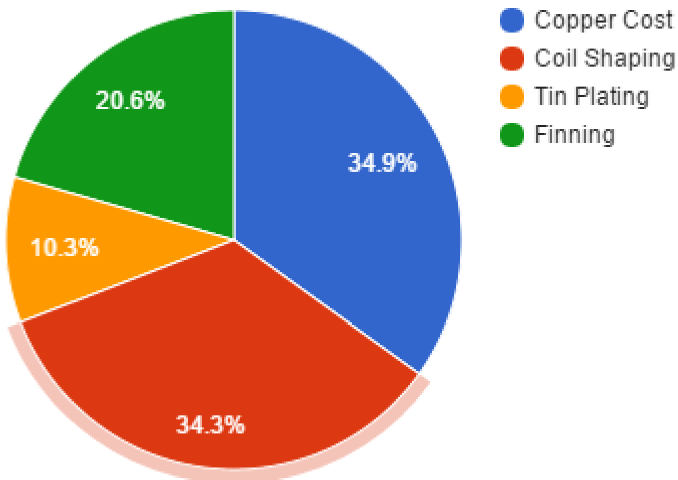

FIGURE 8: COSTS TO PRODUCE THE COIL

As the project has progressed the availability of alternative material coatings for the particular application have proven to be more and more unrealistic. Due to the fact that the application is influenced by high temperature cnstraints and a strict food safe requirement the potential options were restricted to food safe epoxies and a new method patented by liquiglide coatings. The epoxy coatings are both significantly higher in cost as well as time required to complete, at the moment this option does not seem appropriate. Attempts have been made to contact Liquiglide to further discuss potential product mating, but due to time constraints will require additional pursuant.

The final portion of our prototype design analysis included the introduction of a baffle. The purpose of the baffle was to simulate a smaller vessel size to encourage more rapid heating of the water. The baffle includes four small cuts which promote mixing within the tank. In terms of manufacturability it is relatively straightforward. You begin with large sheets of high density polyethylene (HDPE) and stamp out the pattern. After the pattern is stamped it must be rolled into its final shape. The likely choice for sealing the two free ends would be sonic welding, this process requires preparation of the surface, introduction of heat and pressure, and lastly cooling. The prototype material was manufactured from an existing HDPE sheet which Amtrol currently uses in other lines within the facility. Overall the cost of material would introduce roughly a two percent cost increase of the total cost to manufacture the existing heat exchanger. The bulk of the introduction of new cost would arrive from machine modifications to accommodate the stamps. The cost of the material is extremely low, forty-eight inch sheets of the material at lengths of 200 feet cost $12 through retail sources. Amtrol has not disclosed their trade pricing at the moment however, the retail sources are what have been used to calculate cost analysis, likely leading to a slight overestimate.

In addition to raw material costs and manufacturing methods it is important to be thorough in encompassing all aspects that drive the financial direction of the project. Throughout the research phases of the project collectively each member has logged 60 hours of research, innovation, and engineering design. This totals 300 hours for all members. In addition to engineering design, each member fulfilled lab and prototype testing responsibilities. Each member logged 40 hours within Amtrol's lab for a collective 200 hours. Overall the members have spent 500 hours pursuant to the goal presented by Amtrol.

3.1 Projected and Actual Cost

As previously highlighted within the preliminary cost analysis. The projected and actual cost should be nearly identical to the current incurred costs due to manufacturing and assembly. As a reminder, the overall process to manufacture remains the same, but the cost analysis can follow two routes, one which follows existing processes and uses existing contractors, the other option is to pursue the purchase of a finned tube coiling machine. The initial annual cost of purchasing the machine carries a very high up front cost, however due to the decreased cost per coil after shaping, the ROI is astounding. This section, unlike the previous will focus on equipment purchases, manufacturing costs, and labor.

After weighing all the costs associated with manufacturing the heat exchanger, a potential pursuant is the purchase of a finned tube coiling machine and a tube finning machine. After several correspondences it was determined that the due to floor space constraints, the potential of purchasing a tube finning machine is rather unlikely. The tube finning machine is nearly 100 feet in length and consists of a multi step process. When finning material the initial step consists of obtaining raw copper stock pipe. The material then enters the machine where rotary blades grip the material and begin to shape fins. After finning the copper the material is then washed down and prepped for hydrogen treatment. The washing cleans the material of any impurities, a process which is vital for potable applications. The hydrogen treating is then carried out in order to remove any corrosion that resulted from the cleaning process. Finally the material must be annealed because the finning has hardened the copper. The annealing is necessary because the copper would break when inserted into the mandrel to finally become the helical coil it was intended to be. Ultimately as previously stated this finning machine is not a pursuable option because of a number of reasons. The initial reasoning is the floor space required to operate the machinery is too cumbersome for Amtrol's current facility. Secondly the initial purchase price is astronomical. An initial quote suggested the purchase price could be in the range of one million USD, this cost excluded any customization whatsoever. What made this even more unreasonable is the maintenance costs associated with failures in the rotary blades and tooling is near 25 percent of the initial purchase cost of the machine. Lastly what makes this an entirely unviable purchase is the fact that the purchase price does not include the machinery required to both wash and hydrogen treat the material. These two steps would require separate machinery which in turn requires additional floor space. The sheer volume of finned piping that would need to be manufactured annually in order cover initial purchase price is significantly higher than any requirements Amtrol needs to meet. Since finning of copper is completed at an extremely reasonable price, sticking with the original manufacturer is extremely realistic.

Moving from an unrealistic purchase to a more realistic acquisition is the purchasing of an MS32 finned coiling machine. This machine is semi automated which requires some input from the operator in order to effectively operate. The pre-finned copper is placed into a rotating mandrel by an operator and the operator proceeds to complete shaping of the coil. The total cost of the machine 450,000 USD, this cost includes delivery and tasteful modifications to guarantee smooth operation on site.

As previously stated in preliminary cost analysis, which holds true here as well.

- MS32 finned coiling machine - $450,000 - cost per unit new.
- Preventative Maintenance & general upkeep - 25% of initial purchase price per year = $112,500
- 2 Shifts of operators - $126,000 annually for labor costs

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The preliminary cost analysis holds true for the projected and actual cost as well. The same volume of material is used as well as the same processes used to shape the material.

3.2 Project Budget

Team Intercambiadores has a unique task when it comes to budget allocation. Although the university has granted $500 toward purchasing orders and related expenses it soon may lead to the exploration of additional venues. Amtrol has not specified a specific budget however, they have explicitly stated that no option is unpursuable if “adequate proof of concept” is provided. When initially considering alternative materials and dip tube geometries team Intercambiadores was lucky enough to form a relationship with FW Webb, a plumbing and heating specialist. FW Webb was generous enough to donate several sample lengths of alternative materials which will be beneficial for straight length testing purposes. They have encouraged the team to reach out to them in the future for any additional material inquiries and research purposes.

The collaborative engineering efforts and hours logged at Amtrol facilities by team Intercambiadores required travel expenses. Collectively the two vehicle drivers have logged 1,176.5 miles over the course of two semesters. A total of 65 round trip drives were made from University of Rhode Island to Amtrol's Warwick, Rhode Island location. According to the Internal Revenue Service for 2016, the standard mileage rates for the use of a car for business is $0.54 per mile. This total for business travel reimbursement is $635.31.

To properly execute the entire engineering process it is vital to maintain a balanced research and materials budget. The University of Rhode Island was gracious enough to provide five hundred dollars toward team Intercambiadores undergraduate research. Of the initial amount granted only $136.25 was spent. This leaves a surplus of $363.75 which will return to the University.

4. QFD

To understand the pertinent parameters and important features of the current Amtrol design, a thorough quality function deployment analysis was done. A quality function deployment, or QFD, is an organized approach to establishing customer requirements and converting them into distinct criteria to produce a product to meet those demands. Customer needs are satisfied by producing the highest efficiency of heat exchange and power output. The quality characteristics of the overall heat exchanger affect the satisfaction of consumers. In order to understand the consumer needs, the market for indirect fired hot water heat exchangers must be analyzed. This includes the analysis of Amtrol's competitors. Once all consumer needs and heat exchanger characteristics are quantified, the most influential design features can be found.

When comparing Amtrol's indirect fired water heater to five competitors, Weil-Mclain, Triangle Tube, Bradford White, and Burnham, Amtrol's product was weak in the first hour heating output and overall heating output.

In order to address these limitations, components of Amtrol's heat exchanger were compared to each other to determine which element or elements would have the highest impact and ease implementation on both the first hour and overall heating output. The two parts chosen based on heat output and ease of implementation are the dip tube and coil geometries and positions.

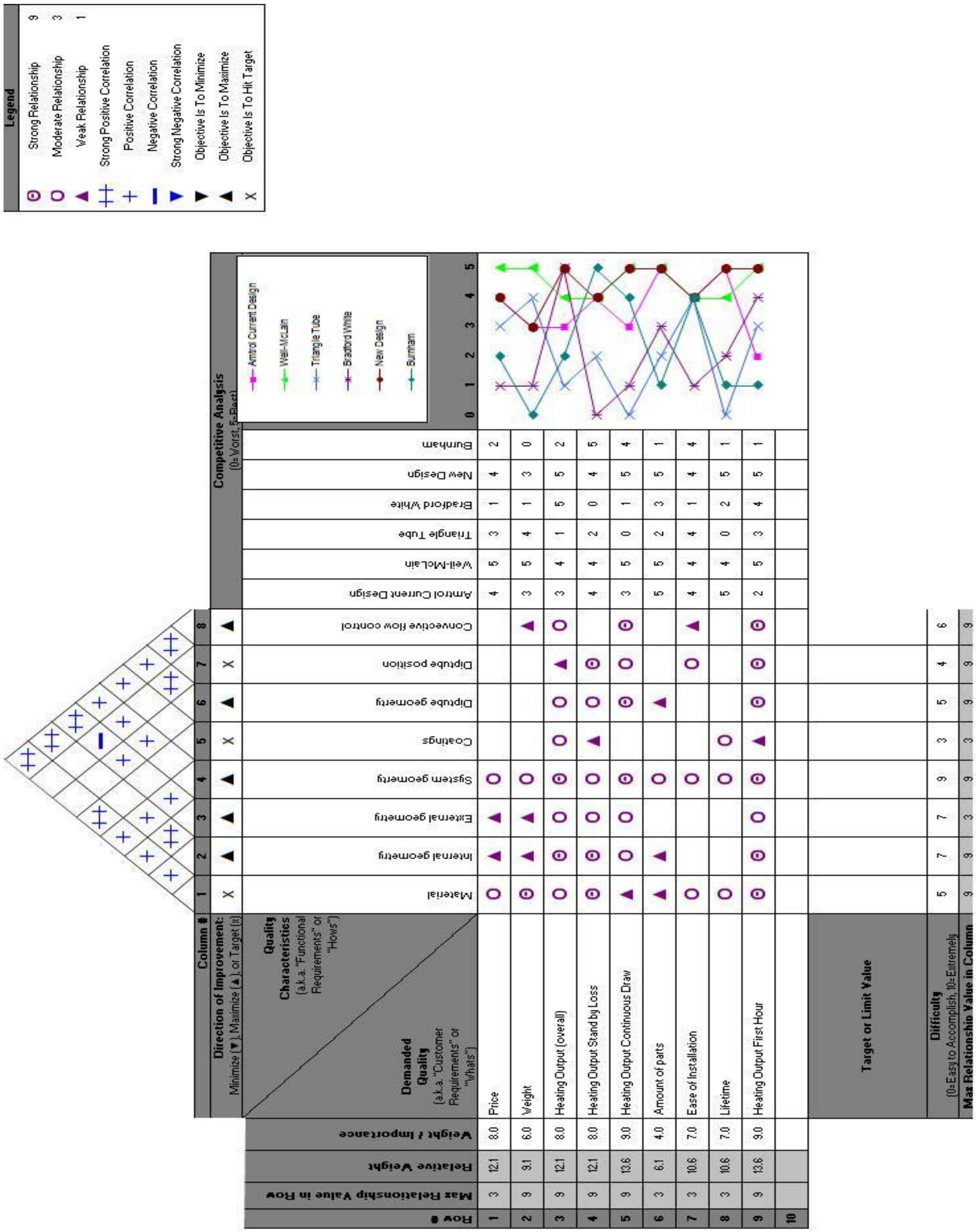

FIGURE 9: QFD - COMPARISON OF COMPETITORS AND COMPONENTS OF AMTROL

5. Patent Searches

5.1 List of Patents

Patent Number: US 6142216 A
Patent Number: US 7007748 B2
Patent Number: US 7063132 B2
Patent Number: US 5596952 A
Patent Number: US 6688261 B2
Patent Number: US 9151540 B2
Patent Number: US 4132264 A
Patent Number: US 8186719 B2

5.2 Evaluation of Patents

- **US 5596952A**: This patent was filed in 1995 and is current on all fees and payments. It was filed by Bradford white corporation, a direct competitor with Amtrol in the indirect fired hot water heater market. This patent is for a hot water heater which uses a separate heat source which circulates a working fluid throughout the heat exchanger. It is described as “providing an efficient and inexpensive water heater.”. The water heater uses a single walled heat exchange chamber, similar to Amtrol’s current design. The aforementioned patent is relevant because its geometric configuration is certainly a limiting factor of concept generation. However due to the fact that the removable plate at the top of Amtrol’s Hydromax has a diameter of 6 inches, the geometry described in this patent is not in direct competition. Additionally it was deemed irrelevant due to the likelihood there were higher losses to the environment when compared to Amtrol’s Hydromax which centers around the idea of a central helical coil heat exchanger. This theory can is demonstrated from the image below. At the bottom of the tank where the boiler water switches as a return to the “water to boiler”, the area is very close to the bottom wall of the tank.

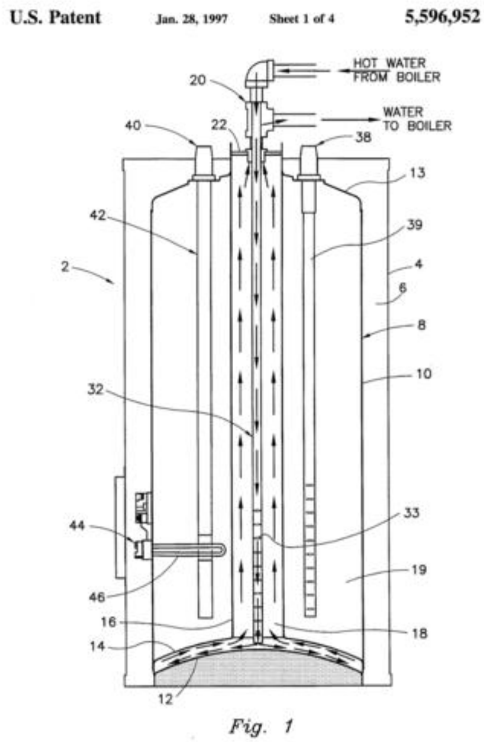

FIGURE 10: TANK GEOMETRY

- **US 6688261B2**: This patent is relatively new in relevance to the world of indirect fired hot water heaters. It was filed in 2002 and finally granted two years later in 2004. The patent was assigned to Conematic Heating Systems Inc which is more commonly known as Hybritherm. Hybritherm is a low volume specialized heating solutions company, due to their volume produced and performance output numbers they are not in direct competition with Amtrol. The patent describes this system as "A heater comprised an enhanced surface area heat transfer vessel which is situated co axially in a hot flue gas plenum. The plenum is formed by a dual-wall heating jacket. Liquid flowing through the jacket is heated concurrently by the flue has before the preheated liquid is conduced to the top of the vessel for countercurrent heat exchange." Essentially this heat exchanger is considered a dual stage heat exchanger similar to the theory behind the concept generation outlined later in this paper. However due to the overall geometry of this patent it is inapplicable to Amtrol. Due to the fact that the system also uses hot flue exhaust gasses it is not relevant to Amtrol's design. Amtrol relies on solely the use of a heated working fluid (water) from the boiler. The patent concept can be viewed below:

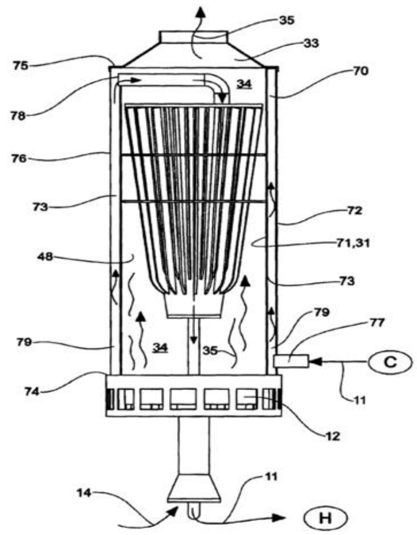

FIGURE 11: ENHANCED SURFACE AREA VESSEL

- **US 4132264A**: This patent discusses the application of organic polymers as the material selection for heat exchangers. Because of the low initial cost and weight of organic polymers they may prove advantageous to their metal counterparts despite the lack of thermal conductivity. These polymer systems can be made for complex shapes and still produce smooth piping. This provides us with a direction for an alternate material giving options to reduce cost and change the style of functionality in fluid thermal mass transfer.

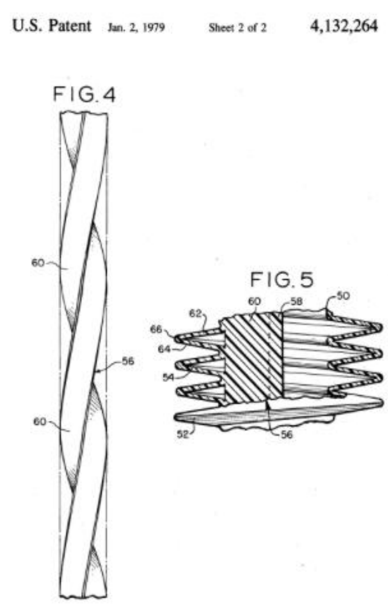

FIGURE 12: POLYMER PIPE GEOMETRY

- **US 8186719B2**: A pipe connector configured to be attached to a tubular connecting port extending from a connector-mounting surface of a heat exchanger body includes a plate-like or block-like shape base, an insert portion projecting from one side of the base facing to the connector-mounting surface and configured to be fit in and connected to the connecting port, and a leg portion projecting from the one side and configured to be abut on the connector-mounting surface.

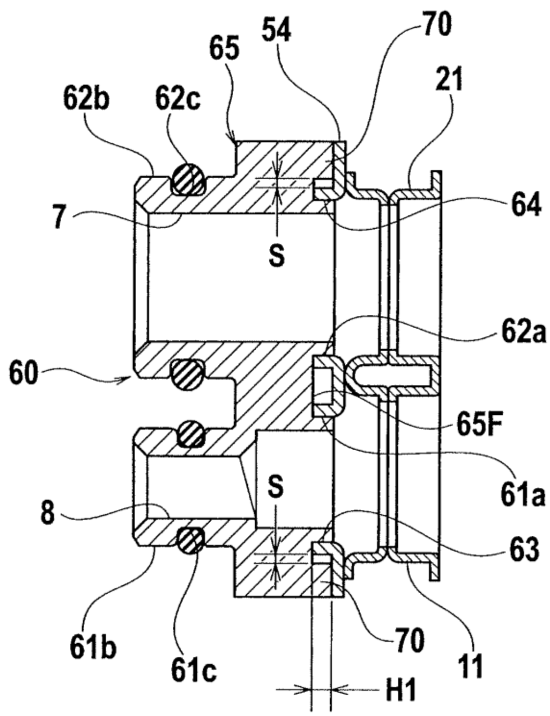

FIGURE 13: PIPE CONNECTOR

- **US 9151540B2:** This patent which describes the structure of a multichannel heat exchanger for use of cooling is useful for low pressure situations but given the internal pressure of the current design is very high relative to the normal function described in this patent the amount of losses through this system would be very large and therefore impractical.

- **US6142216A**: This patent is for a residential or commercially used indirect water heater. The hot water that is heated is stored in a glass lined storage tank. The heat source, which is indirect, heats a fluid which is circulated in a closed loop. This device was intended to heat and store domestic water by indirectly heating the fluid in the storage tank. This device is unique in the design of its circulating coil and storage tank material and geometry.

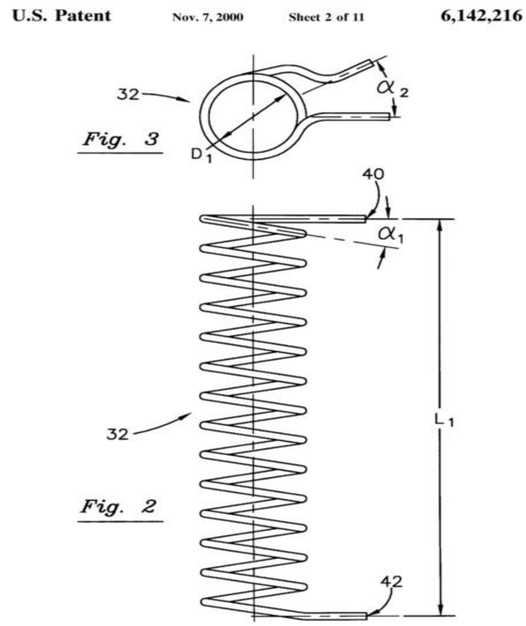

FIGURE 14: COIL GEOMETRY

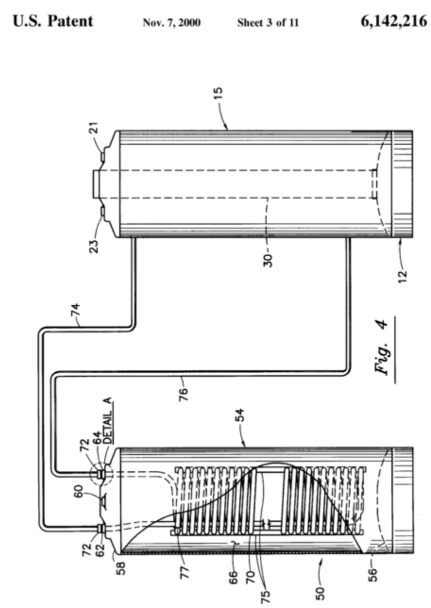

FIGURE 15: TANK GEOMETRY WITH OPEN VIEW OF COIL

- **US 7007748B2**: This patent is for a heat exchanger that was adapted for use in a water tank. It includes a tube and coiled portion. It relates to an indirect water heater and heat exchange for a water tank. This device is unique in its coil design as well as its inlet and outlet location. This patent covers the design and manufacturing of the indirect water heater seen in figure 16.

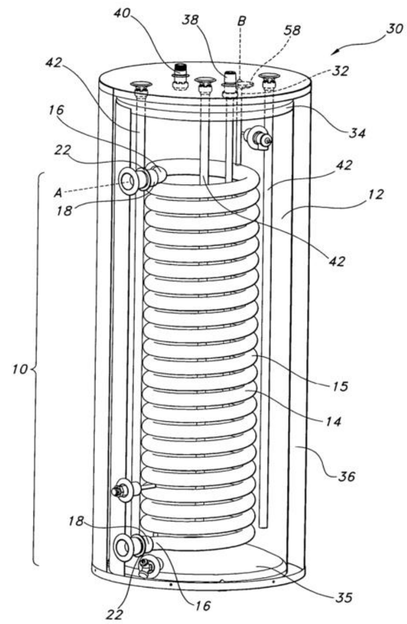

FIGURE 16: INDIRECT WATER HEATER DESIGN

- **US 7063132B2**: This patent is for a multi wall heat exchanger used for heating water. The heat exchanger is positioned in the tank and is surrounded by an interior wall. The outer tube has a wall and thin surface. This invention is unique because of its compact design and use of multiple walls.

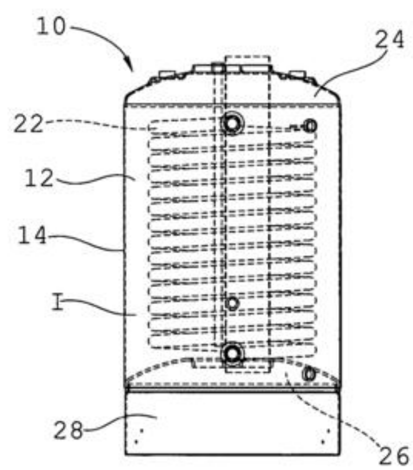

FIGURE 17: MULTI WALL HEAT EXCHANGER

6. Evaluation of the Competition

In understanding the issue that the team was faced in innovating and optimizing Amtrol's current heat exchanger design, the market was considered. The target market must first be analyzed to comprehend the requirements to be a successful product on the market. The specifications provided by Amtrol allowed the market to be narrowed down to residential heat exchangers capable of providing enough hot water to a standard household. Thus, the market for hot water heat exchangers is very large and there is a significant amount of competition. The goal for the team is to create a heat exchanger design that would be relatively cheap and light, efficient, with a good power output, and can be accurate. All of these performance targets are relative to the other products currently on the market.

These heat exchangers have been on the market for decades, therefore some of the technology has not been changed for some time. The common design for competitor products include a coiled, finned tube connected to a boiler. All competitor products must be FDA approved and potable which puts restrictions on materials and coatings. Typical hot water tanks for residential use are approximately 50 gallons with some reaching as much as 80 gallons and as small as 30 gallons. The heat exchanger the team is to design is for a 41 gallon tank. Thus, the market for this product will be around the quintessential amount in a hot water tank. Many products are similar and last very long, consequently consumers do not switch between companies and products often. Thereby, it is very important to differentiate the product the team is to design. This can be done by exceeding the performance targets mentioned earlier. Many companies have attempted to optimize the heat exchanger using different materials and different coil geometries although there is always room for improvement and innovation in this market. In essence, every heat exchanger manufacturer would love to make products with unlimited copper finned coils to optimize heat exchange due to copper's high heat transfer coefficient. Although this is not feasible as the product would be too expensive based on the price of copper. The standard working pressure within hot water tanks is approximately 150 psi, which is necessary for the water to be distributed to the desired destinations. The output power of the heat exchanger is dependent on the power output of the boiler which varies for each residential system.

6.1 Bradford White

One of Amtrol's competitors, Bradford White use an interesting technique in heat exchange using a glass coated steel coil. This is a trademark of theirs and allows for a relatively good amount of heat transfer per foot of coil. This is different to most competitors that typically have copper coiling. Bradford also has a product with a double wall heat exchanger using the same glass coated steel. Their tank also has 2in. thick foam insulation similar to other competitors. Most of their products contain two aluminum anode rods in the middle of the tank to attract charged particles that would otherwise be contaminants. These rods must be replaced upon build-up which requires more maintenance. This product is relatively heavy compared to other heat exchangers on the market which is not good for advertising purposes. Bradford White has tanks in all different size ranges, but the most similar to Amtrol's is 40 gallons. This model is different to Amtrol's in which it has a bottom-up design [1]. This means that the hot water from the boiler enters near the middle of the tank and exits at the bottom of the tank. The cold water inlet is also at the bottom of the tank, which is different to the dip-tube design Amtrol currently has.

