APPLICATION OF DESIGN METHODOLOGY TO THE COOLING SYSTEM OF AN IN-LINE MACHINE VISION SYSTEM

By

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ABSTRACT

A complete design methodology and design of a cooling system is presented. The methodology was developed from an extensive literature review of design processes. The cooling system designed is intended for a machine vision system to be installed in-line at a rolling bar steel mill. The design is generalized for other similar setups to be designed by others. The final design established is an improvement over pre-existing designs. The verification of the system was done entirely numerically with the FLUENT computational fluid dynamics simulation software. Results showed an improvement of 3 ^{o}C for a specific point air temperature with the current model. The new system is intuitively more robust and imposes a lower risk of damage to the electronic equipment, by improving weaknesses in the old system which led to failures.

CHAPTER 1

INTRODUCTION

Design is not a concrete science, it can be envisioned as a soft or hazy science, because it lacks sufficient mathematical basis [1]. There are no set of natural laws defining design, explaining why the definition of design remains obscure. In contrast, phenomena, such as gravity are very specifically defined; gravity is the tendency of objects with mass to accelerate towards each other. This is based upon the fundamental law of universal gravitation [2]. The fundamental law is a basis achieving a universal. Thus design has a variety of definitions. Design has been defined as “the application of science and mathematics to develop economical solutions to technical problems” [3], “the application of science to fit the needs of humanity” [4], and also “systematic, intelligent generation and evaluation of specifications for artifacts whose form and function achieve stated objective and satisfy specified constraints” [1]. However, for the purposes of this paper design shall be defined as: the systematic application of creativity, mathematics, and fundamental laws to produce a solution to a given technical problem.

Most definitions of design have a minimum of two components in common. First, all applications of design require a problem; secondly they all have the goal of a solution to this problem [5, 6, 7]. The research described in the following uses the engineering problem associated with the cooling of the Hoteye^{TM} Rolled Steel Bar (RSB) unit produced by OG^{TM} Technologies, Inc. at Ann Arbor, Michigan.

The single most important element to design is creativity, for without creativity we are simply re-inventing the wheel [8]. Creativity is the dimension that makes design both difficult and challenging, unlike analysis which can be approached exactly as the last problem in order to derive the only answer to the problem. Design must be approached to a specific problem. Yet the mistakes of previous design challenges should not be repeated [9, 10].

The design process is a small fragment of the product development process. A need or want must be identified by marketing or sales, since after the design process is complete the product must still be manufactured, marketed and sold to customers. Indeed, the product lifecycle often includes the servicing, warranty replacement, and disposal of the product, in which case the lifecycle can extend years beyond the actual design process [5, 6, 9].

1.1. Hoteye^{TM} Technology

The HotEye^{TM} is a breakthrough technology in non-contact sensing. This is an imaging technology designed for high temperature applications. This technology has been tested to capture the image of an object that is as hot as 1,450°C with the same image quality as if the object were at room temperature. This innovation is protected by US Patent 6,859,285 [ref?] as well as several other international patents pending and approved.

1.2. Hoteye^{TM} Rolled Steel Bar Application

The rolled steel bar (RSB) application of the technology has been the most successful for OG^{TM} Technologies, Inc. in terms of sales. There are several working systems currently installed in steel mills worldwide. The system won the R&D 100 Magazine top 100 inventions for the year 2006, in the category of mechanical systems [11]. The system is designed to be integrated into a hot rolling steel mill. The system is integrated into the line such that the steel passes through the unit for inspection. Steel bars can reach 14 km in length and travel at speeds reaching 110 m/s. The system provides real time feedback regarding surface defects in the processed steel to the mill. The significant benefits of the system include improved steel quality, improving safety in critical components, and energy consumption reductions in the mill. The system is comprised of a sensor module, a processing module, and a link between the two. The research discussed in this paper focuses on the cooling of the sensor module. This application is protected under US Patent 6,950,546 and other international patents.

CHAPTER 2

PROBLEM DEFINITION

Defining the problem is the single most important step in the design process. The correct problem needs to be identified to solve the problem [5, 6, 12]. Defining the problem, logically, can be approached by several methods, and the use of more is an excellent double check.

Abstraction of the problem is a recognized way to ensure the problem is encompassed. The higher the level at which the problem can be phrased with specific meaning, the more general the problem becomes. A more general problem helps elicit creativity instead of the reuse of existing design concepts [5].

Another well documented method of defining a problem is to construct an objective tree. An objective tree is a tree diagram that breaks down the objectives for the solution in a hierarchical pattern. Such a diagram can help establish root problems [13].

A functional interrelationship diagram helps isolate the subsystems required to solve the problem. By choosing an appropriate detail level such a diagram provides the flows in and out of the components. This type of diagram utilizes the concept of a black box for anything below the level of detail pictured. The flows shown are typically those of energy, mass, and signals [5, 6].