FIGURE 18: BRADFORD WHITE TANK DESIGN

6.2 Weil-Mclain

Another large competitor of Amtrol is Weil-Mclain. They carry a variety of different sizes of indirect hot water heaters, similar to Amtrol. Their model is different to Amtrol's in having a bottom-up design similar to Bradford White's. Also, Weil-Mclain's design includes a magnesium anode rod that is replaceable which increases maintenance. The tank that holds the heat exchanger is insulated with 2in. dense foam similar to most products on the market. The most similar size comparison to Amtrol's that Weil-Mclain carries is the 45 gallon tank. Their coil geometry at the bottom of the tank includes several tightly wound stainless steel coils with the inlet at the the top of the tank and the outlet near the bottom [2]. This is inefficient as the hottest boiler water is closest to the colder tank water. The cold water inlet is also at the bottom of the tank allowing the coldest water to stay at the bottom.

FIGURE 19: WEIL-MCLAIN TANK LAYOUT

6.3 Triangle Tube

Another company that competes with Amtrol is Triangle Tube. Their product is different to the traditional coiled heat exchanger. It is essentially a tank within a tank, with the inner tank being the heat exchanger. The boiler water surrounds the inner tank, thus there is more area over a shorter period of time for the heat exchange to occur. The suspension of the inner tank allows it to expand and contract easily. Also, the inner tank is corrugated which amplifies movement, preventing build-up. Triangle Tube carries a variety of sizes of heat exchanger products but the most similar to the team's design is the 45 gallon tank. The inner tank is made of stainless steel which is relatively good for heat exchange. The selection of copper for the inner tank of this product may be a more efficient choice, although significantly more expensive. The outer tank is insulated using polyurethane which is similar to most products on the market [3]. This product is one of the lighter heat exchangers on the market which is attractive to consumers for installation purposes.

FIGURE 20: TRIANGLE TUBE TANK LAYOUT

6.4 Crown Boiler

A company that has been directly competing with Amtrol is Crown Boiler. Crown Boiler has unique products. The tanks are porcelain-enamel coated, and use anode rods instead of tin coating to prevent fouling effects. The price points are about the same but Crown Boiler offers a two inch thick CFC-free foam insulation to keep the water hot during standby periods. The appearance of the water heater is moderately appealing. Other than the entrance and exit locations for hot and cold water, the tank is almost identical in performance.

FIGURE 21: CROWN BOILER MAXI-THERM 2

7. Specifications Definition

In order for any engineer to improve upon a system or solve a problem the problem or system must first be established, and understood parametrically. In regards to the heat exchanger being designed for Amtrol this task was more simple than one might have expected because despite the fact that this product is designed for the common household the biggest customers of Amtrol are the contractors who are in some way already technically informed about the product. This can be coupled with the fact that the indirect water heater has been a product at Amtrol for over 20 years (CITE) which means that quantifying their functions have been well established by the company.

In order to quantify any general parameters of a given object's function one must first ask the basic questions, examples of such could include:

- How much does this cost?
- How well does it work?
- How much will it cost to maintain and run?
- How heavy is it?
- Do engineering decisions indirectly affect what already works?
- Is it easy to install?
- Is it easy to manufacture and assemble?
- Do modifications incur additional costs?
- Do modifications affect the manufacturing process?
- Will there be a profit made from this device?

These questions may come from a variety of standpoints. As a design engineer one must cater to all levels of customers including in this case, the homeowner, the contractor or plumber, the manufacturer, marketing team strategy, and the company in which the engineer is employed. Because there is already an existing indirect heat exchanger design produced by Amtrol a lot of the parameters values will be based on or compared to the existing specifications of the current model. Below is a chart showing the question and the parameter associated with it.

TABLE 1: PARAMETRIZATION OF GOALS

Question	Parameter	Goal
How much does this cost?	Cost	< $1230.72*
How well does it work?	Thermal output	10% greater than current model
How much will it cost to maintain and run?(Water heater)	Efficiency/Reliability	5% less run time**, and 7 year standard lifetime
How heavy is it?	Weight	< 144lbs
Is it easy to install?	Design for ergonomics	Connection size .75in (standard), connection height 55in
Is it easy to manufacture and assemble?	Number and complexity of parts	< 2

* The price marker is set to be equal to less than or equal to the current market value of the Hydromax(CITE), but depending on what other advantages are introduced in this new model Amtrol may decide to sell the product for more, which is why the last question from the list above is not listed in this chart.

** The 5 percent less run time will result in a savings in oil and therefore will reduce the cost of operation for the water heater and reduce emissions, a nice selling point for Amtrol; the five percent decrease in run time is based on the increase in thermal efficiency.

8. Conceptual Design

Team Intercambiadores was given the problem to improve the Hydromax® 41 gallon Indirect-fired water heater. The first part in the process of accomplishing this was to generate concepts in order to get the team focused on the problem and eventually better understand what it would take to solve. This conceptual design process generated over one-hundred and fifty concepts.

It was then organized into a list of thirty brief titles of the concepts per group member, (8.1). Through the design process, discussed in sections 2.0 through 2.4, the concepts were narrowed down and separated into two distinct sections; concepts used in the preliminary design with reasons (8.2) and concepts not used in the preliminary design with reasons (8.3). Designs that repeat, with discretion, were not included to the list of concepts used and concepts not used.

8.1 List of Concepts Generated

<u>Matthew Jackvony's Concepts</u>

1. Sectional tubing and PEX design
2. Copper tin plated new external fringe design
    a. random cut flanges
    b. spiral cut flanges
    c. Longer external flange length
    d. Exploration of flange thickness for optimized heat exchange through free convection
3. Opposite flow optimization (like gills on a fish)
4. Internal barrel design
    a. Use a cone like structure for more even cold water distribution
    b. Use an open but leading conical and spiral structure in the dipstick to more evenly disperse water
    c. Guide rings on the internal barrel to encourage less loss due to external turbulence
5. Design the heat exchanger so that time to temp is obsolete(aka the design heats water first so that as it passes through the high section of the tank the water is warm having a more cyclical behavior in heating)
6. Compartmentalize the water heater to better distribute heat exchange so that the hottest water is working on the coldest water initially
7. Internal pipe geometry ideas
    a. Rifling of the internal pipe (evaluate the angle at which rifling is optimal)

b. Ribbed sections in the pipe (perpendicular to flow but not continuous)
c. Oblong bump geometry
d. Tube twisting (not 360 but oscillating 180 degrees)
e. Large scale bump pattern
f. Rough but random internal surface
g. thin pipe (non-circular)

8. Dipstick geometry design
    a. Curved dipstick for more control of cold water flow rate and direction in order to encourage cleaner distribution
    b. Small subchamber to have premixing of cold water with hottest section of pipe in order to get early exposure to heat source
    c. Dipstick designed to run along the edge of the barrel to the bottom in order to isolate the turbulence in the system
    d. Insertions of 1/x output spout to put cold water our at a height following to the edges
9. Do not use piping at all but instead use flow through large curved plates
10. Spiral pipe (overall geometry)
11. Use plate to form external cone (conic section maybe hyperbolic)
12. PEX large flexible tube to run along the base of the system like a heat plate
13. Inverted spiral (elliptical) about the x or y axis as compared to the z axis
14. Different shape pipes (largest surface area per ratio of area and manufacturing cost)
15. Splitter to flow hot water through a network of pipes in order to have water of the same relative temperatures at any given height of the barrel
16. Corrugated pipe sections to allow for more flexibility of the pipe structures so more pipes may be fit in the design
17. Very large pipe diameter to encourage flow and reduce head loss
18. Output of dipstick direct onto the up flowing portion of the hot pipe structure to suck out any remaining heat
19. Flow regulating valves in order to control flow and optimize exchange based on individual flow

<u>John Papa's Concepts</u>

1. A disc shaped piece that will attach to the end of the existing dip tube.
2. A spherical object that will attach to the end of the existing dip tube
3. Holes will be added to the sides of the existing dip tube.
4. Holes will be added to the sides of the dip tube and the end of the dip tube, which is open now, will be closed forcing the water out in the directions of the cut holes.
5. The heat exchanger coil will be made of PEX and larger than the diameter of the top of the tank. It will have the hot water return on the outside of the large PEX coil.
6. The heat exchanger coil will be made of PEX and larger than the diameter of the top of the tank. It will have the hot water return on the inside of the large PEX coil.

7. A portion of piping with a higher diameter than the pipe of the heat exchanger will be attached to the top of the heat exchanger.
8. A small finned length of tube with a larger diameter than the heat exchanger coil will be attached to the bottom of the hot water tank.
9. More copper coils will be added to the existing heat exchanger.
10. The pipe diameter of the heat exchanger will be increased.
11. The heat exchange coil will be wound vertically instead of longitudinally.
12. The existing fins of the heat exchanger will be made larger on the interior of the copper tubing.
13. The heat exchanger finning will run right to left instead of up and down.
14. The outside of the heat exchanger will have increased finning.
15. An insert the encourages water to move in a vortex will be added to the interior of the heat exchanger.
16. An insert that uses a wire secured in tension will be added to increase vibration of the fluid.
17. A number of small copper tubes will be used instead of one large tube for the heat exchanger.
18. The copper tube used in the heat exchanger will be twisted. This will change the tube from a cylindrical shape to an oblong geometry.
19. An insert that encourages mixing will be added to the inside of the heat exchanger.
20. Instead of copper a PEX coil will be used. The PEX coil will be tightly wound and secured using wraps.
21. The heat exchanger will be separated into two fittings. The first a large diameter tube where the water is brought into the tank. The second is a reducing connector that connects the larger diameter to a smaller diameter where the hot water will return to the boiler.
22. A large coil at the bottom of the tank will be used instead of the existing copper heat exchanger coil.
23. A baffle will be used to separate the temperature layers of the water within the tank.
24. A baffle with holes in it will be used to separate the temperature layers of water but will also allow for circulation within the tank.
25. A stainless steel tubing will be used instead of copper.
26. PEX tubing will be used for the coil instead of copper.
27. A flat plate heat exchanger will be used at the top of the tank.
28. The tank will be adapted to allow for a higher diameter copper piping.
29. The cold water input will be a tube within the hot water tube.
30. A large diameter single u shape will be used instead of a coil.

Adam Camillo's Concepts

1. Taking a look at current design and investigating if the fin length is optimized as well as the inner pipe radius
2. Micro-pipe diameter, d</= 1.0mm
3. Many inlets from boiler to different piping allowing more surface area for heat transfer

4. Using PEX material instead of current copper design
5. Non-circular pipe cross-section
6. Flat plate heat exchanger
7. Tankless water heater
8. Hybrid tankless water heater
9. Inlet of cold water in tank with a shower like nozzle to distribute the cold water evenly throughout the bottom of the tank
10. Helical coils for overall pipe configuration
11. Longitudinal fins on external pipe geometry
12. Corrugated inner pipe geometry; thin-walled smooth tubes
13. Studded finds; individual studs could be welded or cut in specific patter on outside of heat exchanger pipe
14. Helical or helical-segmented fins on outside of pipe
15. Serpentine pipe configuration
16. Allow hot fluids to enter tank using hot fin plates rather thank piping design
17. Flat or continuous fins on an array of tubes
18. Wire-form outer pipe fin geometry
19. Using valves at inlet of hot fluid to regulate the optimal flow rate to meet specific temperature and time constraints
20. Multiple heat exchangers within one tank
21. Line outside of tank with PEX
22. Using pipes, line the inner tank in the longitudinal direction
23. Disperse cold water at bottom or top of tank
24. Using optimal pipe geometry and configuration, plastic material could be used
25. One larger vertical pipe that loops around and converges into a smaller diameter pipe that wraps helically around the larger portion
26. Holes cut longitudinally into pipe wall
27. Using stainless steel or aluminum compared to current copper design
28. Zig-zag fin design on outside of pipe
29. Wavy fin design on outside pipe
30. Proportional hot and cold flow rates

Francesco Palumbo’s Concepts

1. Increased coil density near the bottom of the heat exchanger.
2. Increase the overall diameter of the shaped coil
3. Multiple cone shaped heat exchangers.
4. Dual stage heat exchanger
5. Shower head style dip tube.
6. Spherical hot plate heat exchanger
7. Porous material for cold water inlet dip tube
8. Match inlet and exit velocity of the heat exchanger
9. Multiple high pressure misters as inlets for the cold water.
10. A combination of both produce style misters at the top of the dip tube, as well as a shower head.
11. A circulation pump situated within the tank to promote turbulence.

12. A temperature activated valve within the tank.
13. A manifold which splits incoming boiler water into multiple interweaving pipes or coils.
14. A top down style tube and shell heat exchanger.
15. Cylindrical heat exchanger which sits at the center of the tank.
16. A pre-shaped flexible material that can fit within the tank because its volume is small deflated.
17. Use a shower head type distribution head that is connected hydraulically to a pressure driven wheel.
18. A spherical style cold water inlet which more evenly distributes inlet water.
19. A pressure driven hydraulic wheel which stirs the tank.
20. Replace existing helical coil heat exchanger with an internal shell and tube heat exchanger.
21. A shell and tube heat exchanger that has rotating tubes within the enclosure.
22. Prepacked UV sterilizer.
23. A dual stage style heat exchanger but less complex than those previously mentioned.
24. Replace the tin plating on the coil with a cheaper synthetic.
25. Recycle the gas emissions from the flue.
26. Change the plate size at the top of the tank
27. Alter the poly bottle to accept a baffle more easily
28. Change the insulation material to a more exotic material
29. Paper clip style hot water heat exchanger
30. Serrated fins on heat exchanger

Javier Sesma's Concepts

1. External barrel design
2. Reduce the thickness of the materials forming the barrel in order to reduce costs without neglecting heat losses.
3. Try to reduce the weight of the barrel to decrease costs as transportation.
4. Investigate about a barrel design that can be manufactured quickly and practically automated.
5. Improve the sealing of the barrel to avoid heat loss.
6. Internal barrel design
7. Try to optimizing the cold water distribution using a "cone" structure.
8. Internal lining design. Try to get a better lining to reduce the heat loss.
9. Materials models that include the barrel.
10. Fluid inputs and outputs.
11. Pipe diameter - Larger diameter reduces head loss and increase the flow rate.
12. Decrease the diameter of the pipe to reduce costs and space.
13. Decrease the size could increase the difficulty of cleaning.
14. When determining the thickness of the pipes must leave enough space in the inside for corrosion that might occur.

15. Try to do more pipes increasing the length and decreasing the diameter, because they are cheaper.
16. Corrugated pipe sections would allow more flexibility.
17. Corrugated pipe sections because it increases the turbulence of the fluids and therefore this solution increase the efficiency.
18. Finned tubes to increase the heat exchange area.
19. Must leave enough space in the pipes for corrosion that may occur.
20. Study the pipe layout to try to reduce the internal space of the barrel and decrease costs.
21. Try to design the heat exchanger with multiple steps because that improve the efficiency in the heat exchanger, relative to single step.
22. Study the possibility to change the design to a free convection heat exchanger.
23. Study the possibility of improve the forced convection.
24. Spiral pipe reduces the costs in addition to reduce the pressure drop allow smaller and more efficient fluid moving equipment.
25. Study of materials for the pipe - PEX
26. Spiral Heat Exchangers to increase the efficiency of the space.
27. Spiral Heat Exchangers may be used to reduce the pressure drop, the pumping energy, the costs and to improve the thermal efficiency.
28. In order to increase the efficiency we can study the use of mechanical aids, surface and fluid vibration and the use of electric and magnetic field.
29. In order to increase the efficiency we can study the use of fluid additives and devices to increase fluid turbulence.
30. Try to avoid the corrosion and oxidation of the materials that form the pipes and the barrel.

8.2 Concepts used in project with reasons

1. **Variable pitch heat exchanger:** In exploration of the thermal behaviors of this extremely complex system composed of conduction and free and forced convection it was found that the difference in the temperature of the water in the piping versus outside the piping played a critical role in encouraging heat exchange. In order to take advantage of such a system the heat exchanger must have a geometry such that the hottest water is flowing through the pipe that is exposed to the coldest part of the tank as much as possible. In order to do this without drastically increasing material cost a variable pitch heat exchanger may be used. This design would allow for a section of denser coils at the bottom of the tank which then get progressively less dense where the water has approached thermal equilibrium therefore making the most use out of the incoming energy from the hot water.

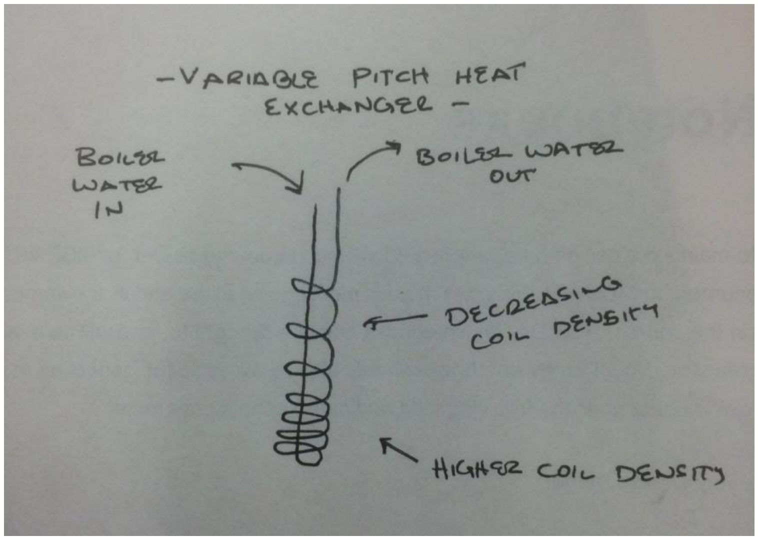

FIGURE 22: VARIABLE PITCH HEAT EXCHANGER DRAWING

2. **Dip tube altering:** The dip tube is where the cold water enters the water heater from the domestic water source. Holes will be put in the dip tube to allow the water to flow in all directions rather than just straight down when exiting the dip tube, towards the bottom of the tank . This should reduce the exit velocity of the water and allow for a smoother temperature gradient within the tank. With the exit velocity reduction, the turbulence within the bottom of the tank should also be reduced.

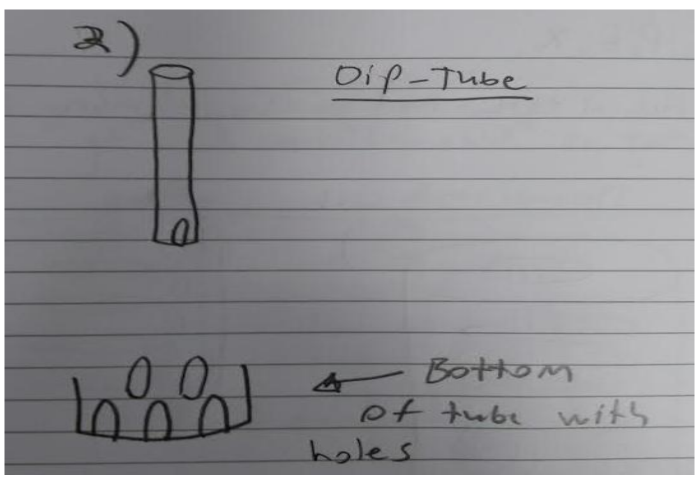

FIGURE 23: DIP TUBE ATTACHMENT

3. **Dip tube altering (Closed End):** The closed end of the dip-tube provides a very specific advantage to the thermal system inside the tank. In order to reduce thermal losses due to unwanted mixing in the tank this closed end will reduce the momentum of the fluid in the y-direction. This shift in momentum direction will reduce the amount

of stochastic behavior in the mid height of the tank, and because the convective behaviors of the tank lead to convective forces in the positive y-direction this will reduce the overall loss for the tank.

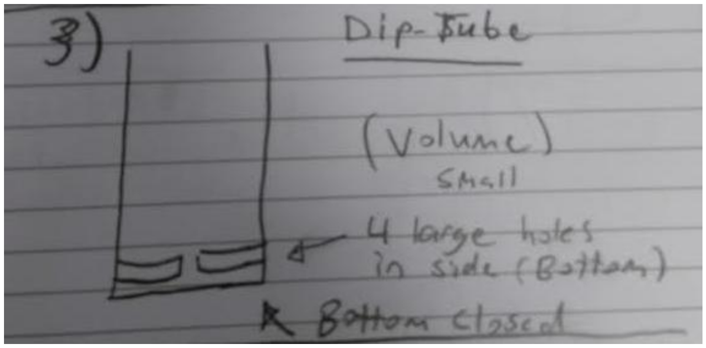

FIGURE 24: CONCEPT #1 DIP TUBE ATTACHMENT

8.3 Concepts not used in project with reasons

1. This design allows for the use of PEX as a more major material in the design of the heat exchangers. As of yet it is unsure whether PEX will meet all of the needs for this system so further testing will be required to affirm its use, but possible advantages include lighter weight, cheaper, more heating length, and more flexibility in coiling environment

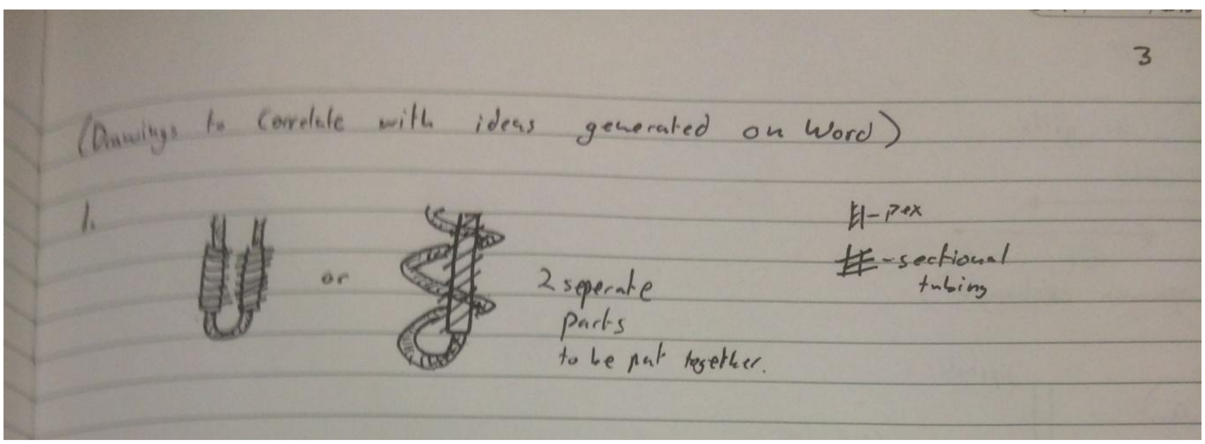

FIGURE 25: PEX SECTIONAL TUBING

2. (a-d) This collection of suggestions deal with the idea of a thorough evaluation of the fin structure associated with the heat exchanger. Careful evaluation could be done to optimize the fin structure and enhance the heat transfer, but the re designing of these fin structures would prove difficult from a manufacturing point of view which presents difficulty. This issue has made this a lesser priority during the design phase and more a possible consideration for Amtrol in the future.

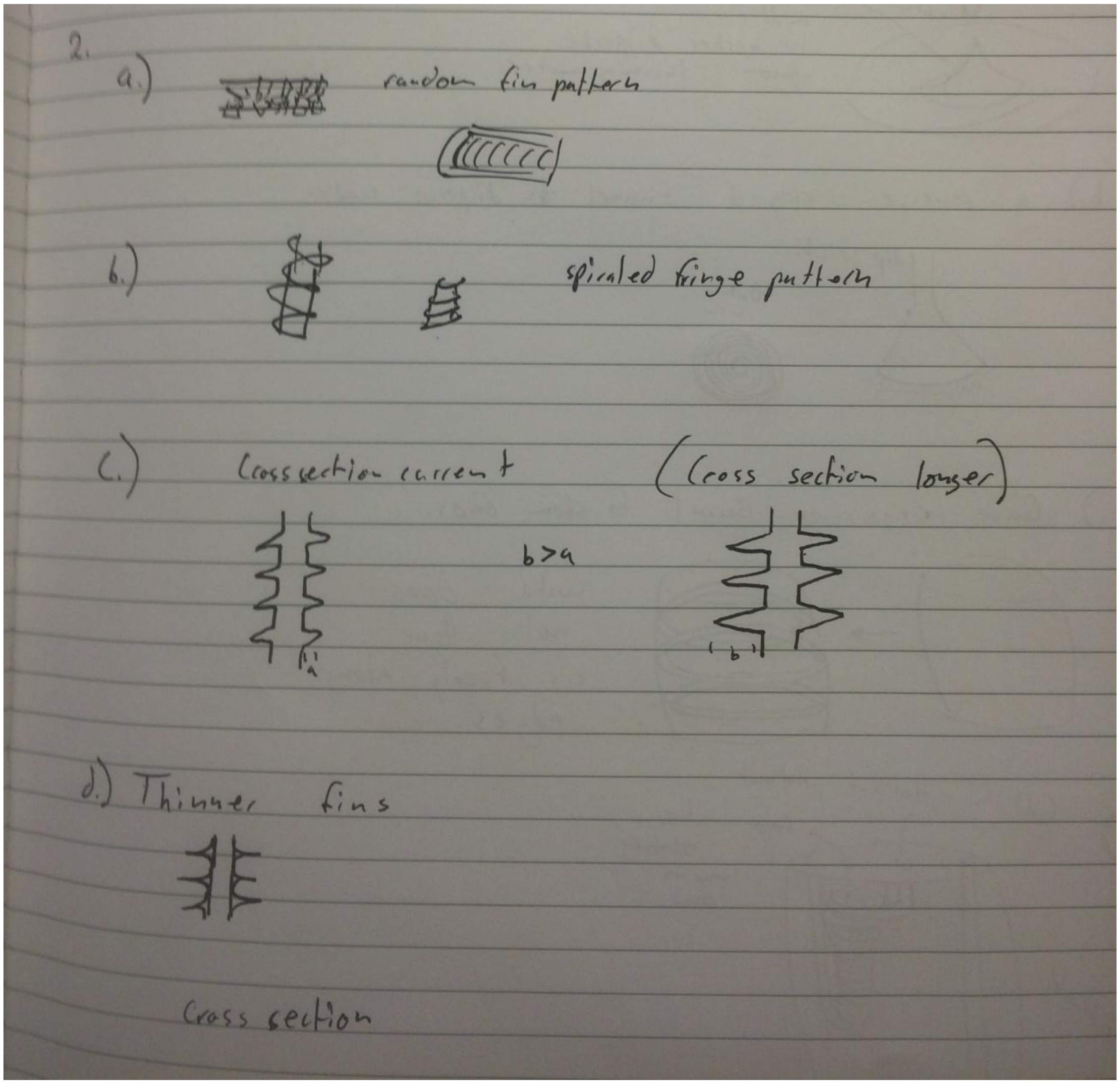

FIGURE 26: FIN STRUCTURE

3. This is more a simple concept worth exploration than a design specifically. In order to optimize heat transfer new designs will encourage heat exchange by making sure the hottest fluids are flowing in the opposite direction of the coldest fluids. This idea will be considered in designs and if possible incorporated.

4. (a-c) The internal barrel design was an early concept of changing the barrel shape in order to promote heat exchange and dampen the loss due to thermal stochastic behaviors. Because of the aims of the revisions for our designs and given the guidance from Amtrol these designs have been removed as options because the barrel design is well established and will not be changed as part of the revisions for the heat exchanger.

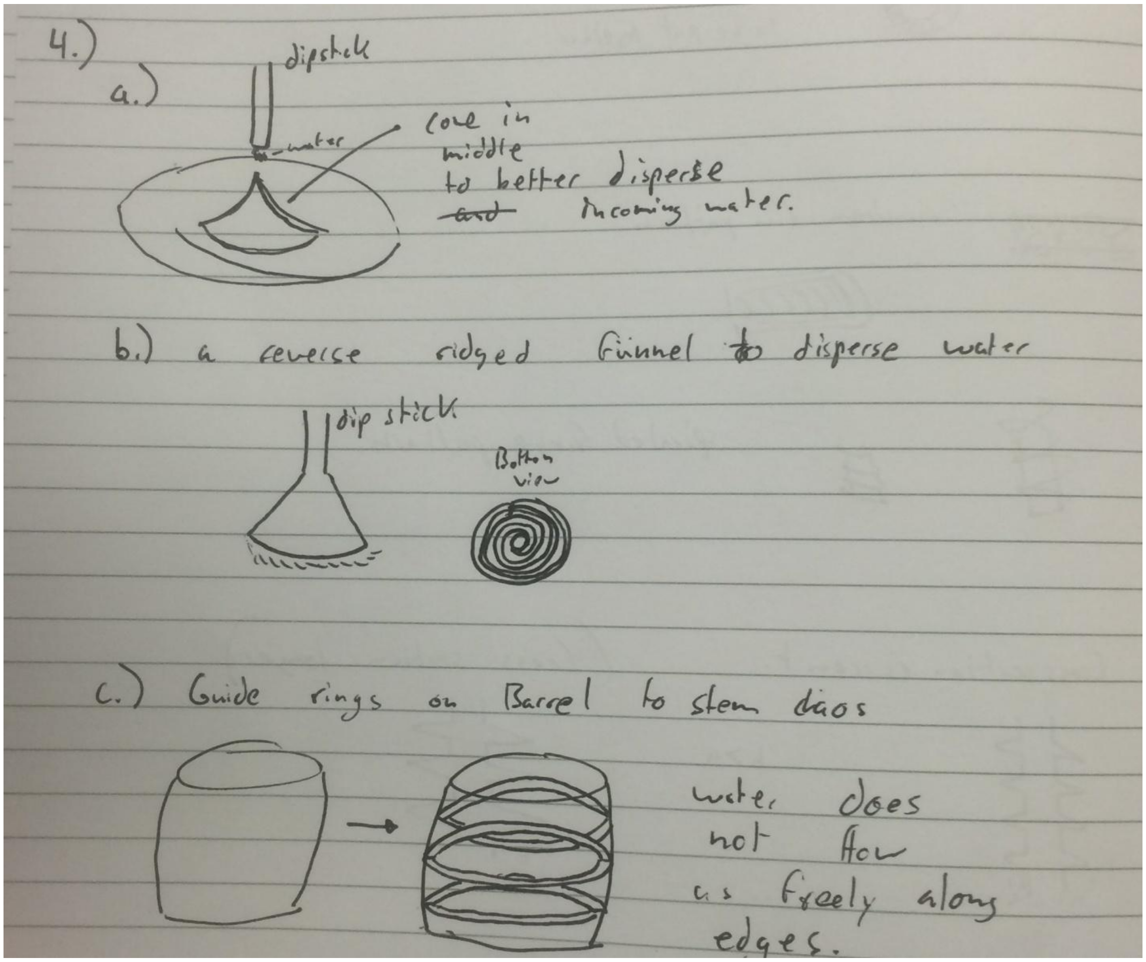

FIGURE 27: INTERNAL STRUCTURE DESIGN

5. This design suggests designing a heat exchanger which acts more as an instantaneous heat exchanger as compared to the current model which is designed to bring large masses of water to temperature but have a lesser localized thermal efficiency.

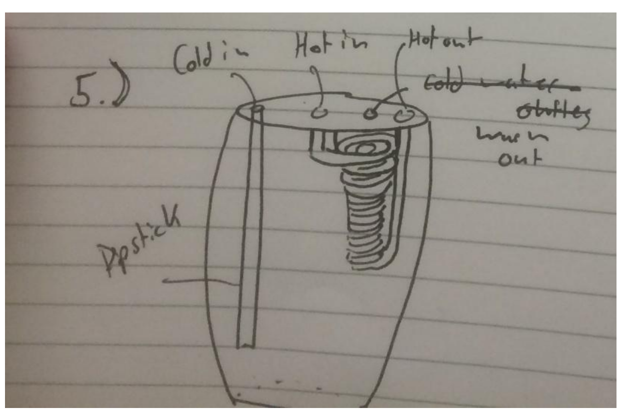

FIGURE 28: INSTANTANEOUS WATER HEATER

6. The idea of compartmentalization, despite being simple, falls under the same issue as previous design suggestions in that there is little desire by the company to change the internal geometry of the barrel. Because this is the best method by which to section off this system this option will not be explored.

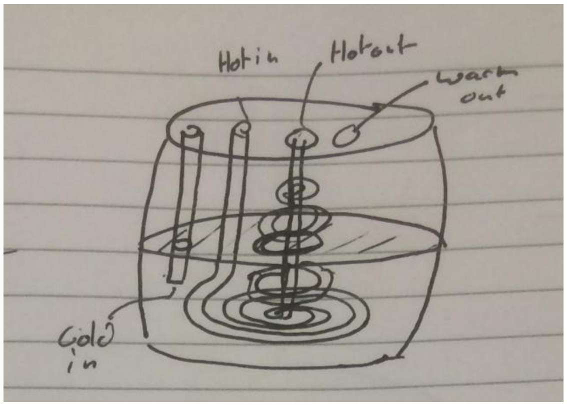

FIGURE 29: COMPARTMENTALIZATION

7. (a-g) Internal pipe geometries is one of the sets of ideas with the most potential to improve or change the current design. There are a wide variety of options and due to the complexity of the system testing must be done in order to determine the benefits of any given geometry. The only constraints are that the geometries must be affordably manufacturable, and it must be able to be coiled into any of the existing or desired external geometric structures.

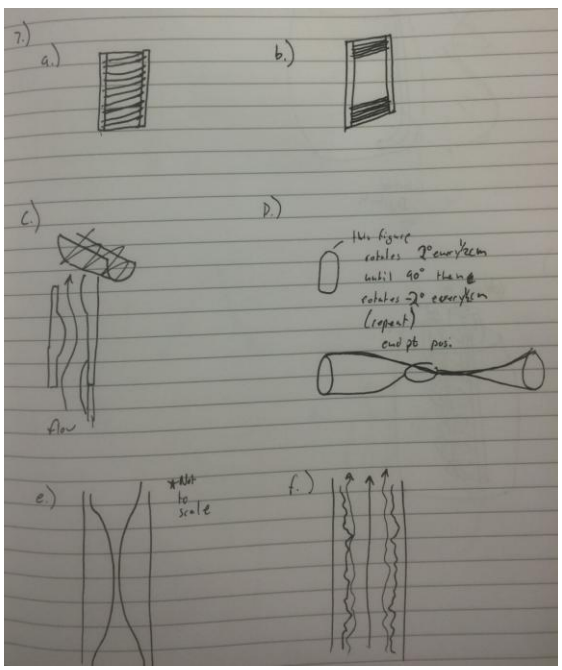

FIGURE 30: INTERNAL PIPE GEOMETRY

8. (a-d) The dipstick is currently an under analyzed part of the heat exchanger system. In order to remedy this part of the design revision process will involve an analysis as to the behavior of the outgoing water from the dipstick given different nozzles on the end of the stick. This will allow for better flow control inside the tank for more predictable results that should yield higher thermal efficiencies.

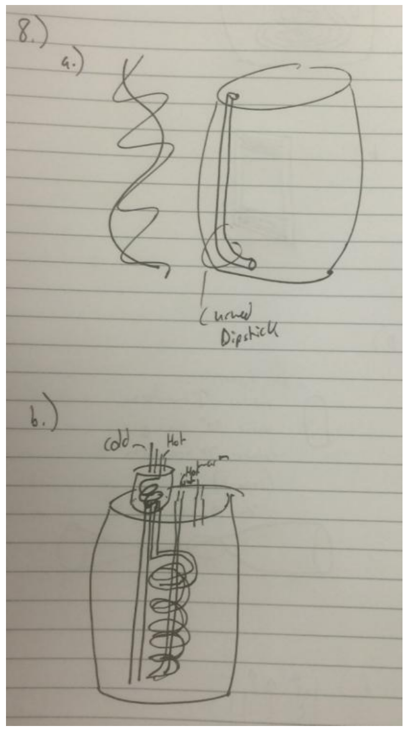

FIGURE 31: DIP TUBE DESIGN

9. The suggestion of flow through cold plates relates to questions of surface area per ratio of thermal mass. If the plate containing the hot water was thin enough it could mean extremely high rates of heat transfer, but a major flaw with this design is that in order to force all of the hot water to follow a set path and truly circulate that system the head loss would be very large and the velocity very small which would result in poor convective heat transfer.

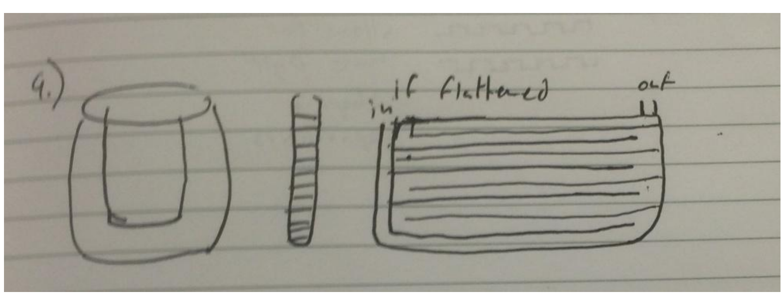

FIGURE 32: PLATE EXCHANGER

10. An overall spiral geometry is already employed in the system, different spiral structures introduce increased complexity and manufacturing difficulty despite unproven potential benefits.

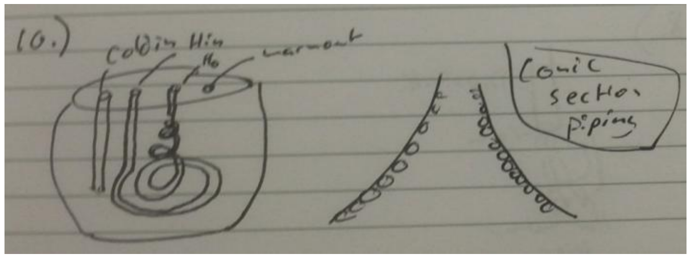

FIGURE 33: CONIC SECTION PIPING

11. This design, like many others, does not take into account the difficulties associated with the manufacturing of such a structure, and with an untested design such as this there is too great a risk of loss to test such an abstract and unproven design.

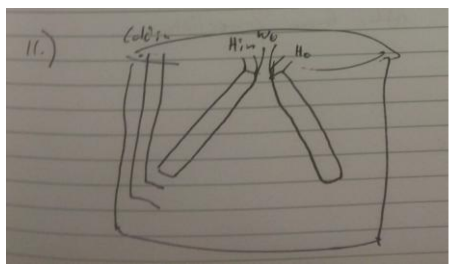

FIGURE 34: PLATE CONIC SECTION

12. While PEX has been suggested before this idea creates a specific functionality for the PEX in this environment. This design takes advantage of the flexible nature of the PEX in order to allow for this wide system to be bent inward in order to allow it through the open orifice of the tank and then expand to fill the bottom of the cavity

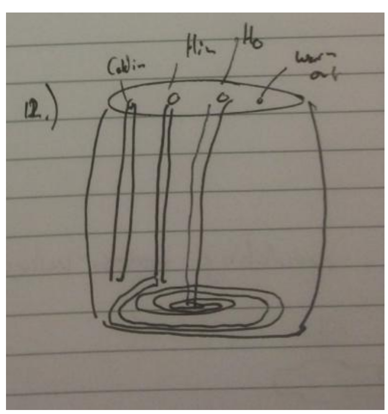

FIGURE 35: PIPE PLATE DESIGN

13. The inverted spiral is an interesting design that incorporates a new type of thinking, but the idea is untested and as a further challenge the bends made to produce this coil geometry will most likely cause kinking in the pipe structure which is the reason this design will not be explored further.

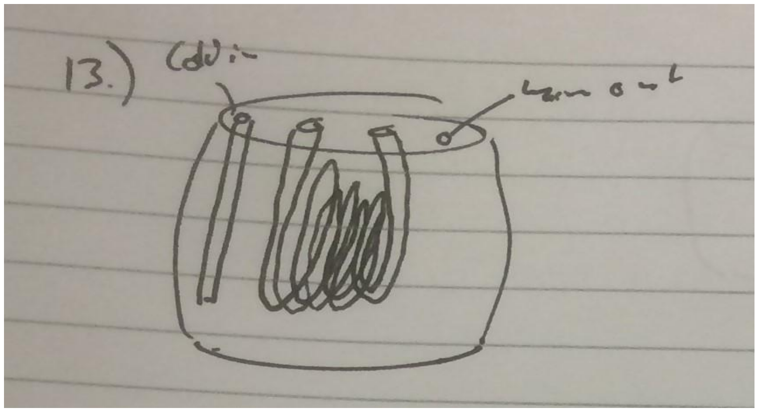

FIGURE 36: INVERTED SPIRAL DESIGN

14. Different shape pipes will change the hydraulic diameter of this pipe system and change the need for fins on the pipe. In order to make this idea practical a supplier must be found who can relatively cheaply produce pipe of abstract geometries. Another issue associated with this concept is the challenge of connecting this abstract shape to a standard pipe of some kind. While these challenges are pressing a few of these lengths of pipes will be tested in order to determine their benefits and detriments further.

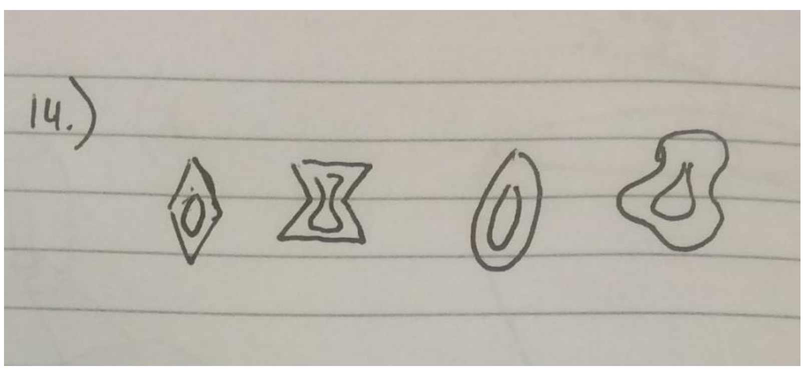

FIGURE 37: EXTERNAL PIPE GEOMETRY

15. This idea involves using a complex piping network to split the flow into a number of smaller channels to increase the overall surface area which would heat up the potable water. In actuality this idea has major flaws because the amount of pressure needed to propel the water through the smaller tubes at a practical velocity would be very large. And the cost of such a complex system is problematic because such a system would introduce a large number of complex parts which would drive up the cost.

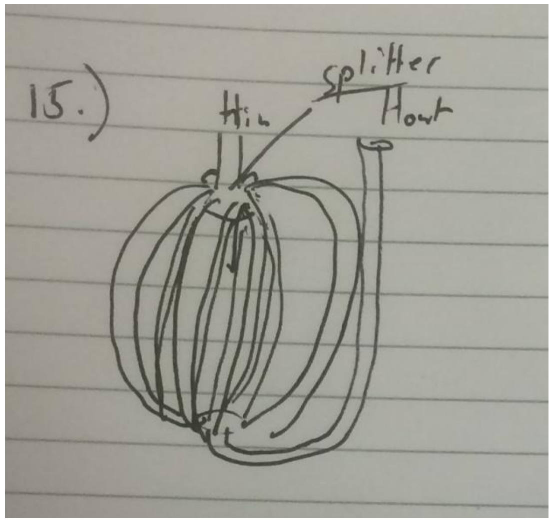

FIGURE 38: SPLITTER DESIGN

16. Corrugated pipe is commonly found in applications such as gas tight piping and is relatively unexplored in the application of heat exchange. The advantage to such a pipe structure is that it is naturally finned in structure and is flexible and easy to use. The drawback to such a design is that most corrugated pipe is made of steel which presents a significant disadvantage compared to copper in thermal conductivity.

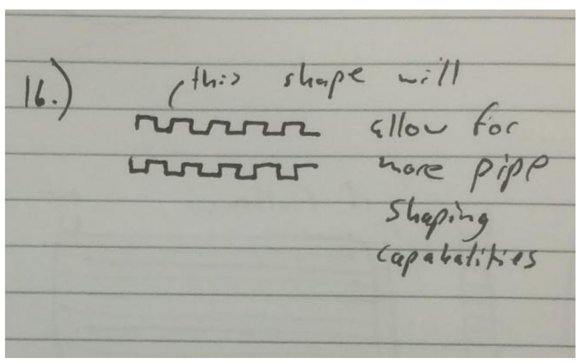

FIGURE 39: CORRUGATED PIPE

17. This has yet to be tested. The basic idea is that with a larger pipe diameter the water will flow faster therefore encouraging a better rate of heat exchange, but the current finning and coiling method do not allow for the change in diameter and so this would add a significant cost to change the manufacturing structure, but this idea is still being explored to be applied for future heat exchangers.

18. Here the idea is to take advantage of the higher outlet velocity of the current design to encourage a localized high rate of heat exchange, but given the current direction of design for the new heat exchanger this type of high localized mass flow rate may no longer exist making this idea impractical.

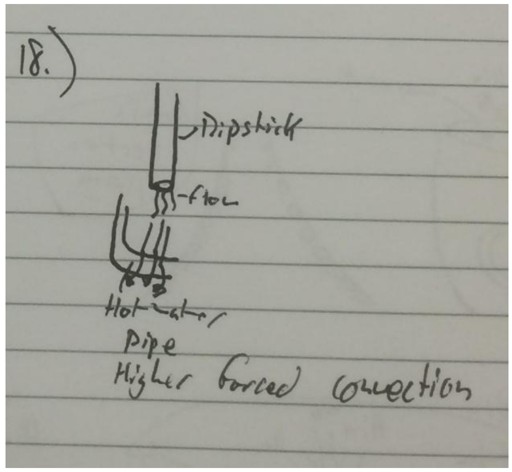

FIGURE 40: FORCED CONVECTION

19. Flow regulation would only work if there is an over flow tank, but it would not serve the advantage necessary as heat exchange takes time and so immediate control would not benefit the system. Thermal mass takes time to react and the best way to control those things.

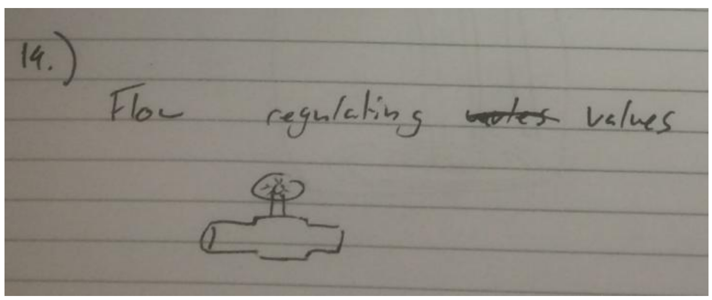

FIGURE 41: FLOW REGULATING VALVES

20. Dip tube attachment (Disc). This idea will improve the heat exchanger by separating the temperatures of water. It will ensure the cold water is at the bottom hot water at the top of the tank. The separation is desired as the water is being drawn from the top of the tank,the hottest therefore should be there. A dip tube attachment was not used in our design because it was an unneeded cost. It was found that the existing dip tube could be altered to accomplish the same goal. This alteration would limit the cost while getting all of the benefits of this idea.

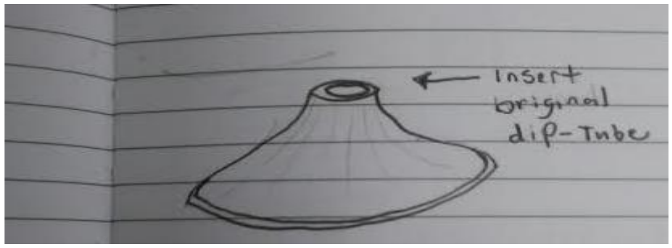

FIGURE 42: CONCEPT - ROUND DIP TUBE ATTACHMENT

21. Dip tube attachment (Sphere). This will help distribute the cold water evenly over a volume rather than an area. This 3-D distribution should allow for even settling.A dip tube attachment was not used in our design because it was an unneeded cost. It was found that the existing dip tube could be altered to accomplish the same goal. This alteration would limit the cost while getting all of the benefits of this idea.

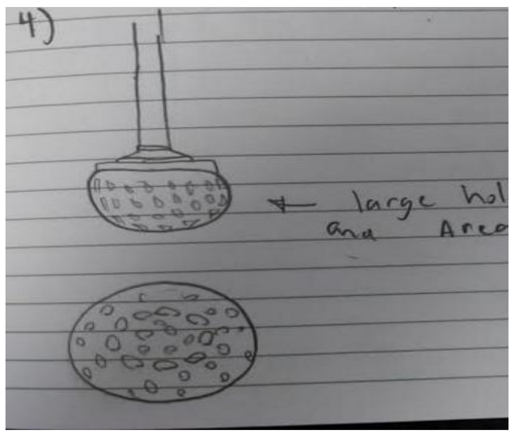

FIGURE 43: SPHERICAL DIP TUBE ATTACHMENT

22. Helical PEX coil (With Hot Return Outside). The coil can be rotated into the barrel of the tank. This will enable a larger diameter coil to be inserted into the barrel than previous. The action of inserting the flexible PEX tubing will give the ability of more surface area inside the tank. The hot water return will be outside the coil allowing for transfer along the wall. The hot water return on the outside proved to be a problem. One of the restrictions on the project is that the group can not alter the top cap of the tank. In order for the hot water return to be on the outside of the heat exchanger coil the top cap would have had to have been altered.

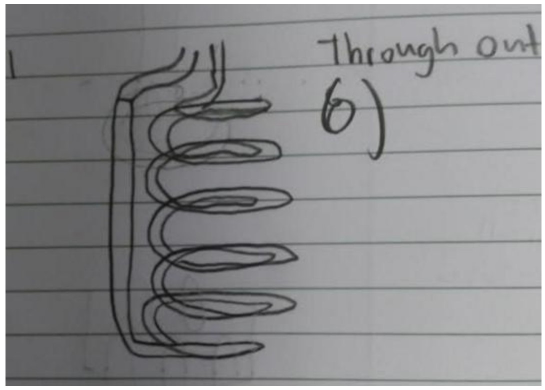

FIGURE 44: HELICAL COIL WITH OUTSIDE RETURN

23. Helical PEX coil (With Hot Return Inside) The coil can be rotated into the barrel of the tank. This will enable a larger diameter coil to be inserted into the barrel than previous. The action of inserting the flexible PEX tubing will give the ability of more surface area inside the tank. The hot water return will be inside the loop allowing for heat transfer within the center of the tank. Although it was possible to have the hot water return go through the center of the coil, it was chosen, as of now, not to use PEX for the primary coil material.

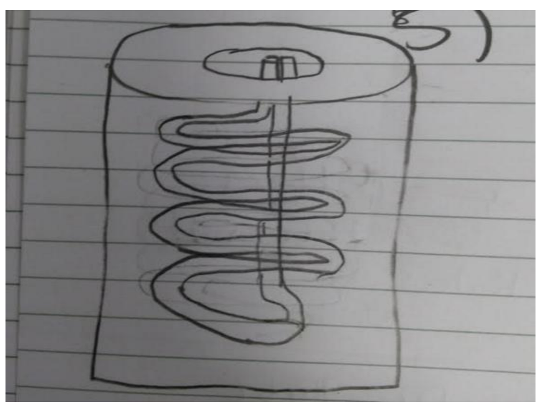

FIGURE 45: HELICAL COIL WITH INSIDE RETURN

24. Small Empty Exchange Tank. A tank with a higher diameter than the pipe will be added to the top of the device right before the hot water out to sap the last bit of energy out the water. An empty exchange tank was not used in the design because it was impractical to manufacture and add to the system. It would have produced a slight increase in efficiency but would not have been worth the investment to implement.

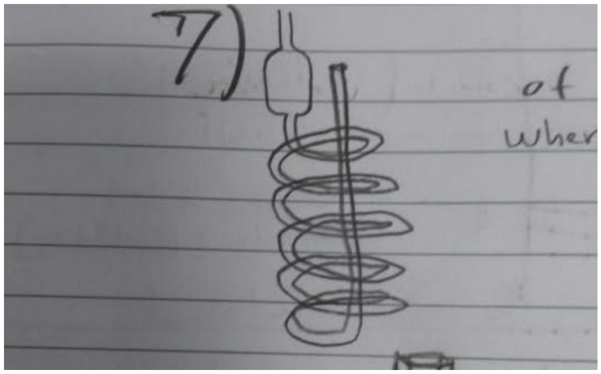

FIGURE 46: EMPTY EXCHANGE TANK

25. Small Finned Exchange Tank (Bottom). A small finned heat exchange tank will be attached to the bottom of the hot water coil in order for the concentration of heat transfer in an area of the tank with the coldest water. The fins will allow for better transfer. It will be finned both within and outside the surface of the tank. The finned exchange tank would have been a large piece of concentrated copper. A goal of Amtrol was to reduce the price of the system. By adding a large piece of copper, the price of the heat exchanger would have been increased significantly.