2.1. Hoteye^{TM} RSB Cooling Problem

The engineering problem addressed in this research is the encompassed within the Hoteye^{TM} RSB cooling system, which manages all three modes of heat transfer, conduction, convection, and radiation. The system has an existing design that functions; however, there are several known incidences of failure, a high number of parts, difficulty in servicing, and an imposed risk to electronic components. Additionally, when the Hoteye^{TM} technology is transplanted to a different but similar application the cooling system is redesigned, starting from a conceptual level, which ideally could be avoided utilizing a base level cooling system design that is adaptable to different layouts, and capacities. The underlying problem is not of a singular nature and therefore any solution requires a balance of conflicting customer requirements. It follows that the problem is not a simple application of analysis to determine a single solution, but a rigorous design methodology needs to be utilized to analyze the problem.

The problem is further defined by a conceptual tree (Figure 1) and the functional interrelationship (Figure 2). In addition, the problem may be abstracted to a problem defined as; a system that both shields equipment from heat transfer, and also removes heat dissipated from the same equipment. This abstract problem does not include the necessary elements of cost effective, low failure rate, low risks imposed to electronic equipment, and a simple design.

The general problem cited identified failures as the key component to the weaknesses of the current cooling system. A first case of failure was the failure of an electrical wire due to thermal radiation. The wire was damaged due to direct radiation from the steel bar (Figure 3). The wiring was subsequently modified so that the wires are not exposed directly to the radiation of the bar. A second case of failure of the cooling system was a water hose Quick Disconnect connector came loose during operation (Figure 4). This leaked water into the system directly exposing the electrical components to water. A third instance of a flaw although not complete failure was a punctured duct in the forced air system which allowed excessive debris into the system, rapidly blocking the optics transmission. Considerable time was required to track back to the source of this fault.

When the technology is carried over to another similar application redesigning of the cooling system used on the Hoteye^{TM} RSB systems is required. An example of such a redesign is carrying the technology to rolled billet inspection. The system was redesigned well beyond what would have been necessary for a more modular system. A far more drastic example of such a redesign was for billet casting. The cooling system for the RSB, a combination of water, forced air, and refrigeration, was changed to a water based system with a limited forced air component. The layouts of the RSB and billet casting systems are shown in Figure 5 and Figure 6 respectively. Each redesign mentioned involved implementing a new system based upon an entirely new analysis.

2.2. Hoteye^{TM} RSB Layout of Components Concerned

Cooling is important to all electronic components in the system. The cooling is not necessary to prevent the chassis from melting, as the steel does not have enough energy for this. There are two items of specific concern for cooling. They are the most costly electronic components, and in the event of over-heating may be damaged. They are both rated for operation in a 40°C environment, and this will therefore be the critical temperature. In terms of layout, the first element sits up top near the air inlet and has an internal fan to draw air through it (Figure 7). The second element of interest is down low and has only a passive heat sink. Having identified the problem it was necessary to form a methodical plan, to approach the problem.

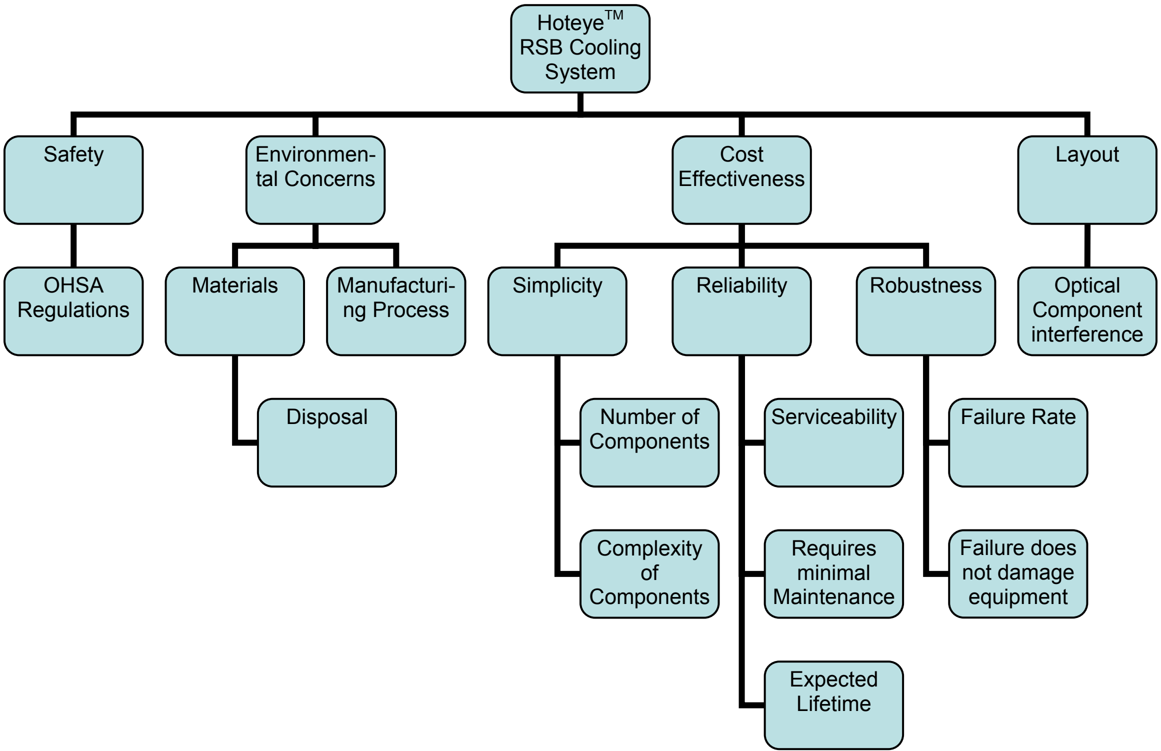


Figure 1. Hoteye^{TM} RSB Problem Tree Diagram

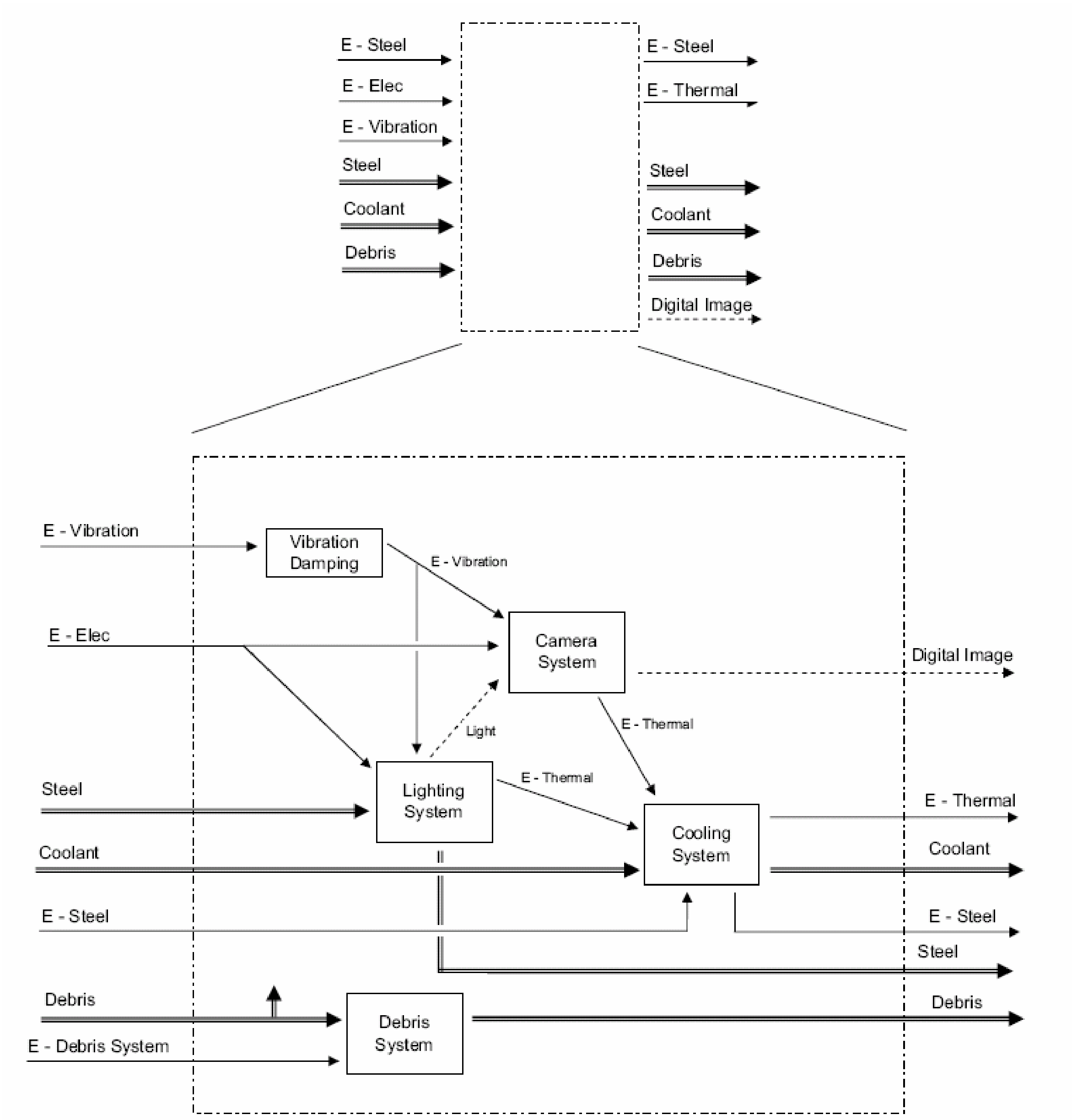


Figure 2. Hoteye^{TM} RSB Interrelationship Functional Diagram

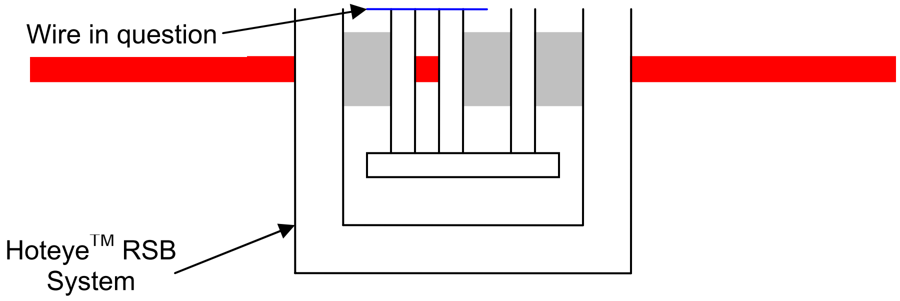


Figure 3. Cooling System Failure with Respect to Electrical Wiring

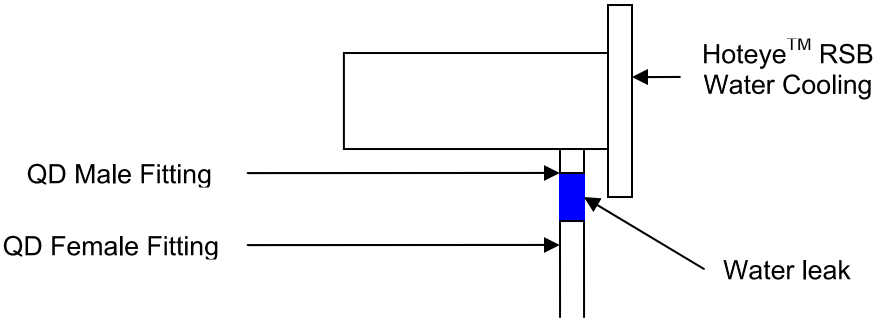


Figure 4. Cooling System Failure with Respect to QD fitting

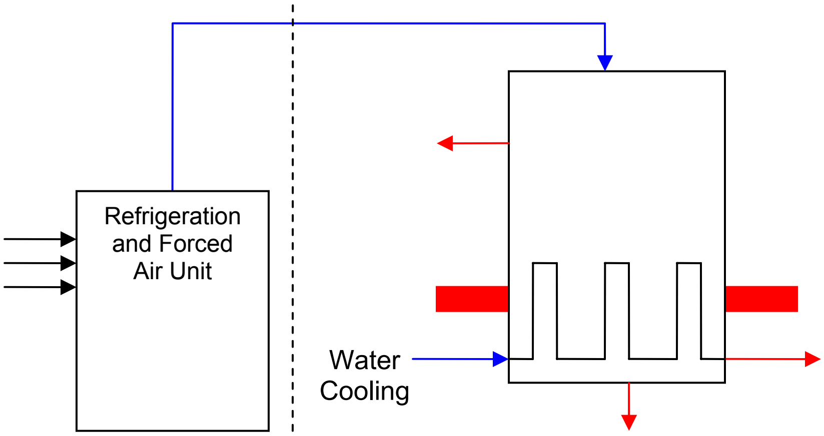


Figure 5. RSB Status Quo Cooling System Layout

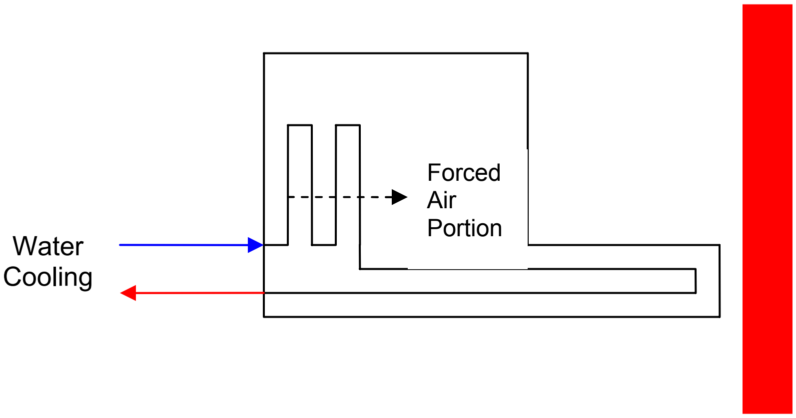


Figure 6. Billet Casting Cooling System Layout

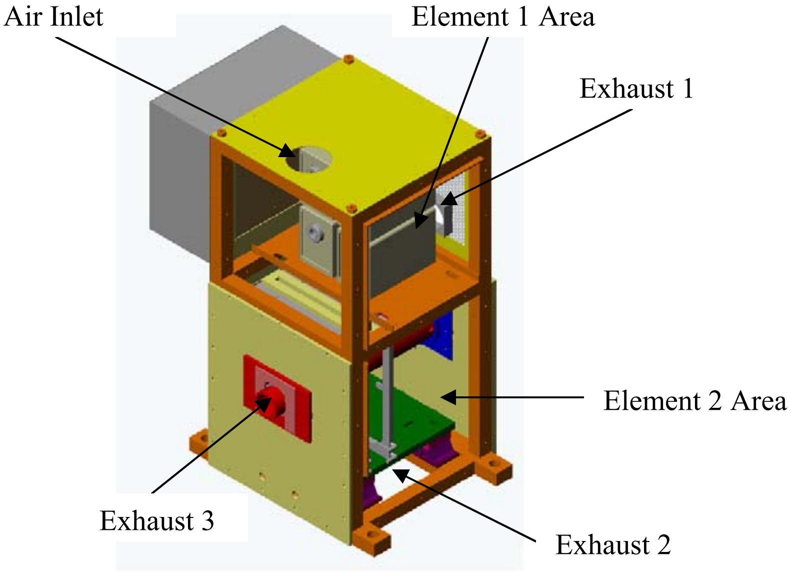


Figure 7. Layout of Temperature Critical Components

CHAPTER 3

DESIGN PLAN

The design process varies for different problems, or else it would be by its own function, the same as analysis. Design is not as simple or singular as analysis, and therefore, the approaches used are neither as simple nor as repeatable. Though design is non-uniform there has been considerable research and documentation, by previous engineers, into methods that have universal application. In order to avoid the mistakes of the past, previous work should be studied [9]. Therefore, the literature by Pahl [5], Ullman [6], Taguchi [14, 15], and Corbett [16] was extensively reviewed in order to formulate this design approach.