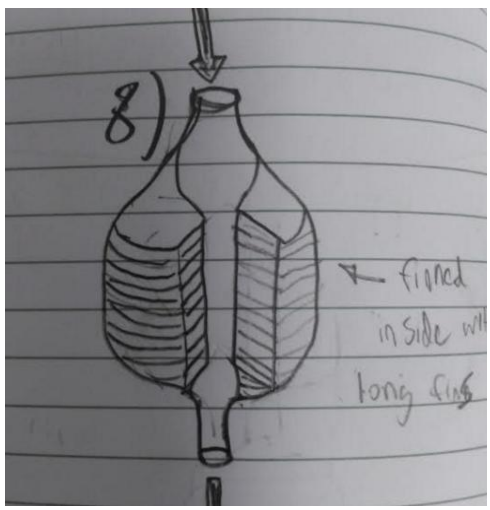

FIGURE 47: FINNED CONCENTRATED EXCHANGER

26. More Copper Coils. Adding more coils of copper to the existing heat exchanger will allow for more surface area, in turn providing better heat transfer efficiency. More coils is possible but as of now we are not adding another coil to the existing system. It seems more practical to adapt the system geometry than it would to increase the number of coils.

27. Increase Pipe Diameter. Increasing the pipe diameter will increase flow rate which will allow for more circulation of hot water, and transfer of heat from the hot water to the cold within the tank. The pipe diameter cannot be increased in the tank. If the diameter were to be increased it will not fit within the top of the tank.

28. Vertical winding. Instead of winding the copper pipe in a helical configuration, the pipe is wound vertically. This will allow the hottest water to get to the coldest part of the tank, making for better transfer efficiency. Vertical winding was not fully explored but the reconfiguration of manufacturing equipment would be very costly to Amtrol.

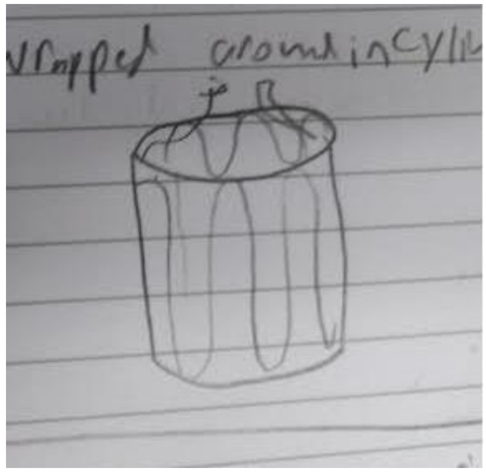

FIGURE 48: VERTICAL HEAT EXCHANGER

29. Changing the Existing Fins. The fins can be made larger on the copper pipe interior to transfer more heat. The fins on the copper tube are already at their maximum length. The material is pushed into a fin shape during a manufacturing process. If the fins were made any larger it would cause cracks and breaks in the walls of the copper tubing.

30. Changing the Existing Fins. The fins can run right to left instead of up and down in order to transfer more heat without interrupting flow patterns. The finning process was chosen to remain the same as altering it would have caused a domino effect on the rest of the heat exchanger manufacturing process. This change was too expensive to implement.

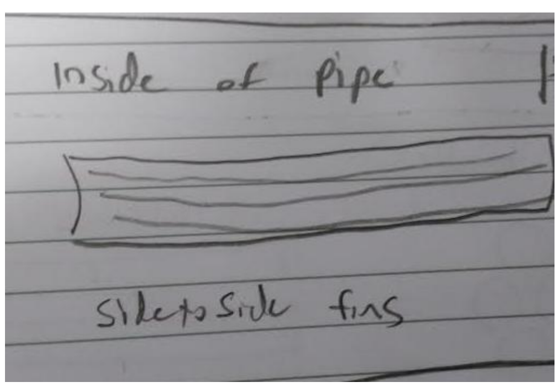

FIGURE 49: LEFT TO RIGHT FINNING

31. Altering Outside Finning. Increasing the length of outside fining should enable the transfer of heat from the surface of the pipe to the outer surface of cold water to be faster and more efficient. This idea was not used because the outside finning could not be

increased. Increasing the fin size would have cause cracks and breaks in the walls of the copper tubing.

32. Use an insert to cause Turbulence (Vortex). A section of the pipe is fitted with a helical insert that rotates as the water flows over it. This rotation reduces fouling effects and causes turbulence. Turbulence is desired in the process of transferring heat. This insert was not used because it would have decreased the volumetric flow rate too much. By reducing the flow rate the temperature differential would have also been dramatically decreased reducing the efficiency of the heat exchanger.

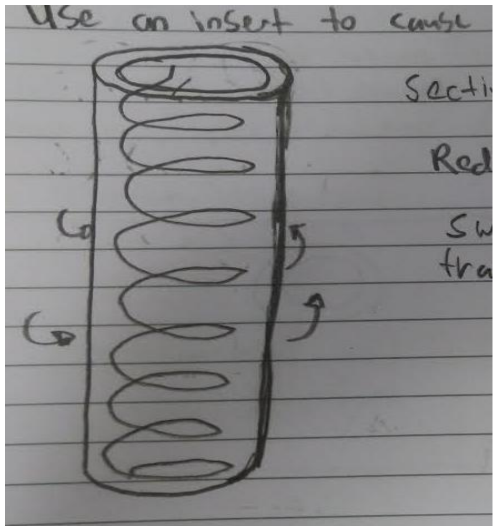

FIGURE 50: VORTEX INSERT

33. Insert. (Vibration). A section of tubing is fitted with an insert that is fixed in tension. When the water passes over the fitting the vibration creates a new boundary layer and prevents the buildup of sediment on the pipe. This insert was not used because it would have decreased the volumetric flow rate too much. By reducing the flow rate the temperature differential would have also been dramatically decreased reducing the efficiency of the heat exchanger.

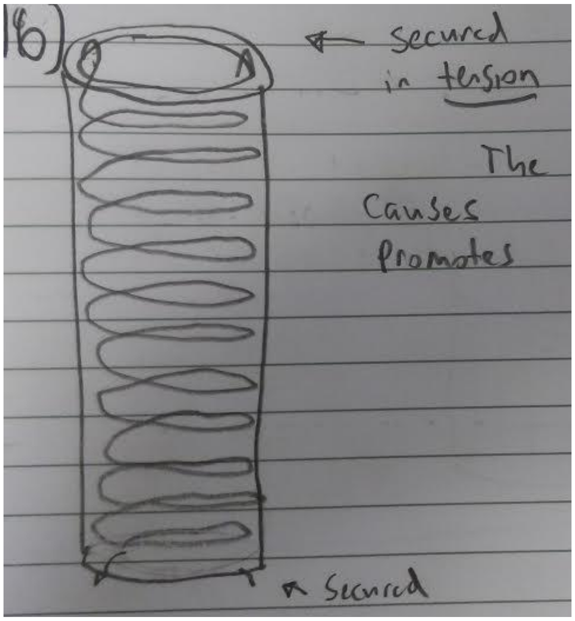

FIGURE 51: TENSION INSERT

34. Tube Bundles. A number of smaller tubes can be used instead of one large tube. This will allow for more surface area on the interior of the tank for heat transfer. It may reduce volumetric flow rate depending on the number of tubes and their diameters. Tube bundles were not used because they were too cost inefficient. The surface area would have been increased but the cost of copper would have gone up. This was a tradeoff Amtrol and Team Intercambiadores was not willing to make.

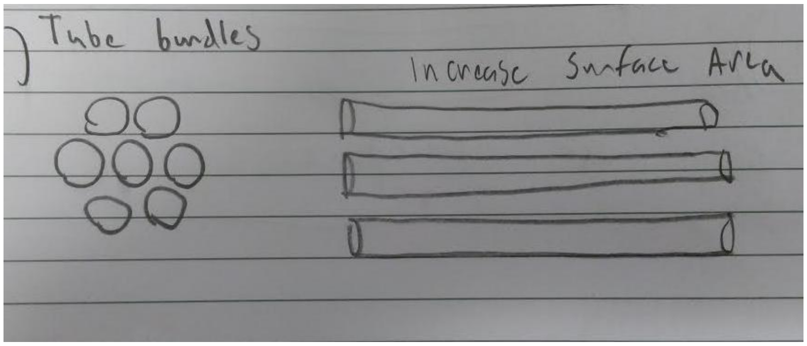

FIGURE 52: TUBE BUNDLES

35. Twisted tube. Internal tube geometry can be changed in order to force the fluid into a spiral, turbulent pattern. Twisted tube seemed viable but was ultimately not used because it is very difficult to analyze mathematically. There haven't been enough studies done on this geometry to commit money into its use for heat exchange for a domestic indirect fired water heater.

36. Mixer Insert. This insert will perform the same task as the twisted tube but without the structural changes to the tube. The insert forces water to one side of the tube and switches direction of the water allowing for more turbulent flow and reduced sediment build up.This insert was not used because it would have decreased the volumetric flow rate too much. By reducing the flow rate the temperature differential would have also been dramatically decreased reducing the efficiency of the heat exchanger.

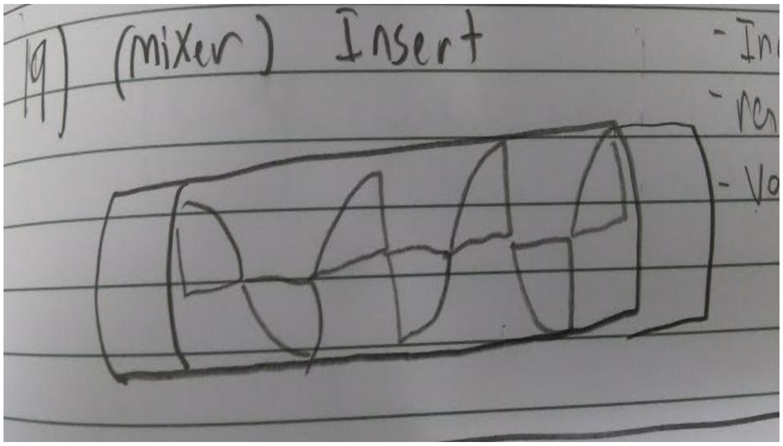

FIGURE 53: MIXING INSERT

37. PEX coil. A PEX coil is tightly wound and secured using wraps of some sort. It is then lowered into the tank and the wraps are released allowing for the PEX coil to expand beyond the inlet diameter. PEX coil has not been completely ruled out but as of now there seems to be no way of knowing if the increase in tubing amount will be worth the sacrifice of thermal conductivity.

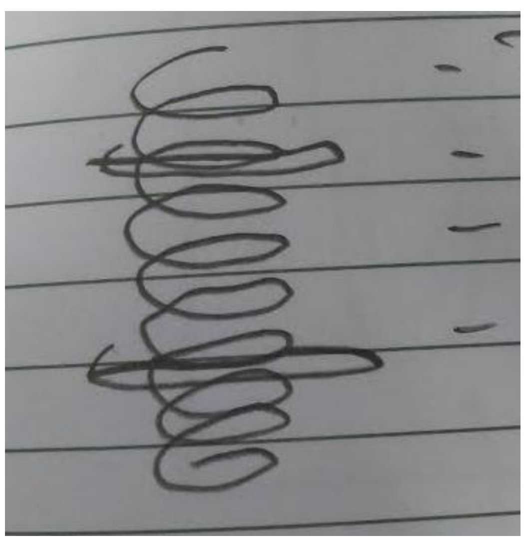

FIGURE 54: TIGHTLY WOUND COIL

38. The heat exchanger is separated into three fittings. The first of a larger diameter tube where the hot water is brought into the tank. The second is a reducing connector that

connects the larger diameter pipe to the smaller diameter hot water return pipe. This design would work in theory but was ultimately not used because the more components a system has, the more opportunities that system has to fail. Along with that philosophy, the manufacturing cost would have been increased dramatically if instead of using one piece of copper with a uniform geometry, three fittings were used with different geometries for each.

39. A large coil focuses all the heat at the bottom of the tank allowing for all the transfer to occur there. A large coil was not used because it would not fit in the top of the heat exchanger. The top plate can not be altered so this idea was ruled out.

40. A baffle is inserted in the center of the tank to encourage separation of temperature layers. The baffle was a promising idea but proved to be too difficult to implement. There was no way to secure the baffle to the inside of the tank. It would have been beneficial to use but finding a way to secure the baffle to the inside of the tank without altering it was too large of a challenge.

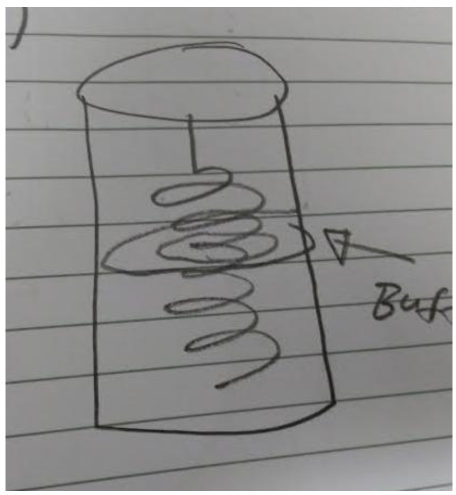

FIGURE 55: BAFFLE DESIGN

41. A baffle with holes in it is at the center of the tank to encourage natural convection patterns and circulation within the tank. The baffle was a promising idea but proved to be too difficult to implement. There was no way to secure the baffle to the inside of the tank. It would have been beneficial to use but finding a way to secure the baffle to the inside of the tank without altering it was too large of a challenge.

42. A stainless steel tube is used instead of copper to allow for comparable transfer without the need of a coating. The stainless steel can resist hard water. Stainless steel has not been ruled out but a preliminary cost analysis showed that it would increase the price of the overall system. This would be detrimental to our efforts to reduce or maintain the overall cost of the indirect fired water heater.

43. PEX Tubing is used as the coil instead of copper. PEX does not allow for build up of material on the tube. It is cheaper and easier to twist than copper. PEX has not been ruled out of use. It has properties that are desirable but further investigation needs to be done to determine if the loss of thermal conductivity, copper, is worth the benefits.

44. Flat Plate Transfer. A flat plate is used at the top of the tank to transfer heat with a small loop going through to the bottom of the tank. A flat plate heat exchanger was not used because as a team we decided adapting existing components and reconfiguring them would be more cost effective than designing, manufacturing, testing and approving a new system on the outside of the tank.

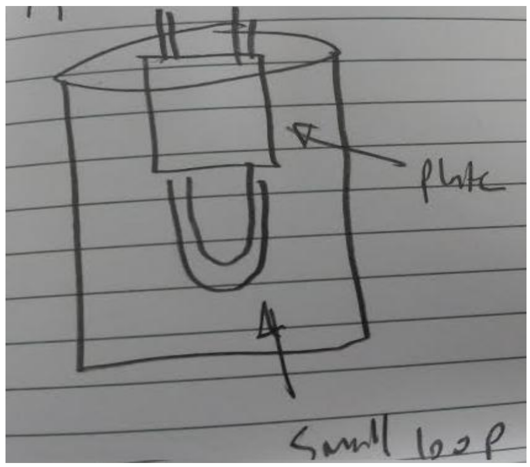

FIGURE 56: U-SHAPED HEAT EXCHANGER

45. The tank is adapted to allow for higher diameter copper tubing. Although this process of machining update will be expensive the investment will allow for optimum heat transfer, due to an optimized tank. This design was immediately thrown out because the top of the tank can not be altered in any way.

46. The cold water input and hot water input will be one tube within a tube. The hot will be on the inner diameter and the cold will be on the outer diameter. This will allow for heat transfer all the way around the hot water tube and through its full length. This concept was modeled in solidworks but ended up being too ambitious. It was chosen not to be implemented because the tolerances and intricacies of the geometry would have been too great for manufacturing at an affordable price.

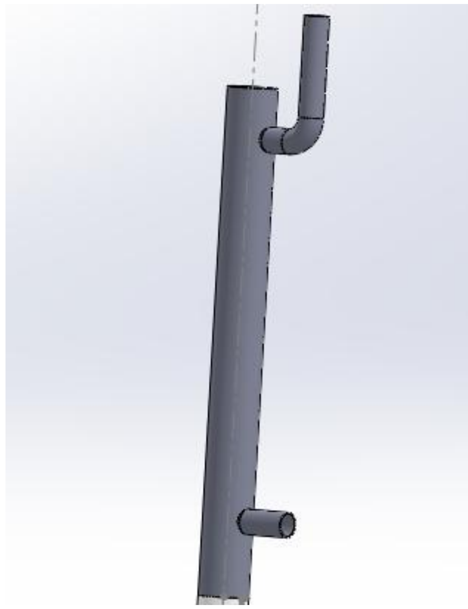

FIGURE 57: HOT WATER ENCLOSED DIP TUBE

47. A large diameter single U shape. This will allow for the highest volume of water to flow through. If the water can be moved fast enough it should allow for the highest transfer of heat. A large diameter single u was not used because it did not have a high enough volumetric flow rate than the other designs. The top plate also could not be changed to accommodate this increased diameter piping.

48. Taking a look at current design and investigating if the fin length is optimized as well as the inner pipe radius. With this, heat transfer can be optimized. Thickness of fins also plays a factor. Thin and tightly spaced fins optimize heat transfer. Looking for most efficient ratio of pipe diameter and fin length and thickness.

49. Micro-pipe diameter, d</= 1.0mm. In order for this design to be effective we would need to increase Reynolds's number, thus increasing flow rate. Would also require larger coil, for helical geometry to optimize heat transfer. Also friction and roughness along with pressure can affect this design, as pipe is very small. Fins to still be used for optimal heat transfer, and pump capacity to increase velocity.

50. Many inlets from boiler to different piping allowing more surface area for heat transfer. This design may be costly as much more material required. Fins used on outer diameter to optimize heat exchange. Smaller pipes spirally wound to increase area. Bundle of pipes, thus large specific heat transfer per area.

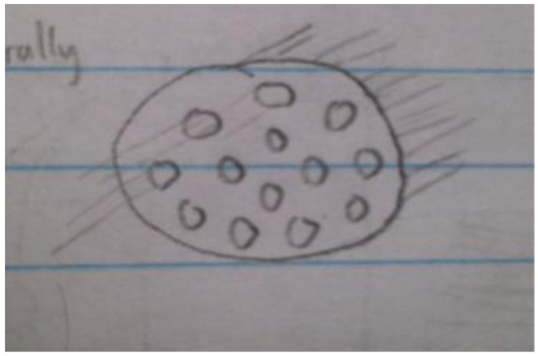

FIGURE 58: CONCEPT #63 MULTIPLE INLETS

51. Tankless water heater; savings in water use, and instant water but is costly. Negative feedback loop used to bring water to the target temperature, warmed by boiler. No tank, thus continuous supply.

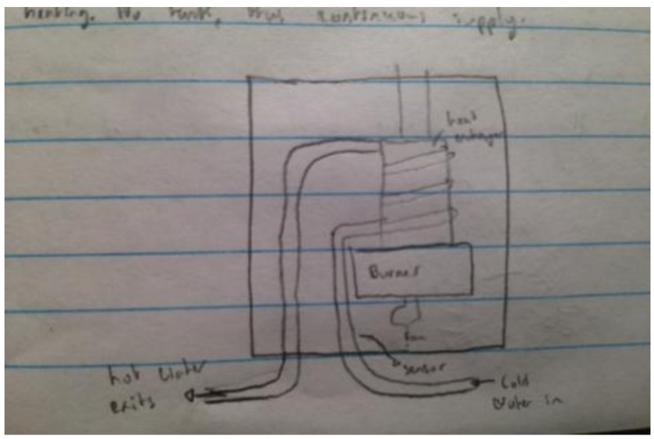

FIGURE 59: CONCEPT #64 TANKLESS WATER HEATER

52. Hybrid tankless water heater. Design has small storage reservoir (pre-warming incoming water) as part of heat exchanger. Sense flow and thermostat control. Have smaller temperature change compared to tankless water heater, and are relatively efficient.

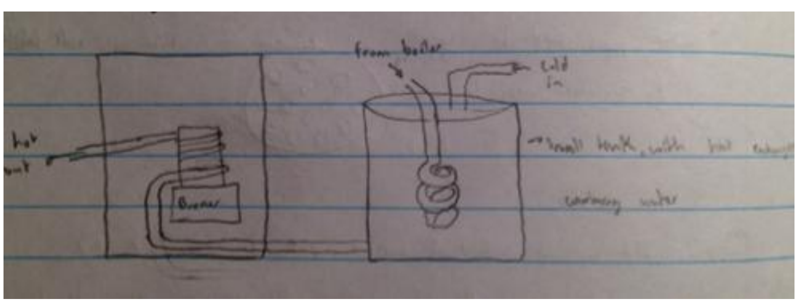

FIGURE 60: CONCEPT #65 HYBRID WATER HEATER

53. Longitudinal fins on external pipe geometry. Allow larger surface area along outside of pipe for heat transfer to occur. Also could have longitudinal inner fins to optimize area within hot fluid to be transferred to water in tank. Thickness and distance between fins would need to be analyzed to optimize design.

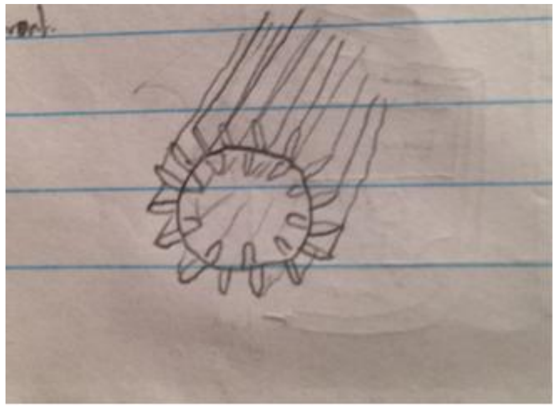

FIGURE 61: CONCEPT #66 LONGITUDINAL FINS

54. Corrugated inner pipe geometry; thin-walled smooth tubes. Results in increasing heat transfer from inside of the tube, particularly turbulent currents. Design would require a specific manufacturing process that may not be available but could optimize heat transfer. Choosing depth angle and indentation carefully. Continuous disturbances of bounding layer of the tube side fluid increases amount of turbulence or Nusselt's number. Providing tube side fluid has higher resistance to heat flow, thus higher overall rate of heat transfer.

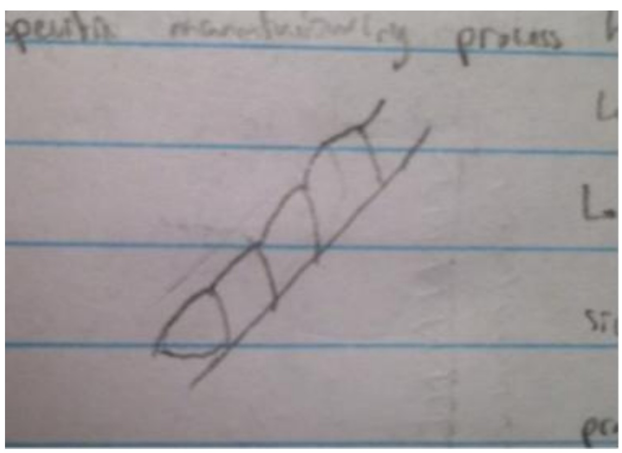

FIGURE 62: CONCEPT #67 CORRUGATED GEOMETRY

55. Studded finds; individual studs could be welded or cut in specific patter on outside of heat exchanger pipe. Design could reduce amount of material required and optimize heat transfer compared to smooth design. May have less surface area than typical annular or helical fins but require less material.

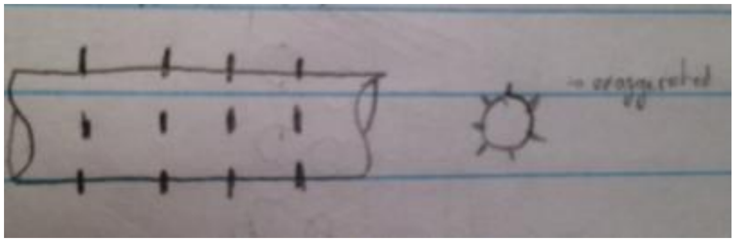

FIGURE 63: CONCEPT #68 STUDDED FINS

56. Helical or helical-segmented fins on outside of pipe. Allow larger surface area while helping flow of water outside tank to be optimal for heat exchange process. Helically wound continuous strip of material along outer pipe diameter. Material is cut into narrow sections for helically segmented design.

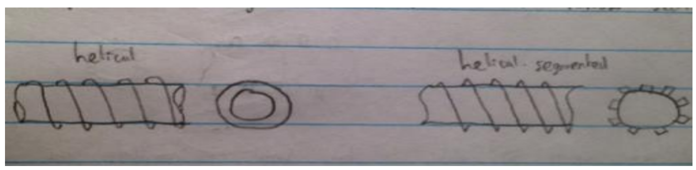

FIGURE 64: CONCEPT #69 HELICAL FINS

57. Serpentine pipe configuration. Pipes to be designed horizontally or vertically with straight portions followed by U or 180 degree turns. To include optimal inner and outer pipe geometry. Could increase surface area and more hot fluid covers larger area of cold fluid within tank.

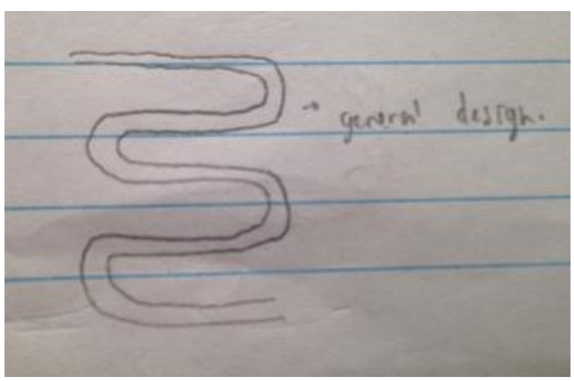

FIGURE 65: CONCEPT #70 SERPENTINE GEOMETRY

58. Allow hot fluids to enter tank using hot fin plates rather tank piping design. Allows more surface area for heat exchange, but could require more material based on design. Flow rate would play a factor thus requires optimal pump. Plates to be blocked on sides from other fin plates or inner tank.

59. Flat or continuous fins on an array of tubes. Optimizes heat transfer as more surface area, although would require more material. Hot fluid would need to come from a shower like tube or baffle inlet. Fin geometry would need to be optimized; could be helical or annular.

60. Wire-form outer pipe fin geometry. Allows large surface area on fins, also allows cold water to flow through them; helps with heat transfer.

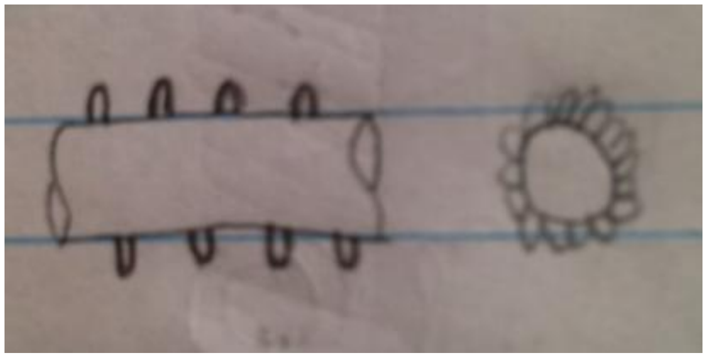

FIGURE 66: CONCEPT #73 WIRE-FORM FINS

61. Using valves at inlet of hot fluid to regulate the optimal flow rate to meet specific temperature and time constraints. Flow rate and inlet hot fluid temperature can drastically change heat being transferred for desired temperatures in limited time.