The following approach is summarized graphically in Figure 8, Figure 9, and Figure 10.

3.1. Understand the Problem

The initial component to this and nearly every design process is to identify the problem correctly and precisely. Given that the problem in this thesis has been extensively defined it will not be discussed further here. Knowing the problem, however, is not sufficient to begin work. A solid understanding of both the problem and the operating environment are necessary early to identify the key elements. This understanding was achieved by researching existing literature related to the topic, determining a scope of the problem, understanding the system structures, and identifying the global aims. It was also helpful to decompose the system into subsystem and sub functions.

3.2. System Requirements

Based upon the assumption that a firm grasp of the problem has been established, it should be easy to develop a set of qualitative requirements for the system. This was done taking into consideration safety, governmental, and environmental regulations. Such qualitative requirements allow for the evaluation of concepts without generating quantitative data for each concept.

3.3. Conceptual Phase

Although the problem posed has an existing conceptual level design, it is important to revisit the conceptual level when there is a true design problem, and not an analysis problem. The reasoning for this is, although the conceptual phase represents a small percentage of the design process, it has a significant impact on the outcome when compared with other steps in the design process. In addition, the possibility exists that the existing design prevents us from visualizing a truly innovative solution. Therefore, a conceptual phase was used to compare different concepts for the cooling system in question. This was to ensure that the concepts applied were in fact suitable for the design problem. Given the lack of formal analysis of the current system it would be a false assumption to assume the concepts chosen were the best without further attention.

Concepts were generated based upon brainstorming, literature searches of existing cooling technologies, an analysis of well known cooling systems, and an analysis of natural systems. The concepts generated were evaluated based upon the qualitative system requirements set forth. Evaluating concepts was complicated as none of the designs were ideal and any flaws in one particular solution do not necessarily exist in all solutions. This is due to the nature of design; any design decision will have a conflicting nature. This evaluation was carried out both subjectively and via a matrix scoring system similar to that described by Pahl [5] and Ullman [6]. The possibility of combining individual concepts was considered and the process was repeated several times for the purpose of improving concepts and producing unique combinations. The looping allows for combinations of concepts that strengthen each others weaknesses.

The fruit of the conceptual phase was a chosen concept for the cooling system. This enables the following step of more detailed specifications.

3.4. General Form Solution

The general form design is intended to be applied to other adaptations of Hoteye^{TM} technology. It provides base working knowledge conceptual form of a cooling system that needs only be implemented on the given layout. From the conceptual phase we have the basic definition of this general form design. The general form is revisited after the detailed design phase such that any mathematical models or information gained from the later design phases can be combined into the general form design.

3.5 Engineering Specifications

With a selected concept the qualitative specifications from Section 3.2 are reformulated into engineering specifications. A quality function deployment diagram served to translate the qualitative specifications into detailed quantitative specifications for the more detailed design levels. Such specifications must have units associated with them. They will be justified by the reference specific laws or analysis.

3.6 Layout Design

The layout design level determines the general layout of components. This step determines the interactions between the systems, their placement, and size. The layout stage is the final phase directly incorporating global concerns, beyond at the detailed stage only local information is needed. First the possible layouts will be systematically generated by varying the layout. The comparisons against each other will be based upon the subjective specifications set forth. Secondly the layout will be taken to an overall dimensional layout where the detailed specifications will be used for evaluation. The comparisons were conducted using a matrix scoring system [5, 6] similar to the concept evaluation in Section 3.3. An iterative approach was used to input the previous best layout to generate new layouts for further evaluation.

3.7 Detailed Design

The detailed design phase is much more analytical than the other phases. It involves the rigorous application of engineering theories and law to produce a completed design. This phase was also approached with an iterative stepping. The detailed design of components was carried out, evaluated, and utilized as the starting point for the following iteration. Decisions at this design level vary in level of complexity and nature. Some decisions at this level were singular and others were conflicting such that serious compromises needed to be made to move forward. This is, however, the only phase in design where simple analytical decisions based upon mathematical modeling and known governing laws exist. Decisions of more complicated nature were based upon the same matrix scoring system [5, 6].

3.8 Review of Design

After the completion of the detailed design, we have created a complete design; however, it can almost certainly still be improved. By comparing the general form design with the detailed design we can evaluate and determine if the design falls short in any aspect. Ideally, there would be minor modifications, as any large changes at this point negate significant amounts of work already completed. In the long term the changes made to the general form of the solution, are much more valuable, as they will be applied numerous times. Anything learned from the later design phases can be applied to the general form such that it takes a more tangible form. These additions to the general form also reduce the amount of engineering required to adapt this solution to a different layout.