62. Multiple heat exchangers within one tank. One could potentially be coming from the top and the other from the bottom. The hot fluid from the boiler would need to be distributed to both heat exchangers with optimal pipe geometry and configuration. Could optimize heat exchange, although it may be very costly. Upper heat exchanger would not need to work as hard as the lower one due to warmer water at in the top of the tank.

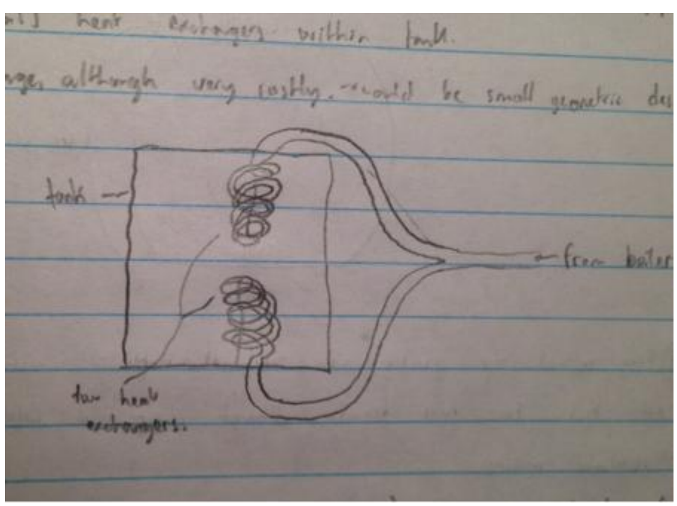

FIGURE 67: CONCEPT #75 MULTIPLE HEAT EXCHANGERS

63. Line outside of tank with PEX (cost-efficient material) to allow optimal surface area and heat exchange with cold water within tank. Have space between inner tank and PEX for hot fluid to flow between, thus large amount of material needed.

64. Using pipes, line the inner tank in the longitudinal direction, flowing from one pipe that flows down the middle of the tank. Large amount of material required, although could be worth it using a cheap material. All outer pipes would come to one outlet. Large amounts of area for heat transfer to occur.

65. One larger vertical pipe that loops around and converges into a smaller diameter pipe that wraps helically around the larger portion. Large surface area, and the larger pipe allows more fluid flow, thus the velocity would increase in smaller section.

66. Holes cut longitudinally into pipe wall to allow hot fluid into smaller cuts and larger cut in the middle. These cuts can wrap helically around larger inner pipe. Keep outer fluids at high temperatures for heat exchange; insulated from inner hot fluid.

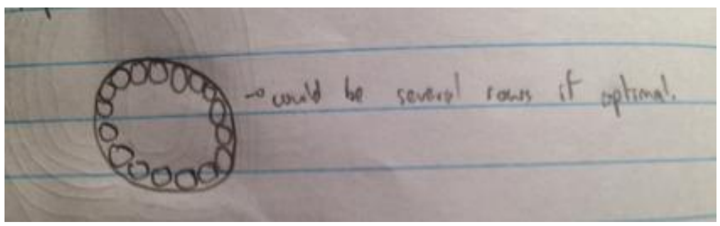

FIGURE 68: CONCEPT #79 PIPE WALL GEOMETRY

67. Zig-zag fin design on outside of pipe. More surface area, thus more material. Could be helical or annular along pipe length.

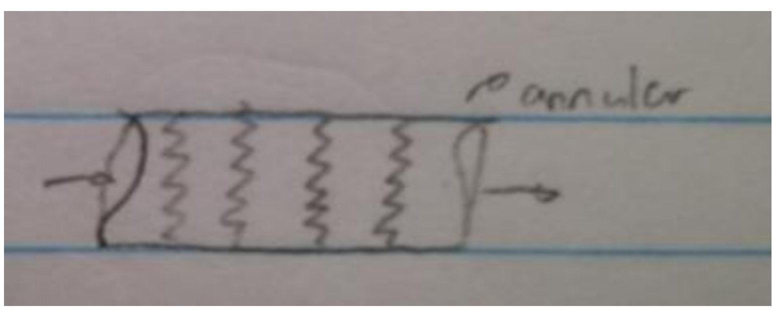

FIGURE 69: CONCEPT #80 ZIG-ZAG FIN DESIGN

68. Wavy fin design on outside pipe. More surface area, and easier for water to flow through compared to zig-zag design. Could be helical or annular along pipe length.

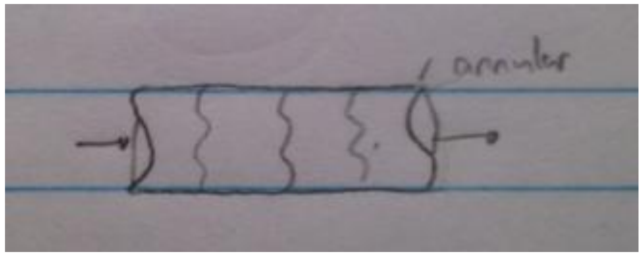

FIGURE 70: CONCEPT #81 WAVY FIN DESIGN

69. Proportional hot and cold flow rates. Disperse cold water at a low flow rate and have this line up with optimal hot fluid flow rate through heat exchanger to optimize heat exchanged to coldest fluid at each moment in time.

9. Design for X

9.1 Design for Manufacturability

The initial development phase of this project called for limitless brainstorming of concepts. Many of the concepts generated with conceptually sound and intellectually feasible. However what may seem possible in the early phases of development, it is important to consider the “How” when it comes to how an idea can eventually lead to its final phase of manufacture. The group initially began with over 150 general concepts, these concepts were eventually narrowed down to approximately 10 which seemed more realistic for both time frame and implementation in the product line. As the concept generation and design phases progressed one of the main driving factors behind what made the cut for proof of concept, was the design practicality. Ultimately practicality is what drove much of this project. Many of Amtrol’s current geometrical constraints had severe impact on the attainable goals the group had initially set. Luckily this further narrowed our concept generation down to two possible options. The two options that advanced toward proof of concept are the variable pitch increased coil density and modified dip tube geometry. This outcome of this project is unique in the way that our modifications provide minimal impact on the existing processes in place, and also have ROI that are near net zero in time.

Due to the fact that coil material, finning, and plating services will remain entirely unchanged, the modifications made to geometric shaping are easily executed. The coil shaping machine is computer numerically controlled which means the only modifications that need to be made prior to full scale testing are imported software changes. Secondly the modifications that need to be made to dip tube geometry are simple tooling changes. From speaking directly with the manufacturer of dip-tubes, closing the outlet end into a conical shape is already a process that is executed for other dip tube purchasers but is not currently in the manufacturing lines at Amtrol.

When finning material the initial step consists of obtaining raw copper stock pipe. The material then enters the machine where rotary blades grip the material and begin to shape fins. After finning the copper the material is then washed down and prepped for hydrogen treatment. The washing cleans the material of any impurities, a process which is vital for potable applications. The hydrogen treating is then carried out in order to remove any corrosion that resulted from the cleaning process. Finally the material must be annealed because the finning has hardened the copper. The annealing is necessary because the copper would break when inserted into the mandrel to finally become the helical coil it was intended to be.

Tin is used as a coating material for the exchanger on the potable side. Tin has a thermal conductivity of 66.8 W/mK, while copper has a thermal conductivity of 385 W/mK.

This vast difference in thermal conductivity makes it clear to see that the tin acts not only to protect the copper from degradation and deposition, but it also acts as a thermal insulator. In order to reduce the effects of thermal insulation the new prototypes have a tin coating that is one third the thickness of the current models. This change in thickness requires a different manufacturing process. In place of simply dipping the copper exchanger in molten tin the new process involves …Ask Mike!!... Despite this process being more expensive than previous processes, the total consumption of tin decreases dramatically as a result of the thinner coating, this results in a net zero change in production cost. And because the coating provider currently working with Amtrol is capable of the new coating methods in large volumes the time for manufacturing as well as the time spent switching the manufacturing platform experiences nominal changes.

Introduction of a baffle into the system adds the manufacturing need for the product. Assuming the use of a PVC plastic sheet as the raw material for the plastic, the material will be acquired and manufactured externally. There are only a few steps necessary to produce the baffle. A few cutting tools will be necessary to cut the PVC to properly sized sheets, and then another set of cutting tools will be used to cut the openings in the baffle. After which the sheet will be wound into a cylinder and welded together using ultrasonic welding or adhered using an industrial and food safe adhesive. The baffle itself is a simple part made homogenously out of one material allowing for ease of manufacturing.

9.2 Design for Regulatory Compliance and Safety

Drinking water standards vary mildly from state to state, but the Food and Drug administration (FDA) regulate all potable city water to certain standard. While other forms of potable water, most commonly occurring in wells, are held to a standard as defined by the state. For Rhode Island, and most of its neighboring states, the potable water standards do not deviate widely from FDA regulations. This means that in order for any product which interacts with potable water as part of its function needs to satisfy the FDA requirements in order to be safe and therefore legal to sell.

Because the heated water is used at all points of the residence, including faucets, the FDA requires that all surfaces in contact with potable water be held to standards that prevent any kind of dangerous contamination or bacterial growth under these temperature conditions. In order to accommodate this in the current design Amtrol uses a tin coating on their exchanger, to prevent bacterial growth, and they use an inert form of PEX for the dip-tube. In the new design because the material selection has not been changed safety was not a concern as the overall shape of the heat exchanger will not affect any of these safety concerns.

9.3 Design for Reliability and Flexibility

When designing all of their products, Amtrol strives to deliver goods that are both reliable and flexible to the consumer. Reliability is the amount of time the product is expected to perform its duty without failure and flexibility is how adaptive a product is to environmental factors of use.

Currently, Amtrol's HydroMax 41 gallon indirect fired water heater is covered by a seven year warranty. This ensures that the product will maintain its usefulness for a minimum of seven years. To enhance the components reliability, the potable water container is made of a HDPE, which is corrosion proof and the heat exchanger coil is coated in tin to minimize corrosion on the copper tubing within.

The water heater is able to be used in areas all over the world due to the sizing of its tubing. The inlet and outlet tubing of the Hydromax system is sized to a standard copper diameter of ¾" making its integration into an already existing system seamless. By adhering to one of the major copper tubing standard sizes, Amtrol's product can be effectively utilized by a large number of people and geographic locations.

When redesigning the indirect fired water heater for Amtrol, Team Intercambiadores must consider factors such as the material and pipe sizes in order to maintain reliability and flexibility. We must also look past the current expectations and try to enhance reliability and flexibility of the system to ensure Amtrol is providing a quality product, and the consumer is receiving one.

9.4 Design for Portability

One of the most important issues for the company Amtrol is the weight of the heat exchanger. On transport, the weight of the exchanger is one of the characteristics that we should study. We have to try to reduce the weight of heat exchanger because it also reduces usage costs, such as save gas, tire wear, etc.

In turn, it is important to ensure that the heat exchanger will not suffer any damage during transport of the same. Due to the range of action of the company Amtrol, we can ensure that the most suitable for this type of transport interchanges is road transport. We could use vans or trucks to transport the heat exchanger from the company to the final destination. This final destination could be a particular house or a small company.

9.5 Design for Cost

Low cost of a product occurs based on the price of materials and manufacturing process. Thus, the cost of a product must be considered in the design phase. The design for cost of the heat exchanger is to minimize the price of material and minimize the cost of changing the manufacturing process of the new design. It would be very beneficial if the new design could work with Amtrol's current manufacturing process. It would be expensive to implement new processes, although it could prove to be worth it if the design is significantly more efficient. It would be relatively easy and cheap to change the dip-tube manufacturing with a fitting. Coating the coil with tin such that the tin layer is thinner than previous designs will add no extra cost as the process does not change but rather the duration of the dipping step in the process changes. As such the manufacturing time and cost do not change dramatically while at the same time using less tin overall. Another minor change in the production cost will occur at the introduction of the baffle. The baffle, being the only piece of the new prototype that is being introduced for the first time, is made of PVC and will need to be shaped prior to installation. This piece was designed to be simple made of cheap material as to keep the cost effect to a minimum. The cuts and shaping of the baffle are simple and quick and can therefore be done in mass quantity without adding a large expense to the design. This product would be produced on a large scale, thus the cost efficiency of the process is important in designing the new product.

9.6 Design for Assembly

In considering designing a product for assembly a different approach must be taken in order to consider the already existent manufacturing process. Because the production of both the barrel and the faceplate occur separately from that of the internal coil and the dip tube the engineer re-designing such pieces must take caution not to take too much liberty in the design. If too much is done to change the design then the number of new parts that may need introduction to make it work with the existing framework may be impractical. It is because of this that careful design consideration has gone into designing the new coil to have the same style of inlet and outlet allowing it to be seamlessly worked into the existing assembly structure. By keeping certain parameters of the coil similar to the original design it becomes easier to narrow down the areas of potential improvement while still keeping the design practical in the current situation, which will ideally allow the product to hit the market sooner. Furthermore additions to such designs such as a baffle or any other external free floating piece must be easily installed and fit seamlessly with the current design. As such it must be able to be placed in the tank prior to the placement of the coil which is then placed inside the tank and the baffle. This simple step in the final stages of assembly will add very little time to the assembly process and allow for an improved heat exchanger.

10. Detailed Product Design

10.1 Design Progression

In the first meeting with our contact at Amtrol we discovered a lot about the overall structure of the heat exchanger and what led to each component as it is now. It came as a surprise that a lot of the design had remained almost entirely untouched for the better part of 20 years. Heat exchangers are not particularly specific devises in the sense that a warm object submerged in a cold fluid will to some extent warm the fluid. The question then and now is how long does that take and how can that process be improved? When one observes the current coil inside an Amtrol heat exchanger one may see that this long piece of coated copper is finned and wound tightly. This overall structure is the result of a number of constraints set up by the environment circumscribing it. In order to explore improving upon such a design one must first understand all of its constraints and why those constraints led specifically to the current design. The first major constraint as listed before is the physical constraint of the tank in which the coil lies. This tank allows for the coil to have a depth of 33 in and the coil must fit through a round opening which is roughly 6 inches in diameter. Manufacturing the indirect water heater involves manufacturing the tank separate from the coil; concurrently the copper tubing is first finned and then shaped into the coil structure, after which it is brazened onto the faceplate of the exchanger and prepared for mounting on the tank. This faceplate coil structure is then mounted onto the tank by lowering the coil into the tank through the round orifice and by bolting the faceplate onto the top of the tank allowing for the tank to be pressurized.

Because this manufacturing and assembly processes are so well established the design team seeked a way to redesign what currently exists while not too dramatically changing the overall structure of the design in order to increase performance without any major adverse effects to the manufacturing infrastructure that is already in place. Through meetings with Michael we discovered interesting information about the behavior of the heat exchanger during various phases of its function. The phases are the following:

Continuous draw: The continuous draw phase occurs when hot water is being used in large volumes in the residence. During this state the water is being continuously fed into the tank at an entrance temperature of 55 degrees Fahrenheit in order to replace the warm water leaving (usually at around 130 degrees). During this phase of heating the potable water must be heated up quickly and more evenly as a function of the height of the tank, and there is higher turbulence in the tank. For this application a length of copper with a distribution of coils which cover the entire length of the tank performs better than a shorter denser packed coil. Amtrol currently has two different models for their heat exchangers. One which is a top down geometry, where the coil is loaded from the top of tank, and a bottom up geometry in which the coil is loaded from the bottom. The top down geometry currently uses a less dense coil distribution spread throughout the length of the heat exchanger, because of this structure the potable water in the tank tends to settle into thermal layers as a function of height therefore being less dynamic, which presents both advantages and disadvantages. The bottom up heat exchanger uses a shorter heat exchanger with a denser set of coils, sometimes two rows of coiling, in order to increase the thermal output. The bottom up coil geometry tends to struggle in this environment as the heating distribution is less even throughout the tank and therefore the potable water that is drawn from the tank tends to have a lower overall temperature or requires a slower volumetric flow rate. The top down coil geometry performs better here as the potable water in this system tends to be less dynamic and heat the water in the tank progressively as each new layer of water reaches different height stages throughout the tank.

First hour heating: First hour heating occurs when a resident does not use hot water for a while then suddenly calls for some large, like washing dishes, amount of hot water. In this stage the tank has been sitting for a while and during that time was slowly converging into thermal equilibrium both with the thermal layers of potable water in the tank and with the outside environment. This causes the overall temperature of the tank to drop and the upper layer of water, which is least dense, to cool. In order to remedy this upon the sudden demand of hot water the heat exchanger turns on and draws hot water from the boiler. In this case because the volume of water used in the activity is small the volumetric flow rate is less demanding. Here the bottom up heat exchanger design becomes advantageous for its ability to introduce more heat to the system faster, and as that water heats up it moves up the tank as a function of effective density therefore allowing for a more immediate draw of hot potable water, whereas the top down coil geometry takes longer to introduce the same amount of energy to the system.

With these designs being evaluated both qualitatively and quantitatively concept generation then occurred in order to speculate improvements to the system. While a number of ideas were suggested that may have proved more thermally or otherwise efficient, the current infrastructure and the constraints set forth by the tank and the existing top plate we decided to go with modifying the current design for more overall efficiency as compared to re designing the system. Although should time permit testing will be done to look at what advantages outside of modifications could be made to produce a better system.

10.2 Project Specific Details and Analysis

10.2.1 Bill of Materials

TABLE 2: BILL OF MATERIALS

BOM (Material Cost for One Unit)		
Raw Material	Amount	Cost in Dollars
Copper	12ft	20.38
PVC (sheet)	2.5ft	0.15
PEX (diptube)	2ft	0.86
Tin Coating	0.44lbs	3.00

10.2.2 Design of Heat Exchanger Coil

The heat exchanger coil is the most vital part of the heat exchanger as it is the medium which transfers the heat into the surrounding potable water. In order to encourage an increased rate of heat transfer and based on the evaluation of the previous designs that Amtrol is using in their current heat exchangers, a combination type coil geometry is to be used in order to provide all the advantages of each structure of heat exchanger in one. In order to accomplish this and satisfy the conditions set by the problem constraints the Hydromax coil framework, shown below, was as a basis for the new coil. In order to make the coil more effective the coil density was changed and made variable throughout the length of the exchanger allowing for there to be more available heat exchanger where the potable water is coolest and the boiler water, inside the coil, is hottest. To prevent the tin coating form insulating the system too dramatically the thickness of the coating was reduced to about one third the original thickness.

FIGURE 71: THIN COAT VARIABLE PITCH COIL

10.2.3 Design of Dip Tube

Improving the dip tube is an important step to increasing the efficiency of the Hydromax® 41 gallon Indirect-fired water heater. The dip tube is responsible for the entry of the cold water into the hot water storage tank. An effective dip tube design will limit the mixing of thermal layers within the storage tank due to the entering cold water. The changes to Amtrol's current model will reduce two major fouling effects. The first of these effects is the volumetric flow rate, reducing this value will allow for a smooth temperature gradient from coldest water, at the bottom of the tank, to the hottest water, at the top of the tank. The second mixing effect to be minimized is the Y-direction momentum. Momentum in the Y-direction of the tank promotes mixing of thermal layers in the storage tank. "To minimize mixing, the fluid must be carefully introduced such that it neither has nor acquires momentum in the vertical direction(Y-axis) {21}.

FIGURE 72: AMTROL'S CURRENT DIP TUBE

10.2.4 Proof of Concept

10.2.4.1 CAD Models

In order to design a practical concept for both the coil geometry and the dip tube structure we first had to understand the dimension of the tank in which these items are going to be implemented in. As defined in the scope of the project we cannot alter or interfere with any of the dimensions of or relating to the tank itself, but only of the internal structures associated with the heat exchanger. Shown below is a three dimensional Solidworks model of the tank, the dimensions can be found on the drawing in Appendix (A).

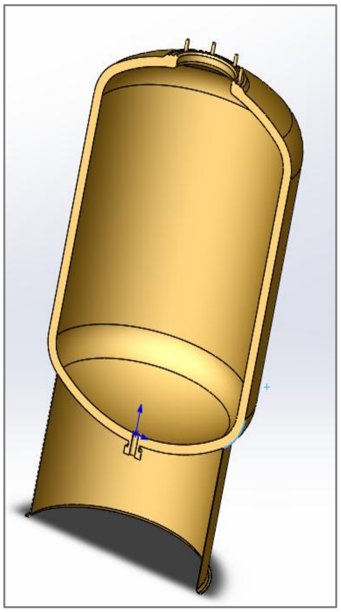

FIGURE 73: CROSS SECTION OF THE TANK

In order to optimize the current coil design a variable pitch coil was introduced. This design is an attempt of utilizing the advantages from both the top down and bottom up coil geometries. As seen below the variable pitch coil geometry adopts a top down coil orientation, for ease of installation, but has a coil density at the bottom more similar to that of a bottom up heat exchanger; for dimensions see Appendix (B). It may be noted that this model does not include the fins, though they were taken into account for the thermal efficiency calculation.

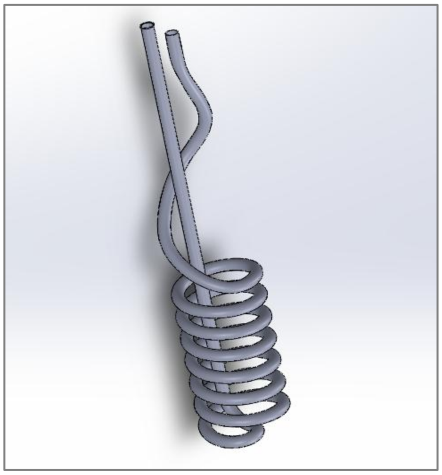

FIGURE 74: VARIABLE PITCH HEAT EXCHANGER

The current dip tube design, figure 75, can be improved by introducing holes in the sides of the tube and closing the end. This design will have minimal cost impact and allow for a slowed exit flow velocity and diminished momentum in the y-direction. The improved model is an attempt to increase the effectiveness of Amtrols' current dip tube without dramatically changing their manufacturing process and overall product dimensions. The progression of models from Amtrols original dip tube to the redesigned dip tube can be seen in figures 75 through 77. The dimensions of Amtrols dip tube and the redesigned dip tube can be seen in Appendix (C).

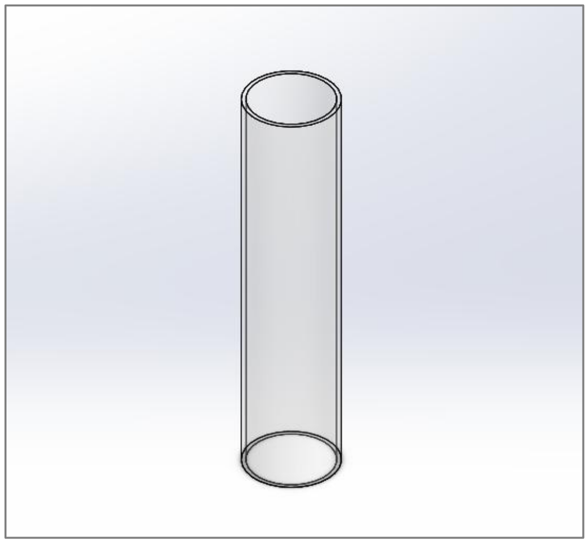

FIGURE 75: AMTROL DIP TUBE MODEL

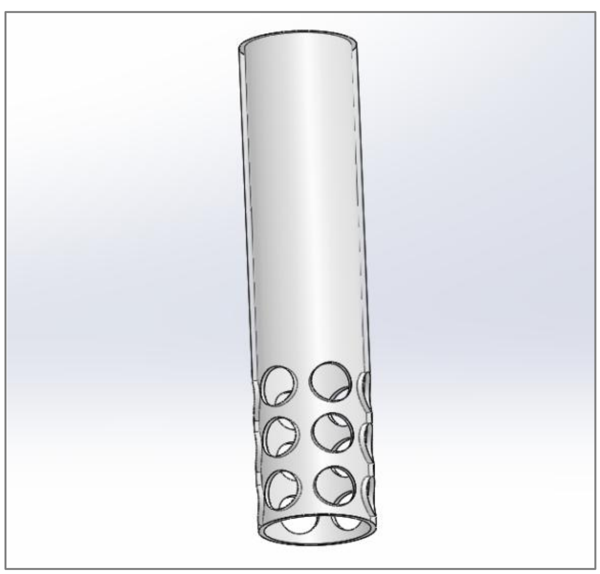

FIGURE 76: DIP TUBE WITH HOLES ADDED

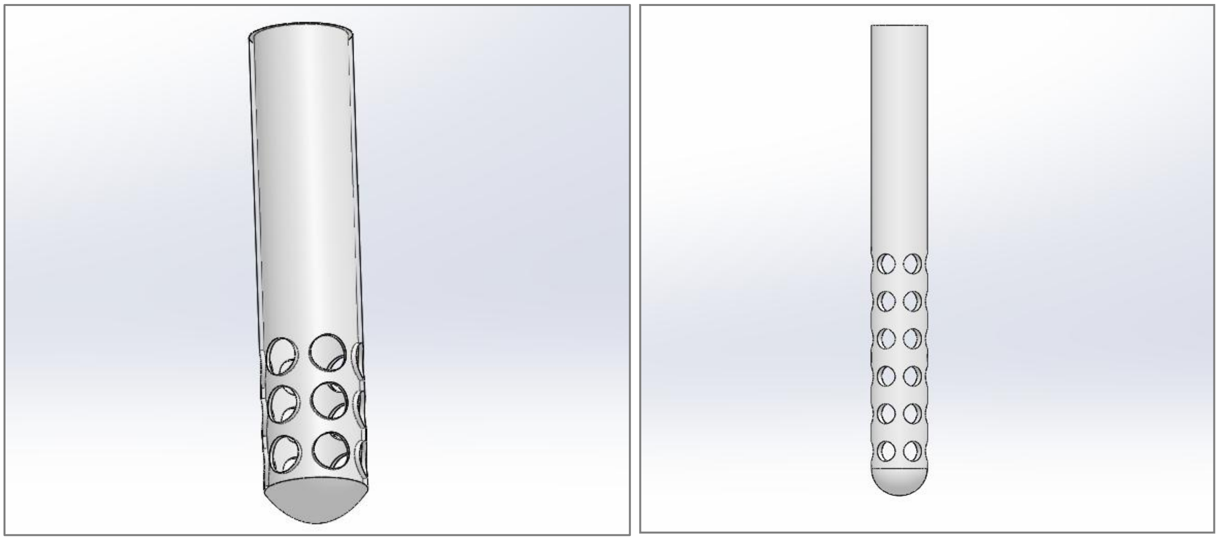

FIGURE 77: IMPROVED DIP TUBE

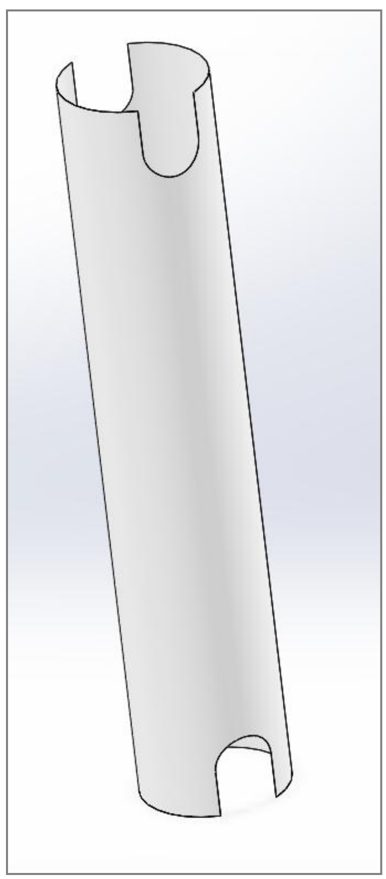

FIGURE 78: BAFFLE

The baffle was introduced to control the flow during dynamic, forced convection, heating conditions. It does this by restraining a majority of the flow such that it is close to the coil in such a fashion that during high flow conditions there is a center column of hotter potable water flowing towards the exit. This proves to be more efficient and increase the thermal transfer efficiency in the system. This efficiency comes about as a result of the velocity of the potable water being higher as a result of the pressure in the tank versus that of the convective forces produced by the coil. Pictures of baffle used in testing found in appendix (F, G, M).