3.9 Design Validation

Validating the design is to be conducted numerically for the purposes of this paper. This will be done using FLUENT a computational fluid dynamics package. Eventually OG^{TM} Technologies will implement the new design or aspects of the design into their RSB sensor such that it may be tested in a fully operating environment. Testing a prototype outside of the operating environment is not a feasible approach since steel at a temperature of 700^{o}C is impossible to handle without appropriate equipment. Additionally, the energy required to heat an amount of steel to actually test the system would be a considerable waste of energy, since we would not be processing the steel. Having designed a complete plan of approach the plan was then applied.

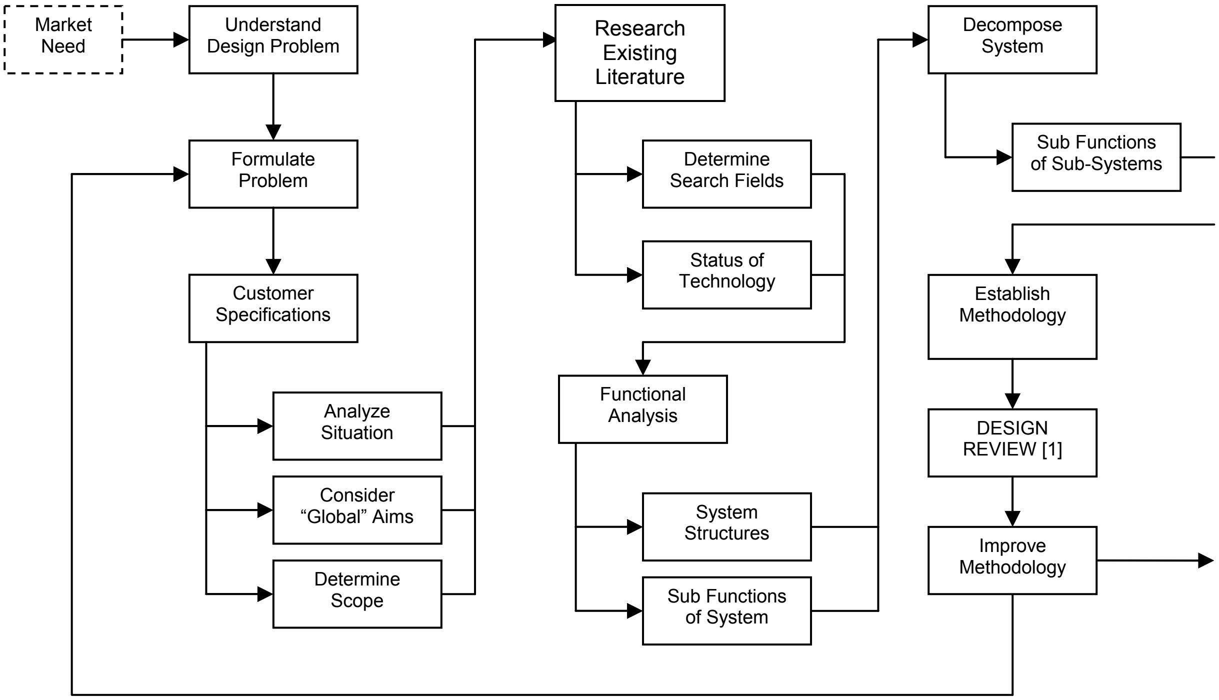


Figure 8. Graphical Design Methodology Part 1

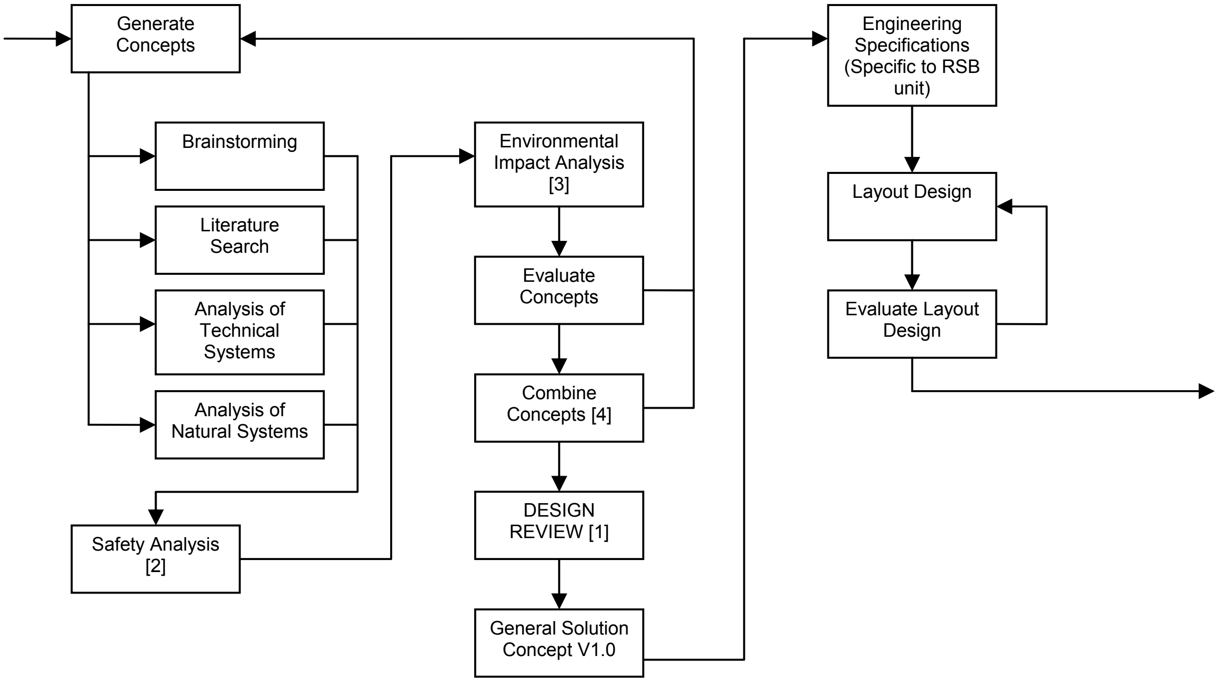


Figure 9. Graphical Design Methodology Part 2

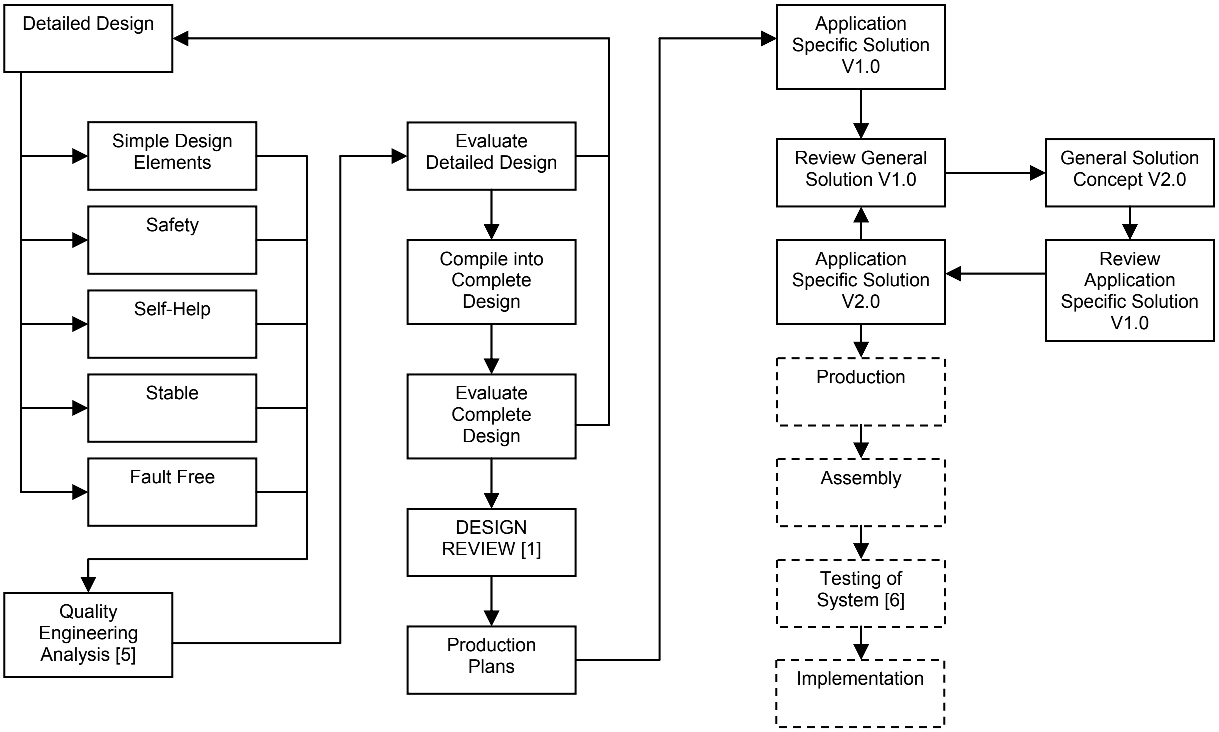


Figure 10. Graphical Design Methodology Part 3

CHAPTER 4

THE DESIGN

The design process is meant to be a fluid iterative process that produces creative, innovative, working solutions to problems. The following work described is the execution of the design process developed in Chapter 3 to form a solution to the problem described in Chapter 2.

4.1. Hoteye^{TM} RSB Cooling Problem

As previously stated in Section 2.1, the Hoteye^{TM} RSB cooling system has a complicated cooling system that manages all three modes of heat transfer: conduction, convection, and radiation. The system has a functioning design that is plagued with several problems as previously outlined, mainly the known failures and redesign efforts. Figure 1 and Figure 2 as previously mentioned define the problem in the form of a problem tree and a function interrelationship respectively.

The known failures of the RSB cooling system are a destroyed wire (see Figure 3), a loosened water connector (see Figure 4), and a punctured air duct.

The cooling system used on the Hoteye^{TM} RSB systems is vastly redesigned when the technology is adapted to a similar application. Such as a rolled billet inspection or billet casting. The layout of the RSB cooling system and billet casting systems are shown in Figure 5 and Figure 6 respectively.