10.2.4.2 Variable Pitch Coil Analysis

Thermal analysis of the variable coil involves the exploration of the thermal behaviors of the current design and how the new design will affect said thermal behaviors. Analytic evaluations showed promising results for the variable pitch coil. In static testing the variable pitch coil performed vastly better than the standard coil, but during the dynamic conditions the performance decreased. In order to remedy this issue and improve heat transfer under all circumstances the thickness of the coating was decreased. The coating, being tin, has a lower thermal conductivity coefficient than copper and therefore stifles heat transfer. By reducing the thickness of the tin in the system the thermal efficiency of the exchanger increases under all conditions.

The variable coil presents a clear advantage over other potential designs in that because it is a modification of the current design the cost and time it would take to change over the current manufacturing infrastructure would be nominal. Similarly because the length of the coil will not change there will be no cost in material and this new coil geometry will not affect any of the manufacturing processes that follow its creation. Because the material and the size of the original piping remain the same processes such as the brazing to the face plate will remain the same further articulating the advantage of this design.

To further improve the heat transfer capabilities of the coil optimal heat conduction conditions within the coil must be achieved. They are achieved by decreasing the amount of thermally insulating material in the system. In this system the thermally insulating material is tin, with a thermal conductivity of 66.8 W/mk, this is relative to coppers 368 W/mk. As such, by reducing the amount of tin in the system the time it takes for heat to conduct from the inside to the outside of the pipe will decrease, which will improve the heat conduction rate of the system and therefore increase the overall thermal performance of the system. Further images of coils used in the testing can be seen in appendices (B, K, L)

10.2.4.3 Dip Tube Analysis

Analysis of the dip tube is comprised of fluid flow analysis within the existing dip tube and geometric analysis of the exit channels of the dip tube. Currently due to the complexity of the exit channels, the fluid flow analysis is done using Solidworks FloXpress. The geometric analysis can be understood using volumetric flow equation but only proved effective through fluid flow analysis. The changes that need to occur to the dip tube system in order to achieve a higher level of heat exchange efficiency are altering the exit channels geometry and, reduction of exit velocity and momentum of the water. These changes can be easily accomplished by adapting the existing Amtrol dip tube, seen in figure 75.

The process of changing the dip-tube would be simple and have virtually zero cost impact to Amtrol. First, instead of having only an open end for the fluid to exit, the dip tube would be post processed with a drilling operation to add holes to the circumference of the lower portion of the exit region. These added holes would allow the fluid to exit in more than one direction with decreased velocity, due to the increased exit area. This is evident due to volumetric flow rate equivalence. These first changes to the existing Amtrol dip tube can be seen in figure 76.

The second part of the dip tube to be changed would be the bottom section of the tube. Currently the dip tube, seen in figure 75, allows for a large volumetric flow rate in the Y-direction. This volume of fluid is carrying a significant amount of momentum in the Y-direction. To limit this exit end of the dip tube would be closed in a post extrusion forming process. This process would also add little to no cost to the production of the dip tube as Amtrol already has the systems to accomplish this forming process. By closing the end, the water will be forced in the X-direction out of the eighteen holes. Along with the increased exit area, the limited Y-momentum is a significant in reducing mixing effects within the lower portion of the tank. The dip tube with the closed end and holes can be seen in figure 77.

The overall design that Team Intercambiadores will be moving forward with for the dip tube improvement can be seen in figure 75. This design allows for the reduction in the mixing effects and is cost efficient. The exact dimensions of the model can be seen in Appendix (C). Further images of dip tubes used in testing can be seen in Appendices (E, H, I, J).

11. Engineering Analysis

11.1. Heat Exchanger Thermal Analysis

In order to approximate the behavior of the heat exchanger to predict the behavior of the new design a formulaic approximation was used to estimate the behavior based on the known heat exchanger geometries in place. To simplify this evaluation convective behavior is evaluated at the final stage of thermal transfer to the potable water. Most simply the formula for convective behavior is:

$$q = hA\Delta T \qquad (1)$$

Where q is the energy transfer due to heat, h is the convective heat transfer coefficient and ΔT is the change in temperature from the surface of the coil to the potable water.

$$h_L = \frac{N_{u_f} K}{L} \qquad (2)$$

The unitless convective heat transfer coefficient can be defined by N_{u_f} which is roughly equal to 1.5, this is defined by the fin distribution on the coil [Number]. k is the conduction coefficient and because the outside of the the coil is lined with tin it has a value of 66.8 watts/(meter Kelvin) and the total length of the coil structure is 3.66 meters. This yields a convective heat transfer coefficient h_L is equal to 27.395 Watts/Kelvin.

$$A = (A_f + A_c)\alpha \qquad (3)$$

A_f is equal to the area of the fins and A_c is equal to the surface area of the coil without fins. α is equal to a unitless function defining the distribution of the of coils throughout the system.

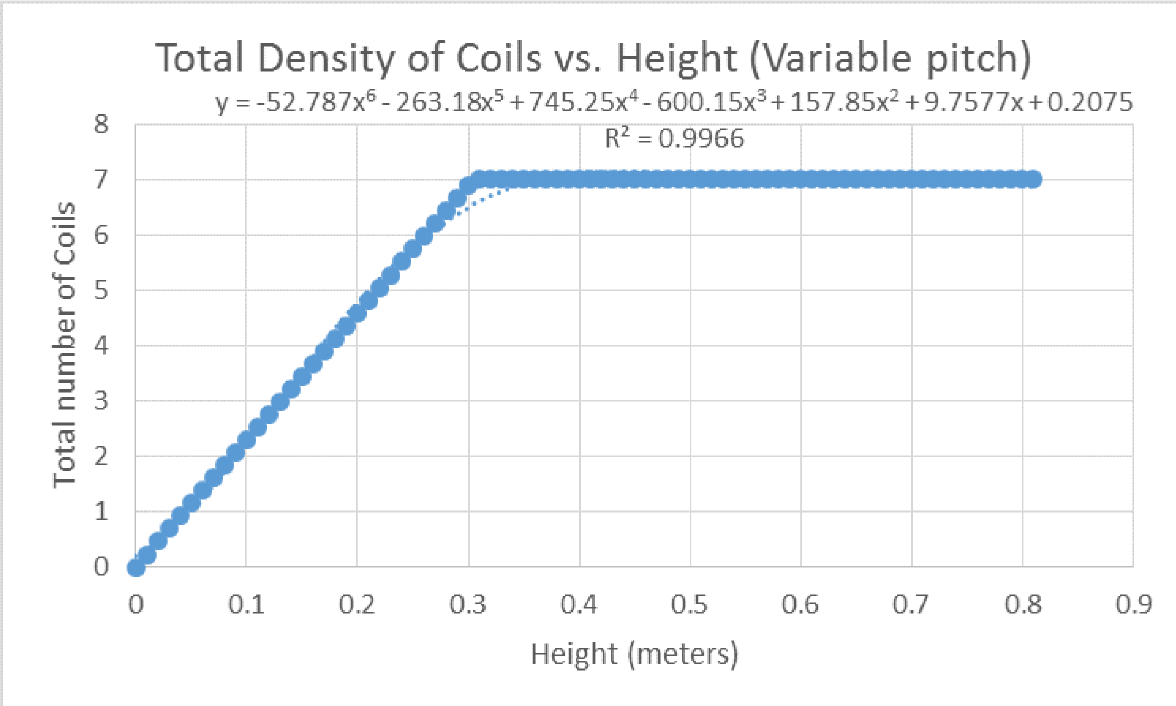

FIGURE 79: α AS A FUNCTION OF HEIGHT FOR VARIABLE PITCH

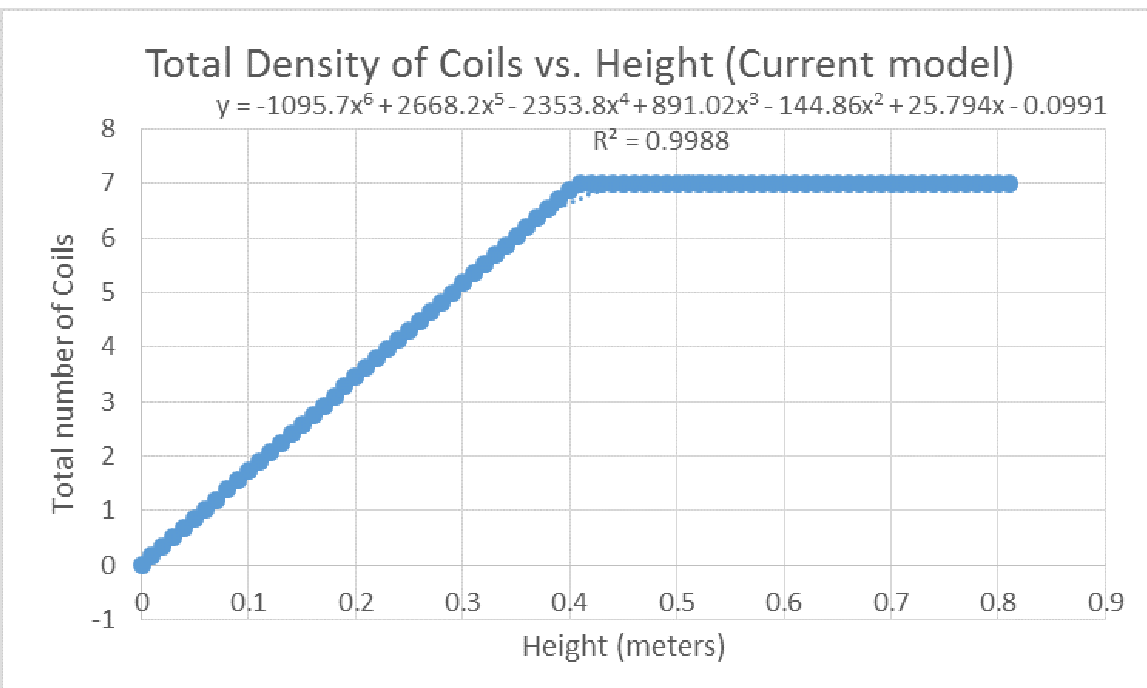

FIGURE 80: α AS A FUNCTION OF HEIGHT FOR CURRENT MODEL

The temperature also varies as a function of height throughout the tank. Using the data provided by Amtrol, found in Appendix (D), a function defining the temperature as a function of height can be derived. For the existing structure has clear data showing its temperature trends, and for the theoretical a predictive temperature distribution was made based on the trends of the current top down model and the bottom up model whose formula can be seen below:

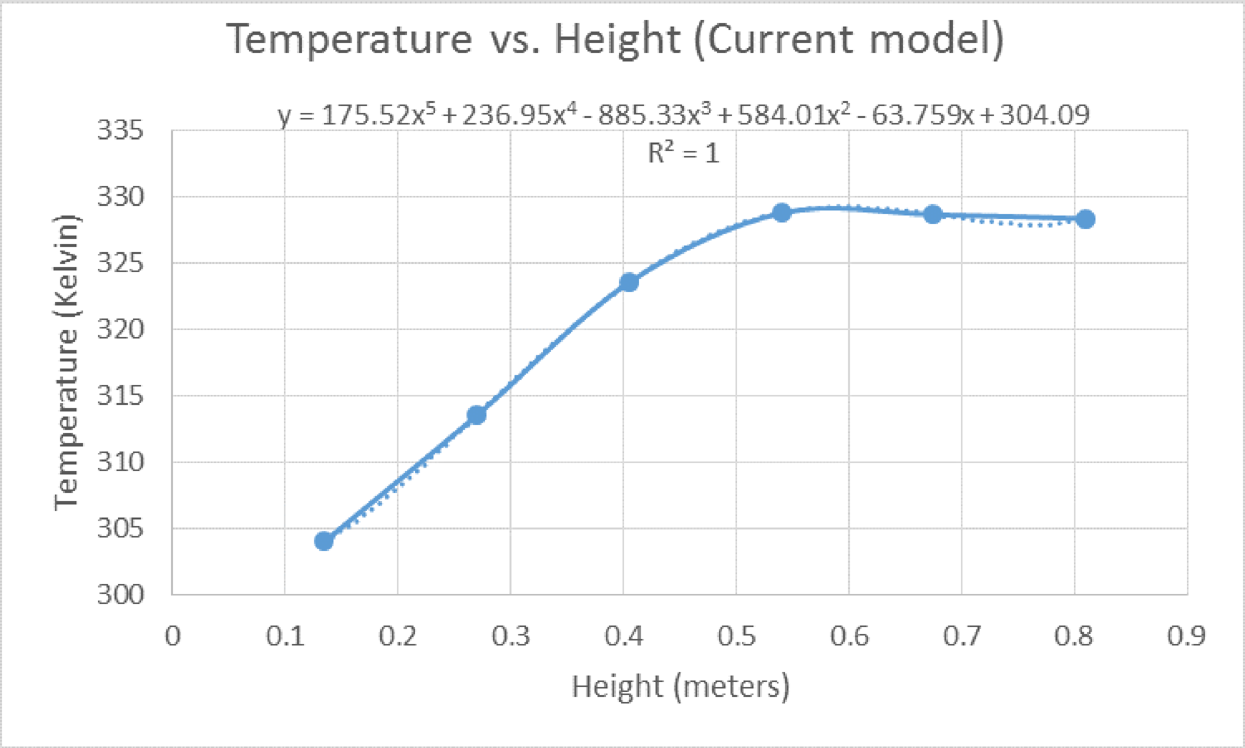

FIGURE 81: TEMPERATURE AS A FUNCTION OF HEIGHT CURRENT

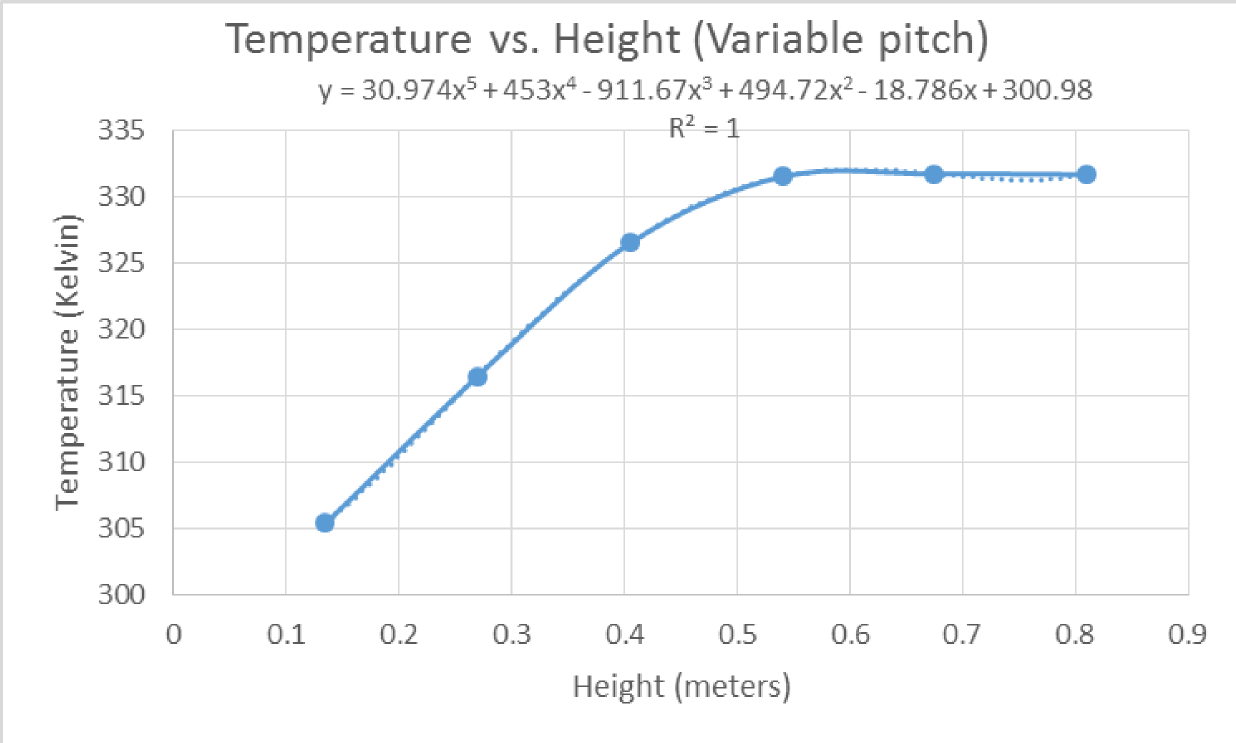

FIGURE 82: TEMPERATURE AS A FUNCTION OF HEIGHT VARIABLE

Using the data above and the convective formula a new formula can be defined to estimate the behavior of the system:

$$q = h_L(A_f + A_c)\int_0^{H_T}\int_0^{\Gamma} \alpha dTdH \qquad (4)$$

For the current model this yields a thermal output of 142,000 Btu/Hr while the variable pitch prototype yields a thermal output of 160,000 Btu/Hr. This is over a 10 percent increase in thermal efficiency. This prediction is not confirmed and will need to be tested in order to confirm the advantage of this new design and provide more data for developing better predictive equations.

11.2 Dip Tube Flow Analysis

In order to optimize the dip tube, simulations were run in Solidworks FlowXpress to understand the behavior of the water as it passed through the dip tube. The simulations were run with scaled parts drawn in Solidworks, Amtrol's dip tube figure 75 and the redesigned dip tube figure 77. The parts with dimensions can also be seen in Appendix **(A)**. The environmental conditions used for the dip tube improvement analysis can be seen below in figure 80.

$$\dot{m} = 0.76 \frac{lb}{s} \qquad T = 55°\text{F}$$

$$Q = 21.2 \frac{in^3}{s} \qquad P = 60psi$$

FIGURE 83: DIP TUBE IMPROVEMENT ANALYSIS ENVIRONMENTAL CONDITIONS

When the redesigned dip tube was compared to Amtrol's original dip tube it was evident there was a reduction in exit velocity. It reduced the exit velocity from 32.8 in/s to values ranging from 11.7 in/s to 16.4 in/s. The improved dip tube decreases the exit velocity of water 50 to 65%. Velocity profiles of Amtrol's current design and the redesigned dip tube can be seen in figures 83 and 85.The simulation also proved the exit flow direction and therefore the direction of momentum was also changed from primarily in the Y-direction to primarily in the X-direction. This can be seen in figure 84 and 86. Note how the strings directions are changed from running completely vertical, figure 83, to running in the X-direction when the water is forced out of the holes in the side in figure 84. An alternate view of the velocity profile of water through Amtrol's dip tube and the redesigned dip tube can be seen in figure 75 and 77 respectively.

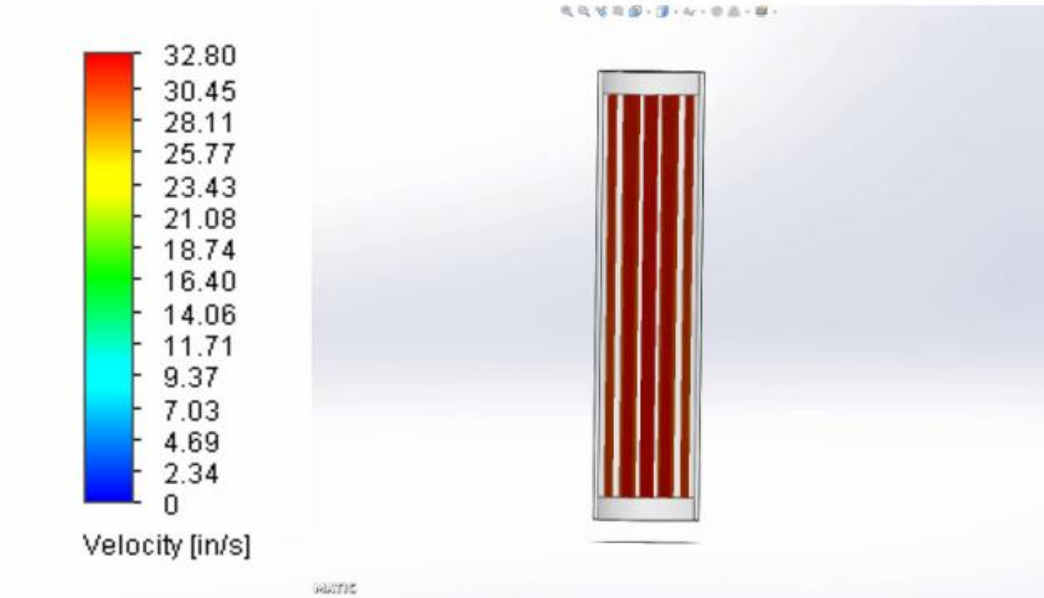

FIGURE 84: AMTROL'S DIP TUBE FLOW SIMULATION RIBBONS

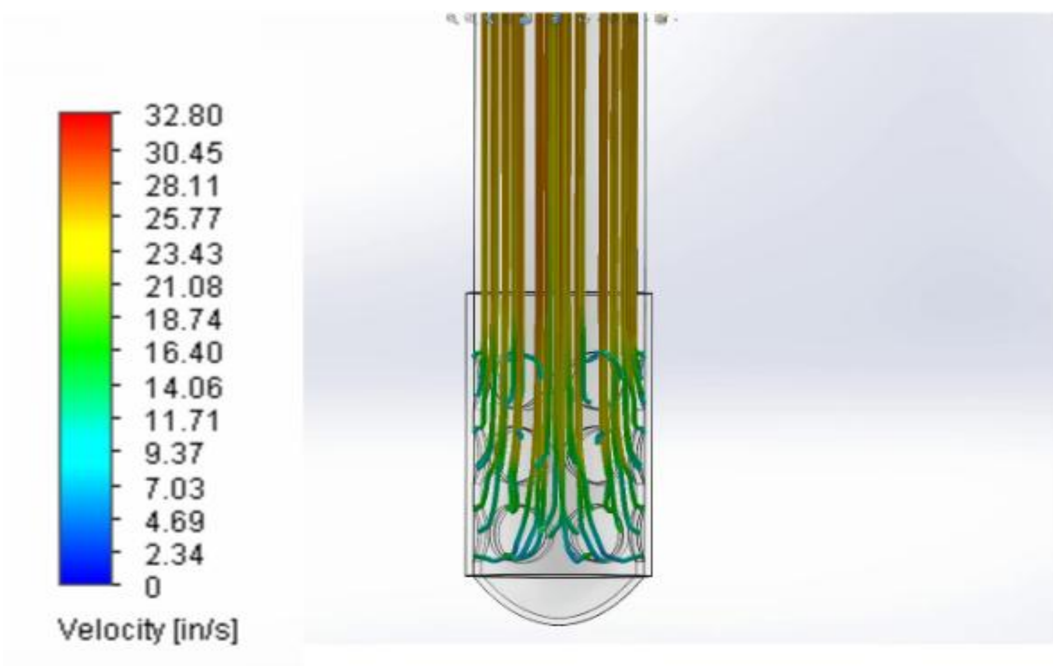

FIGURE 85: REDESIGNED DIP TUBE FLOW SIMULATION RIBBONS

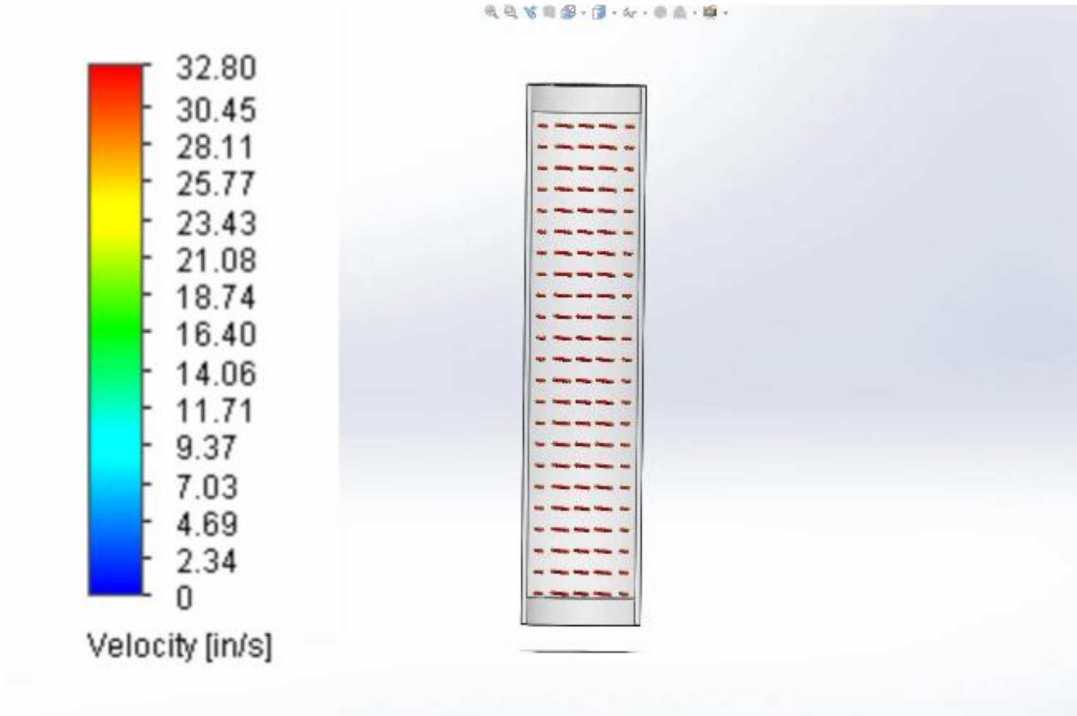

FIGURE 86: AMTROL DIP TUBE FLOW SIMULATION BEADS

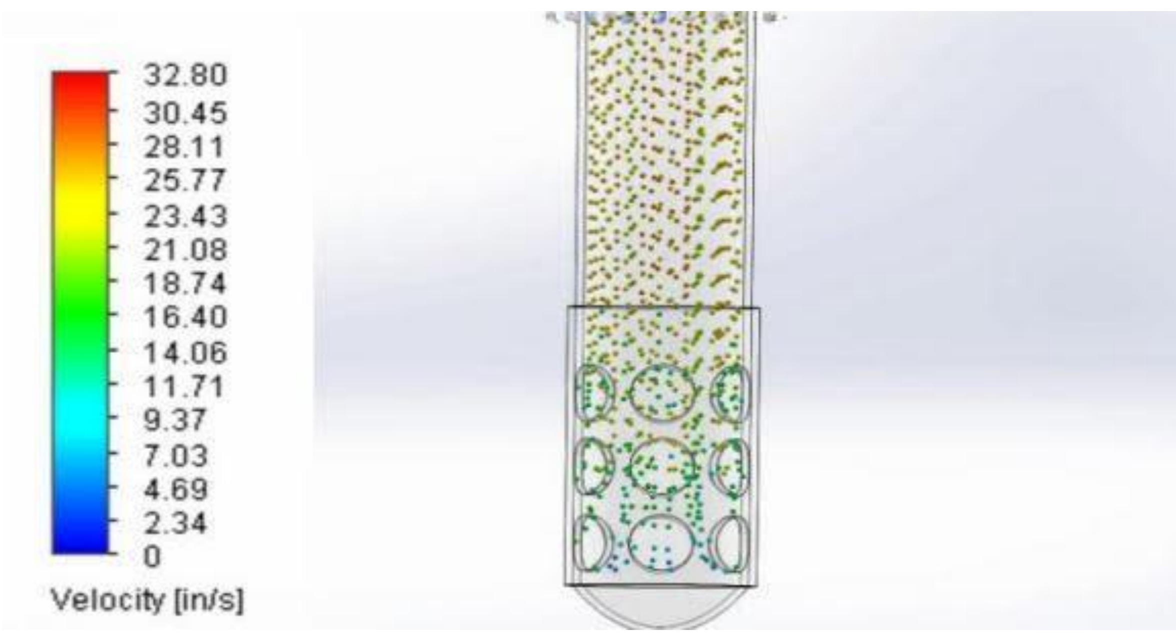

FIGURE 87: REDESIGNED DIP TUBE FLOW SIMULATION BEADS

11.3 Current Coil vs. Variable Pitch Coil

To determine the effectiveness of our new designed variable pitch coil Team Intercambidores conducted a number of cold start static condition tests. The cold start test was run three times for each of the coils and then the data collected for the variable pitch coil was compared to the existing coil to determine the Btu/hr output change based on geometry.

The current coil performed as seen in CITE and the redesigned coil performance can be seen in CITE. The results are plotted as Length vs Btu/hr. The full listed results can be seen in CITE. The results show that the redesigned variable pitch coil outputs a higher Btu/hr for a longer length of coil than the current Amtrol design. This change is evident between lengths 20 through 30 when comparing the current coil to the variable pitch coil.

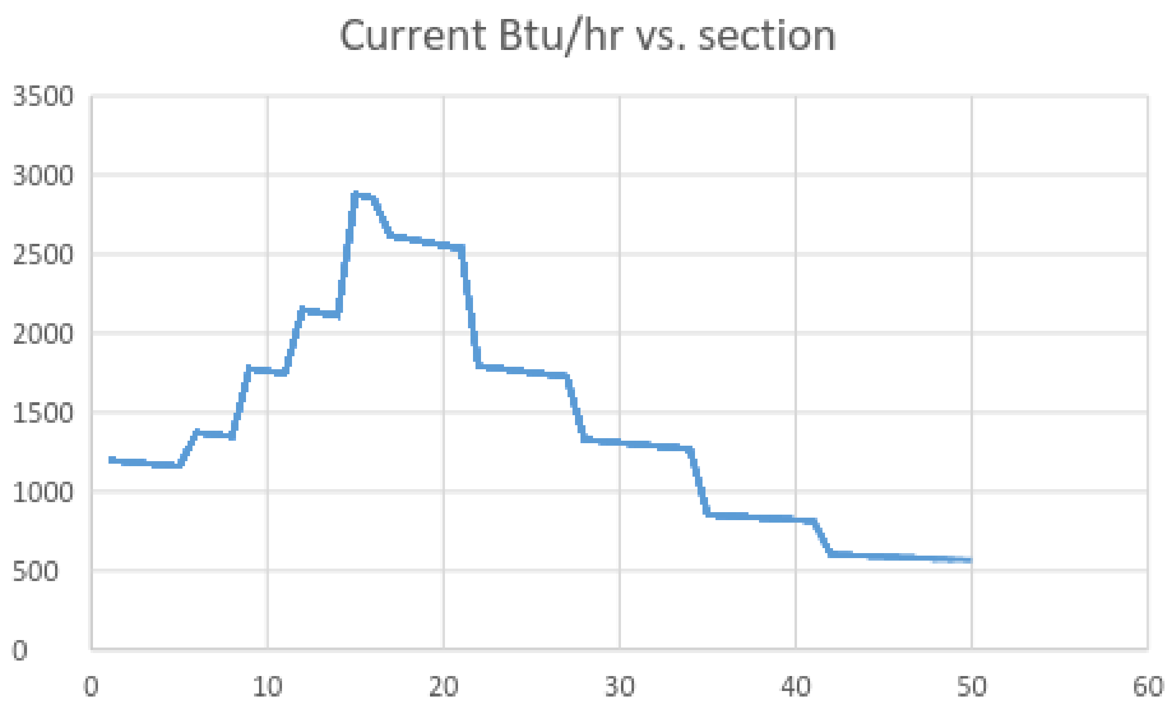

FIGURE 88: CURRENT COLD START ANALYSIS OF COIL SECTION VS. BTU/HR

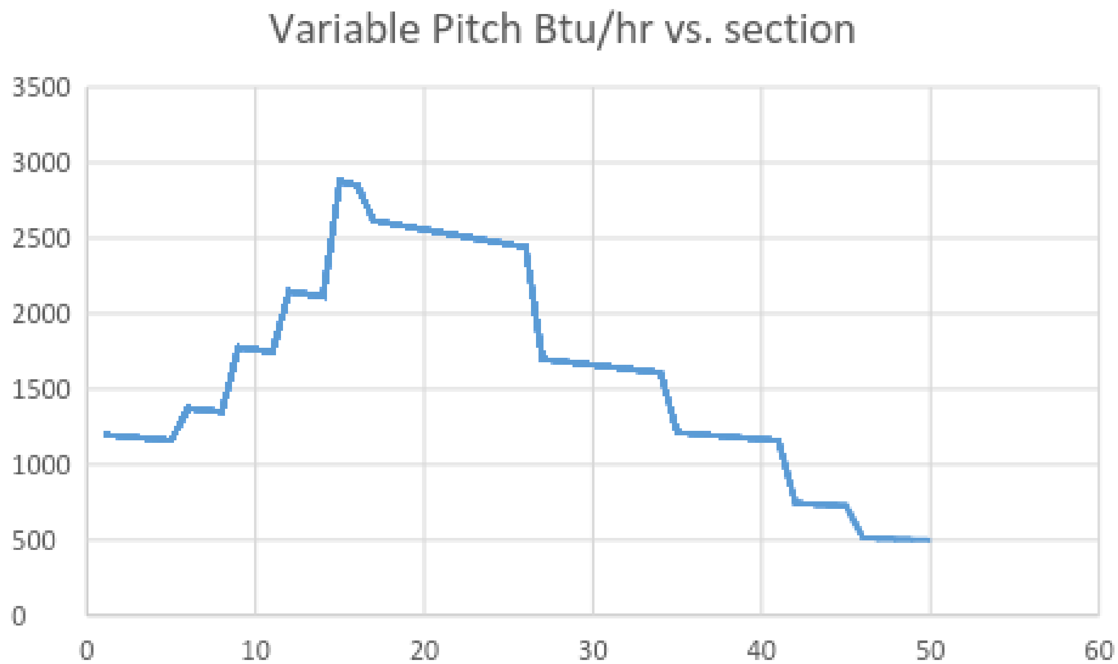

FIGURE 89: VARIABLE PITCH COLD START ANALYSIS OF COIL SECTION VS. BTU/HR

12. Build and Manufacture

12.1 Build

Amtrol has a great deal of existing manufacturing capabilities to allow for the ability to produce all the needed prototypes during this project. The first prototype was constructed by warping the shape of one of the existing coils, and compressed to the desired shape for testing. Constructing the new coil involved using the suppliers for Amtrol to provide materials and services to construct parts of the prototypes. The workshop at the University of Rhode Island was used to produce the dip tubes used in the experiments, while the coil shaping, finning, and coating were done by suppliers for Amtrol. Non-traditional prototypes, such as gastite samples, were constructed by hand in Amtrol's labs by the group. Using a clamp to hold tight one end of the coil and shaping the other side by hand. Building of the baffle included using PVC sheeting at Amtrol and shaping into a cylinder and then cutting the openings by hand.

12.2 Manufacture

The advantage of this system is that the changes introduced do not dramatically affect the manufacturing infrastructure. Because there is no change in the inlet and outlet position in the coil the faceplate needs no change to accommodate this design. A minor software import will allow for the change in the overall shape of the coil. In order to change the thickness of the tin coating the manufacturing process must change slightly allowing for less time for the copper coil to be exposed to the tin coating therefore reducing the overall thickness of the tin on the copper. Manufacturing of the dip tube changes slightly as the tool used at the end of the dip tube changes in order to close off the end of the dip tube. Then an indexer already present in the system, coupled with a drill, may be used to introduce the holes to the dip tube, again introducing an almost zero cost change to the system. Manufacturing of the baffle introduces as challenge as it is a new part to the system. If the baffle is made of PVC then an outside vendor will shape and cut the baffle and preferably use a sonic weld to make it a singular cylinder before shipping it out to Amtrol for installation.

13. Testing

The testing of the heat exchanger designs is based on industry standards. There are two tests that must be conducted in order to properly analyze the heat exchanger versus Amtrol's current design and other competitor designs. One test involves a static condition (Cold Start Test), and the other is dynamic (Continuous Draw Test). Specifics on the testing guidelines can be found in Appendix [CITE].

13.1 Testing Apparatus

Amtrol provided the testing apparatus used to test the designs. This apparatus included a boiler, 41 gallon tank, multiple temperature sensors, and a computer recording the sensor readings. The testing apparatus in Amtrol's lab is shown in figure 89. There are six sensors from the top to the bottom of the tank. Also, there is a sensor at the inlet and outlet of both the boiler and the domestic water. This all adds up to 10 sensors in total. Temperatures are recorded every 10 seconds on the computer. A calculated tank average and delta T between the domestic inlet and outlet are also recorded automatically.

FIGURE 90: TESTING TANK AND SURROUNDING SENSORS

13.2 Cold Start Test (Static)

This test is considered static testing because domestic water is neither entering nor exiting the tank. In order to begin the cold start test the tank must be full of domestic water at a temperature between 40 and 50 degrees Fahrenheit. The boiler must be set to 180 degrees Fahrenheit with a flow rate of approximately 8 gpm. The domestic water is heated until the tank average is approximately 135 degrees Fahrenheit. Depending on how long this takes can determine how efficient the heat exchanger design is.

TABLE 3: STRAIGHT LENGTH DATA DURING STATIC CONDITIONS

Uncoated finned copper			Tin Coated finned copper			Gastite		
Q (average)	23379.84	Btu/hr	Q (average)	20638.98	Btu/hr	Q (average)	25049.83	Btu/hr
Flow rate	10	gpm	Flow rate	10	gpm	Flow rate	11	gpm
Specific Heat	1.007	Btu/lb F	Specific Heat	1.007	Btu/lb F	Specific Heat	1.007	Btu/lb F
Density	8.097	lb/gal	Density	8.097	lb/gal	Density	8.097	lb/gal
Q(av)/cost	9661.090909	Btu/hr dollar	Q(av)/cost	7068.14488	Btu/hr dollar	Q(av)/cost	6036.10327	Btu/hr dollar
Q(av)/mass	36474.00936	Btu/hr lb	Q(av)/mass	32198.10148	Btu/hr lb	Q(av)/mass	227725.7143	Btu/hr lb
Total time	500	Seconds	Total time	590	Seconds	Total time	700	Seconds
Average temp Intial	50.2	degrees F	Average temp Intial	47.5	degrees F	Average temp Intial	46.9	degrees F
Average temp Final	59.8	degrees F	Average temp Final	57.5	degrees F	Average temp Final	61.3	degrees F
PEX			Unfinned Uncoated copper			PVC		
Q (average)	8610.88	Btu/hr	Q (average)	13718.39	Btu/hr	Q (average)	8204.36	Btu/hr
Flow rate	11	gpm	Flow rate	11	gpm	Flow rate	11	gpm
Specific Heat	1.007	Btu/lb F	Specific Heat	1.007	Btu/lb F	Specific Heat	1.007	Btu/lb F
Density	8.097	lb/gal	Density	8.097	lb/gal	Density	8.097	lb/gal
Q(av)/cost	9599.641663	Btu/hr dollar	Q(av)/cost	9331.4	Btu/hr dollar	Q(av)/cost	9430.300807	Btu/hr dollar
Q(av)/mass	78280.71429	Btu/hr lb	Q(av)/mass	21401.54821	Btu/hr lb	Q(av)/mass	41021.80851	Btu/hr lb
Total time	1400	Seconds	Total time	790	Seconds	Total time	1410	Seconds
Average temp Intial	49.7	degrees F	Average temp Intial	49	degrees F	Average temp Intial	51.9	degrees F
Average temp Final	59.6	degrees F	Average temp Final	57.9	degrees F	Average temp Final	61.4	degrees F

13.3 Continuous Draw Test (Dynamic)

The continuous draw test is used to determine how well a design works while domestic water is constantly entering and exiting the system. This is relevant in day-to-day use because it compares to multiple people showering or taking baths at the same time in a household. There are various constraints for this test that must be within a certain range or the test results are not useful. Firstly, the domestic inlet water must enter the tank at 58+/-2.5 degrees Fahrenheit. The boiler temperature must be set at 180+/-2.5 degrees Fahrenheit. Also, the delta T between the inlet and outlet domestic water must be at 77+/-2.5 degrees Fahrenheit. Initially, the test is run for 15 minutes with these ranges to be maintained to ensure that steady state has been reached. After these 15 minutes, the test is run for 30 minutes with all the water from the domestic outlet being retained in a barrel.

After these 30 minutes is complete, and the ranges are maintained, the total domestic water out is weighed. This weight is used to calculate the flow rate of the domestic water outlet, which thus determines the efficiency and power output of the heat exchanger design used.

14. Redesign

14.1 Detailed Description of Improvement Process

The advantage of this design is that each part of the exchanger may be optimized in order to create a more effective product. This compartmentalization allows for quick testing of components in order to determine which additions will provide the most benefit to the system. In the initial testing it was found that the variable pitch coil struggles to perform during dynamic testing while performing drastically better than the original model under static conditions. In order to remedy that issue a new dip tube was introduced. The new dip tube controls the flow behavior of the incoming water in order to increase the convective heat transfer that occurs during dynamic conditions by increasing the rate of flow in direct contact with the coil and by decreasing the overall momentum in the y-direction. While this increases the performance in the system it did not provide enough improvement in order improve upon the original systems performance.

Therefore other approaches must be taken in order to practically improve upon such a design. In order to do this without drastically affecting the current manufacturing infrastructure a change in the thickness of the coating was implemented. This was done by changing the parameters of the process of coating the coil such that the resulting tin thickness was one third that of the original. Because tin has a much lower thermal conductivity than that of copper it acts to insulate the system. Therefore by reducing its overall thickness we eliminate some of the insulation from the system expediting the heating process that occurs in the tank specifically during dynamic conditions within the tank.

Testing the thinner coating on the coil yielded a positive result in both the dynamic and static conditions. Opportunity for further improvement in the dynamic testing was seen in the introduction of a baffle. The baffle, which would be made of a cheap thin sheet of cut plastic, would help concentrate the faster flowing potable water around the coil. By doing this it isolates the faster flow resulting from external pressure to allow for a more effective heating area during dynamic testing. By cutting small openings in the top and bottom of the baffle the water is capable of flowing in a convective cycle during static heating conditions. The introduction of the baffle will slightly stifle the efficiency of static conditions in order to improve the performance dynamically.

TABLE 4: PERFOMANCE OF FULL PROTOTYPES IN TESTING

Percent change from existing Amtrol Exchanger				
Design Iteration	Static Condition (BTU/Hr)	Dynamic Condition Vol Output (Ga)	Dynamic Condition (BTU/Hr)	Cost
1 (VP)	24.81%	-4.50%	-0.68%	0
2 (TCVP)	30.42%	2.13%	6.10%	0
3 (TCVPwB)	24.78%	11.20%	14.84%	2.30%

TABLE 5: PERFORMANCE CONTRIBUTIONS DUE TO COMPONENTS IN DYNAMIC CONDITIONS

Performance Increase per part for Dynamic Conditions Compared to Currently Manufactured Coil		
Part Modified/Introduced	%Btu/Hr increase	% Cost increase
Coil Var. Pitch(M)	-4.71%	0
Diptube(M)	3.08%	0
Coil Thin Coat Var. Pitch(M)	3.02%	0
Baffle(I)	8.74%	2.50%

14.2 Recommendations for Future Design Teams

This design has now gone through three major design iterations. All three focus on major points of designs in the heat exchanger. In order to further improve upon the current design first a careful evaluation of the overall coil structure. While the current coil structure is designed for increase performance, a more in depth analysis of the overall design would be prudent for the success of future design iterations. Another important characteristic for analysis would be the flow behaviors inside the tank. Currently Amtrol does not have the equipment do evaluate such an intricate system in great detail, but the best way to optimize the heat transfer that occurs in the system both in dynamic and static conditions is to determine the flow behaviors throughout the tank and design and exchanger that takes advantage of those patterns.

15. Maintenance

The maintenance of the newly designed heat exchanger is nominal or not necessary unless problems occur within the system. The tin coating on the coil provides protection against deposition and degradation from hard or otherwise mineral dense water. The baffle material either being PVC or a high-density polyethylene can maintain itself in the system for a long period of time without upkeep. This is all based on the fact that the heat exchanger has approximately a 20 year lifetime. During these 20 years there should be minimal to no maintenance. Although after 20 years of continual hard or mineral dense water, the system may suffer from degradation, which may cause required maintenance or part replacement.

16. Additional Considerations

16.1 Economic Impact

The new Amtrol indirect fired water heater presents a number of economic considerations for the company and the consumer. The company will have a product with increased efficiency with minimal to no increase in price. With the introduction of the baffle the cost is increased 3%. Depending on the direction Amtrol goes with their marketing, the product could be available to the consumer for less, equal or greater of a price. If the price is reduced or maintained, the consumer will enjoy the benefits of a more fuel efficient system for the same or less cost.

16.2 Environmental Impact

Amtrol's newly redesigned indirect fired water heater will have a number of environmental impacts. With its improved efficiency the need for fuel, to heat the water, will be reduced in turn reducing the carbon footprint of the consumer. The 12% increase in overall system efficiency will directly affect the amount of fuel needed to produce the same amount of hot water as Amtrol's previous model. Another environmental impact to consider is the reduction in tin coating used on the copper coil. By making the tin a third the thickness, there is less demand by Amtrol for the metal. Tin mining is destructive to the land and can put certain populations of people, animals, and plants at risk. Although the demand reduction is small, it is an important concept and step in preserving our wildlife and natural resources.

16.3 Societal Impact

Amtrol's indirect fired water heater has societal impacts both locally and globally. Locally the water heater allows people to bathe, maintain healthy hygiene, wash dishes and clothes, and a number of modern conveniences and necessities that society has come to know. With the improved efficiency of the system, this will allow potentially more people to come to know these modern amenities in one home in less time. Globally society will be impacted by this product by its function and improved efficiency. Functionally it will increase population health and cleanliness, efficiency impacts will set a precedence that a better product is one that does a quality job with less.

16.4 Political Impact

The heat exchanger designed is used in a residential applications, thus the political impact is minor to nonexistent. Manufacturing practices, which occur in the United States, are subject to political restrictions and influence, but this does not dramatically affect the manufacturing of the product, as such this product does not have any major effects on the political stage.

16.5 Ethical Considerations

The specifications and restrictions set by Amtrol provided the team with guidelines to what was ethical or not in designing the new heat exchanger. It was not ethical to drastically change the manufacturing processes of the heat exchanger because it would likely be more expensive and not beneficial to the overall product. The testing specifications must have met industry standards for all tests to ensure the validity of the designs. Before the actual experimental tests were conducted, theoretical tests were done to provide a basis of what to expect, and to ensure the test was worth the time. The sensors and equipment were checked on a consistent basis to ensure the results were showing the correct values.

16.6 Health, Ergonomics, and Safety Considerations

The tin coating on the heat exchanger provides protection against degradation, which makes the water completely food-safe. Also, the baffle material will not contaminate the water. Ergonomics are considered nominal because once the heat exchanger is installed there is no need to touch it unless problems occur over its 20 year lifetime. When installing the heat exchanger, the faceplate that the exchanger is brazed onto must be properly screwed into the tank. If this is not done properly, the tank may begin to leak or bubble at the top when heated to high temperatures. The system can be dangerous if the pipes connected to the boiler are not properly screwed in. These pipes can get very hot which means that gloves are required to handle them especially if the boiler was recently on. In general, if a professional handles this product correctly there should be no problems.

16.7 Sustainability Considerations

The indirect fired water heater produced by Amtrol is made of copper, tin and plastics. These materials each have their sustainability considerations. Copper is a heavily mined and demanded metal. It is a finite resource but is highly recyclable. End of product life should be highly considered in order to maintain a supply of copper to be used. Tin is a highly demanded and mined metal as well. It is highly used in electronics and the demand for tin is increasing year to year. Plastics are not particularly scarce but, their end of life needs to be considered.

17. Conclusions

Amtrol came to URI seeking a capstone group that could improve upon their current designs for the internal structure of their indirect fired water heater. After careful evaluation of the current model it was decided that the most potential for improvement per ratio of cost and manufacturability was with the structure of the dip tube and the coil structure. In order to address these major factors each of those components were redesigned resulting in the variable pitch coil design and the improved dip tube design. The variable pitch coil design allows for a simple change in the current design, by redistributing the density of coils as a function of height; this change will increase thermal efficiency, of about 10 percent, while not changing the amount of material nor the structure of the inlet and outlet. The variable pitch coil also introduced a 25% net increase in efficiency during static condition. This will allow for an improvement in performance without adversely affecting their current manufacturing structure. The improved dip tube has virtually no cost impact to implement and will reduce exit velocity by around 50%. The decrease in velocity and limited momentum in the Y-direction will allow for a smooth temperature gradient thus increasing the heat transfer coefficient by putting the hottest water in contact with the coldest water. This temperature differential drives the efficiency of the system and will be optimized by the new dip tube design. After careful testing and analysis, it was concluded that to increase the efficiency of the dynamic condition, a baffle could be used. The baffle reduced the static condition efficiency from 25% to 20% but raised the dynamic conditions efficiency by 12%. Team Intercambiadores new variable pitch coil design, optimized dip tube and introductory baffle design will increase the efficiency, effectiveness and price point of Amtrol's Hydromax® 41 gallon Indirect-fired water heater.

18. Further Work

Further market analysis must be done on a number of fronts for the exchanger. The analysis will help determine whether or not the baffle is thoroughly viable as a product addition, and determine the cost benefits from the reduction of tin coating. The challenge with tin coating is that by reducing the thickness of the tin increases the likeliness of an uneven coating. An analysis needs to be done in order to determine at what thickness of tin coverage, the heat transfer is optimized. Using viable manufacturing methods a new baffle needs to be created and tested. New Solidworks models should be used as the basis for the new coils to be paired with the baffle. The dip tube should be applied as soon as possible. Further analysis should be done on coil material and shape in order to optimize them in relation to the flow behaviors in the tank during dynamic conditions.

19. Acknowledgements

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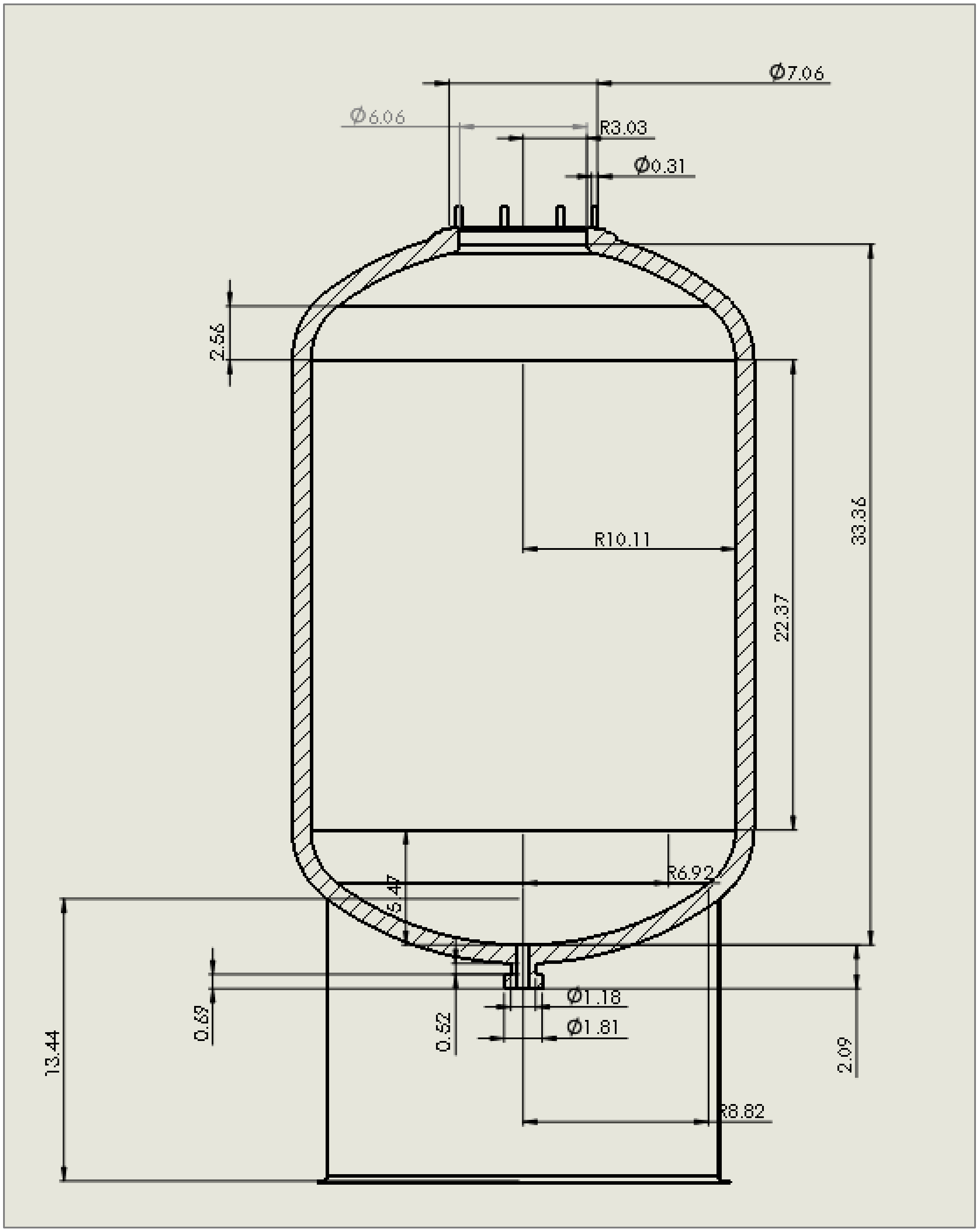
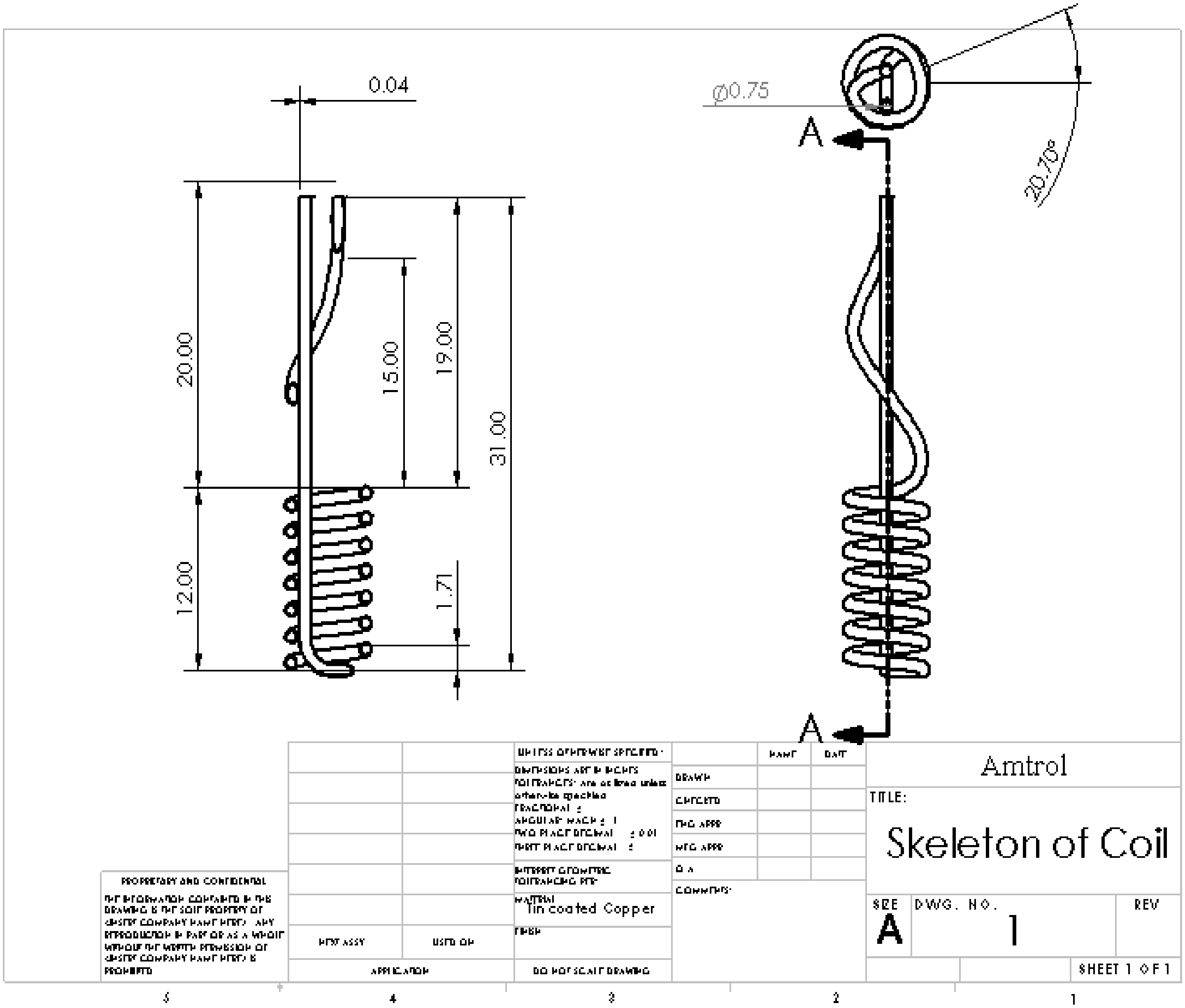
21. Appendices

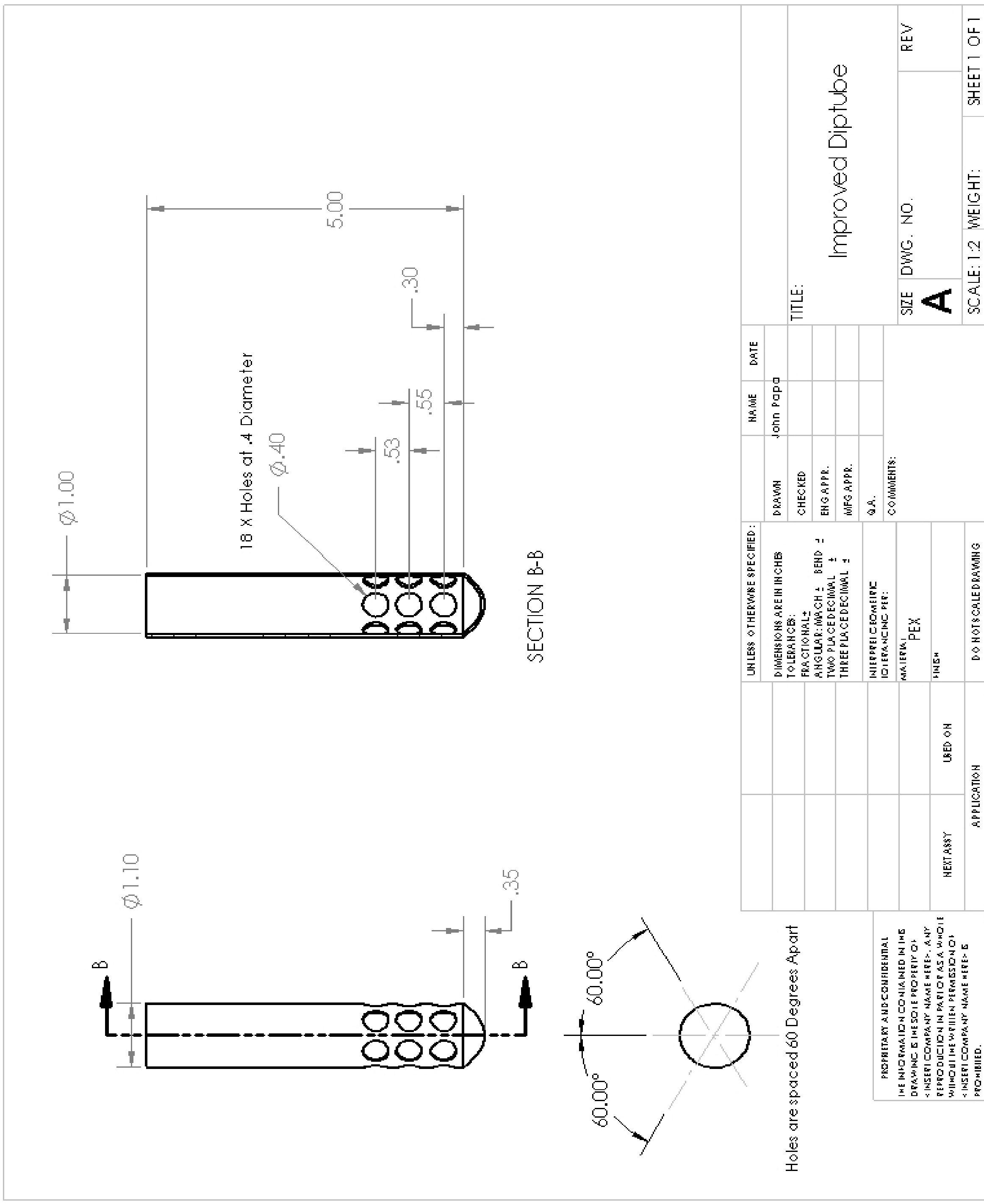
Appendix A



Appendix B


0.04
∅0.75
20.70°
A
A
20.00
15.00
19.00
31.00
12.00
1.71
Amtrol
TITLE:
Skeleton of Coil
SIZE
A
DWG. NO.
1
REV
SHEET 1 OF 1
MATERIAL
Tin coated Copper
DRAWN
CHECKED
NAME
DATE
COMMENTS:
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
PROPRIETARY AND CONFIDENTIAL
UNLESS OTHERWISE SPECIFIED:

Appendix C

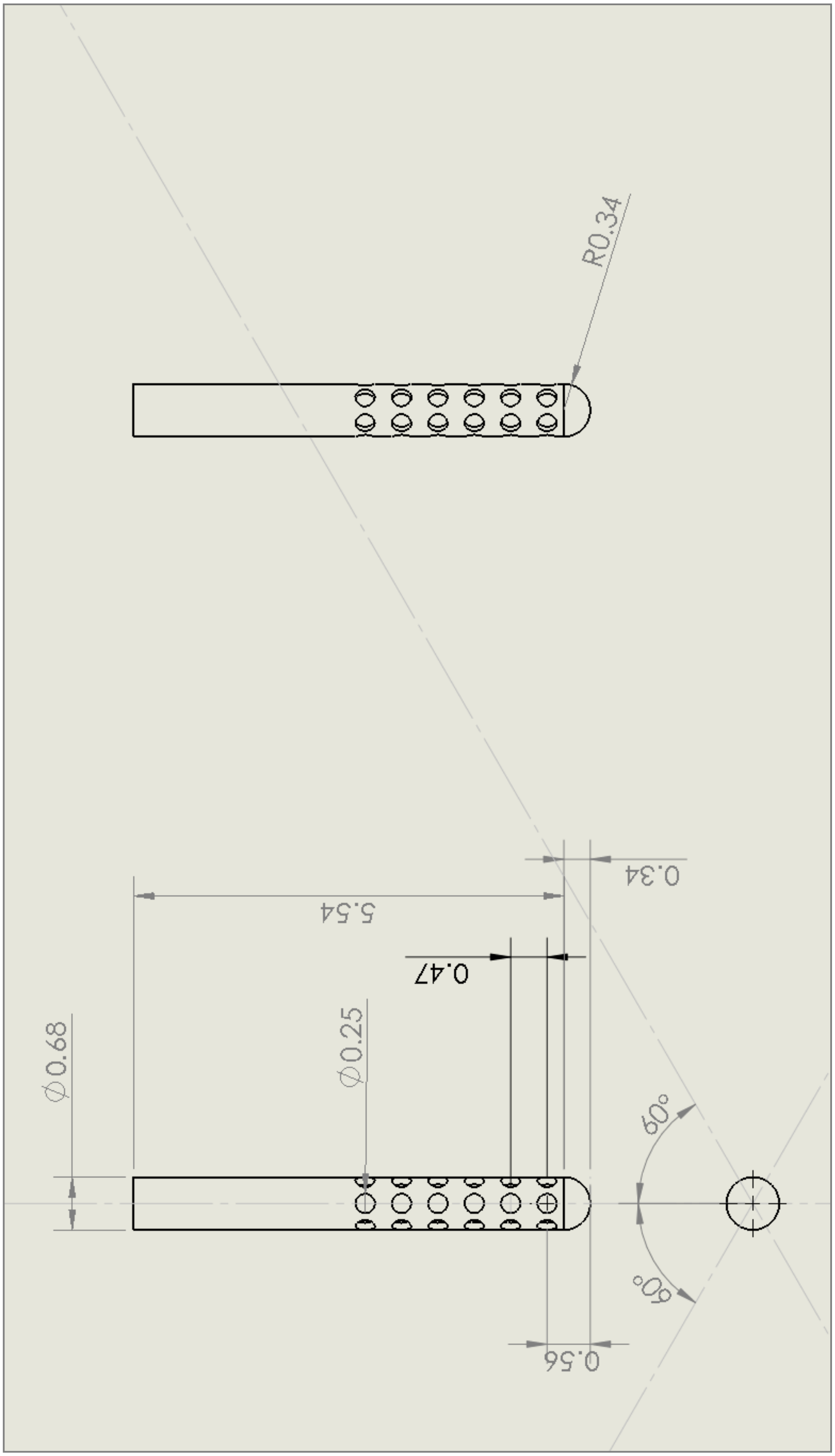


Improved Diptube
TITLE:
SIZE
A
DWG. NO.
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
SECTION B-B
18 X Holes at .4 Diameter
Ø.40
Ø1.00
Ø1.10
5.00
.30
.55
.53
.35
60.00°
60.00°
Holes are spaced 60 Degrees Apart
B
B
DRAWN
John Papa
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
MATERIAL
PEX
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL

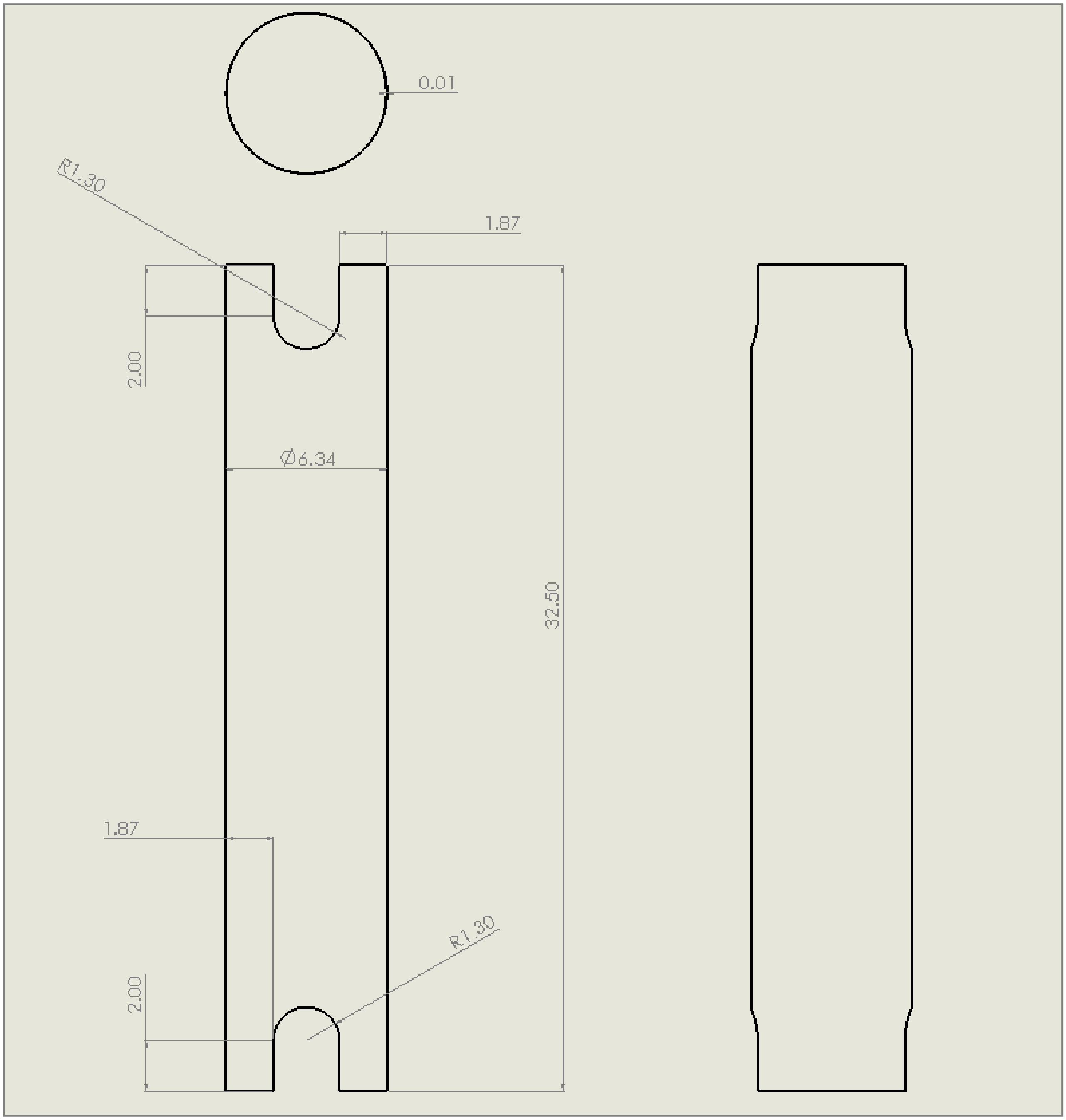
Appendix D

TIME	DATE	BTank 1	BTank 2	BTank 3	BTank 4	BTank 5	BTank 6	TANK AVG	**Boiler Supply**	Boileer Return	Boiler Delta T	**Dom In**	Dom Out	**Domestic Delta T**	Ambient T (Room)	circ on/off
16:28:51	4/12/2011	131.3	131.9	132.1	122.7	104.7	87.6	118.4	**181.2**	159.9	21.3	**59.8**	134.6	**74.8**	73.5	103.4
16:29:01	4/12/2011	132.6	131.9	132.1	122.1	105.3	88.5	118.8	**181.3**	160.0	21.3	**59.2**	134.7	**75.5**	73.0	103.4
16:29:11	4/12/2011	132.6	131.9	132.3	123.3	104.3	87.6	118.7	**181.2**	159.9	21.3	**59.1**	134.4	**75.3**	73.1	103.3
16:29:21	4/12/2011	133.1	131.9	132.0	123.2	104.1	83.9	118.1	**181.2**	160.0	21.2	**59.1**	134.5	**75.4**	73.1	103.2
16:29:31	4/12/2011	132.5	131.9	131.8	122.6	104.2	88.2	118.5	**181.2**	159.9	21.3	**59.1**	134.5	**75.3**	73.6	103.0
16:29:41	4/12/2011	133.1	132.0	132.1	123.0	104.2	84.3	118.1	**181.0**	159.8	21.2	**59.1**	134.6	**75.4**	73.6	102.8
16:29:51	4/12/2011	132.1	132.0	132.1	122.9	104.6	88.3	118.7	**181.0**	159.9	21.1	**59.1**	134.3	**75.2**	73.6	102.6
16:30:01	4/12/2011	133.3	132.0	132.1	122.5	105.4	88.2	118.9	**180.8**	159.7	21.1	**59.1**	134.6	**75.5**	73.9	102.4
16:30:11	4/12/2011	132.4	131.8	132.0	123.1	104.2	85.2	118.1	**180.8**	159.7	21.1	**59.1**	134.4	**75.3**	73.9	102.2
16:30:21	4/12/2011	132.8	132.1	132.1	122.5	103.9	85.2	118.1	**180.6**	159.6	21.0	**59.1**	134.5	**75.4**	74.6	102.3
16:30:31	4/12/2011	132.2	132.0	131.9	122.9	103.8	86.1	118.1	**180.6**	159.7	21.0	**59.5**	134.5	**75.1**	73.4	102.2
16:30:41	4/12/2011	133.2	131.9	131.9	122.6	104.5	87.1	118.5	**180.7**	159.6	21.1	**59.2**	134.7	**75.5**	73.7	102.1
16:30:51	4/12/2011	132.5	132.0	132.0	122.7	104.8	86.7	118.4	**180.9**	159.6	21.3	**59.1**	134.5	**75.4**	73.9	102.1
16:31:01	4/12/2011	133.5	132.1	132.0	122.7	105.0	86.9	118.7	**181.2**	159.7	21.5	**59.2**	134.5	**75.3**	73.7	102.3
16:31:11	4/12/2011	133.2	132.0	132.0	122.4	104.5	85.7	118.3	**181.2**	160.0	21.3	**59.2**	134.3	**75.0**	73.8	102.5
16:31:21	4/12/2011	133.6	131.9	131.9	122.6	104.7	85.8	118.4	**181.3**	160.0	21.3	**59.2**	134.7	**75.6**	73.9	102.7
16:31:31	4/12/2011	133.3	131.9	132.0	122.9	103.4	87.7	118.5	**181.4**	159.9	21.4	**59.0**	134.5	**75.5**	74.0	102.9
16:31:41	4/12/2011	133.2	131.9	132.0	122.8	103.7	86.2	118.3	**181.4**	160.0	21.4	**59.3**	134.5	**75.2**	73.2	103.0
16:31:51	4/12/2011	132.7	132.1	131.8	122.7	105.0	85.9	118.3	**181.4**	160.1	21.3	**59.2**	134.7	**75.5**	73.0	102.8
16:32:01	4/12/2011	132.7	132.1	132.0	122.6	104.3	87.6	118.5	**181.4**	160.1	21.4	**59.1**	134.7	**75.6**	73.1	102.8
16:32:11	4/12/2011	133.9	132.1	132.0	123.2	104.5	88.5	119.0	**181.4**	160.1	21.3	**59.1**	134.6	**75.5**	73.5	102.8
16:32:21	4/12/2011	132.7	131.8	132.0	122.9	104.1	84.6	118.0	**181.4**	160.0	21.4	**59.2**	134.2	**75.0**	73.3	102.7
16:32:31	4/12/2011	133.0	131.9	132.0	122.4	104.7	85.0	118.2	**181.4**	160.0	21.3	**59.1**	134.1	**75.0**	72.5	102.5
16:32:41	4/12/2011	131.5	131.9	132.1	122.8	103.4	87.0	118.1	**181.3**	160.0	21.3	**59.2**	134.3	**75.1**	72.4	102.3
16:32:52	4/12/2011	132.8	131.9	132.0	122.6	104.9	86.4	118.4	**181.3**	159.9	21.4	**59.1**	134.3	**75.1**	72.2	102.1

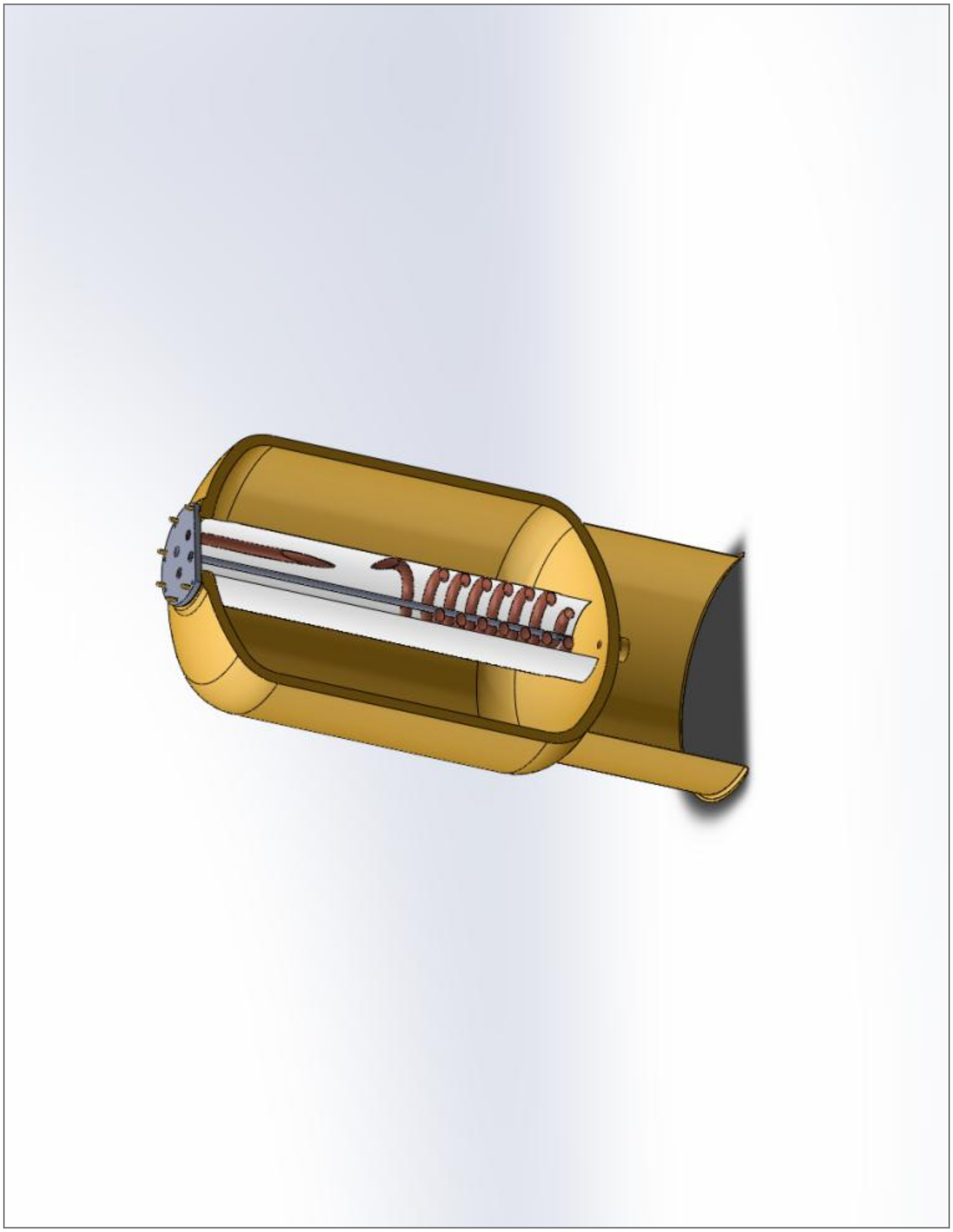
Appendix E



Appendix F



Appendix G



Appendix H

Appendix I

Appendix J

Appendix K

Appendix L

Appendix M

Appendix N