4.2. Reaching an Understanding of the Problem

The status quo Hoteye^{TM} RSB cooling system relies on several water cooling passages, a forced air system, and a refrigeration system. The layout of the system is shown in Figure 5. The refrigeration system is used on the forced air system to cool the air introduced into the sensor. The primary purpose of this chilled air is to remove heat dissipated by electronic components within the sensor module. The thermal radiation energy is removed by several water cooled elements within the sensor module. The arrangement of the water passages is such that nearly all radiation energy introduced into the system is captured directly by the water passages. The water is provided via an open loop system directly from the mill water. Therefore the current system relies solely on the electricity and water pressure from the mill utilities. A sub level functional diagram of the cooling system is shown in Figure 11.

The problem though it can be isolated, has many external factors that are necessary to be included in order to develop a realistic solution. The design has three main aspects, which are shown in the sub level functional diagram, previously indicated as Figure 11; cooling the guide tubes, shielding radiation and removing energy from the optical plates, and removing energy dissipated by the electronics within the system. There is a unique set of intrinsic knowledge required to develop a cooling system for an existing mechanical system. Some of the elements that impact and limit the design of the cooling system are but not exclusive to: mill utilities, line configurations, rolling considerations, and heat considerations.

A steel mill has the typical utilities associated with a plant. The list will always include water, electricity, and compressed air. These utilities are unstable, because of the greatly varying load, related to other heavy-duty cyclic equipment within the mill. The voltage and frequency of the electricity will depend on the location of the mill. The water quality and pressure as well as the pressure and flow of the compressed air will vary over time and between locations.

The line configuration will vary greatly from mill to mill, however typically operational space in the line will come at a premium. Access to both sides of the line will not always be possible. In addition overall height is an issue as there will be an overhead crane that needs to clear the unit.

A hot rolling mill poses concerns for any equipment. Steel is moving at speeds up to 110 m/s. Additionally the steel will almost certainly coble, or exit the desired path. This poses a huge risk to any equipment on the line or in close proximity. Cables or tubing connecting to equipment on the line are also vulnerable.

The processed steel can reach a temperature of 1450^{o}C, which poses an inherent risk of overheating the unit. The bar diameter has an inverse relationship with the rolling speed. Larger diameter bars pose a greater risk to the system than smaller size, because they have a larger amount of energy and are exposed over a longer period of time to the system. The worst case scenario, however, is much worse than a large diameter bar moving through the system, it is a large diameter bar cobbled within the system, until the bar cools.

4.3. System Requirements

The qualitative requirements of the system are listed in Table 1. They were developed based upon the understanding of the problem described in Sections 4.1 and 4.2. They encompass safety, governmental, and environmental regulations as proscribed in Section 3.2. There are also a set of high priority wishes, shown in Table 1, for the system that are not strictly speaking requirements.

The safety standards that are most pertinent to the RSB system are the occupational health safety administration's work standards (OSHA) and the Underwriter's Laboratories (UL) standards. Both of these standards can be approached from a common sense point of view at the qualitative level. From a quantitative approach individual values would be needed for certain design points. The general areas of concern for the RSB system are the following: extremely hot surfaces, extremely cold surfaces, compressed fluids or high pressures, toxic fluids, electrical wiring, noise levels, and all exposed moving parts.

There are no environmental regulations that directly affect this unit's operation, apart from the use of a refrigeration cycle. Refrigerant use is regulated by the federal government, to the extent that it must be operated properly and serviced by a knowledgeable technician. There are many more manufacturing material issues which contribute to the environmental consciousness of the machine. The use of recycled or recyclable materials is always preferred. Additionally the manufacturing process may involve the use of extensive tooling, the less machining needed, the less the use of harmful cooling fluids. These are the central areas of concern with regards to the environment.

4.4. Conceptual Development

The existing design was temporarily ignored for the conceptual development process. The process was broken down into multiple forms of idea generation, evaluation, and iteration as described in section 3.3.

The initial concepts established for this design were developed from several short brainstorming sessions. I sat and wrote down ideas that came to mind for five minutes at a time, as well as any ideas that came into mind during the day. Upon exhausting the well of ideas from this brainstorming, I began a review of the natural laws of heat transfer. This review included the basic laws of conduction, convection, and radiation. Additionally, the review encompassed the conservation of energy and thermal contact resistance. This examination of the natural laws generated further concepts. Finally, a literature search of existing cooling technologies was conducted. This search was conducted using the compendex engineering village search tool. This search yielded far more complex concepts including, but not exclusively: immersion cooled heat sinks, sorption heat pumping, micro channel heat exchangers, pulsating heat pipes [17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27]. The results of this initial stage of concept development are summarized in Table 2, and are sketched in Appendix A.

These preliminary concepts were evaluated first in a subjective manner. This subjective evaluation was based upon feasibility and performance, a chart of these subjective evaluations can be seen in Figure 12.

The preferred concepts, defined as being concepts that subjectively showed good performance, or high feasibility, or both, were selected for a more rigorous evaluation. This evaluation was done with a matrix, shown in Figure 13. This matrix has the design requirements and design wishes compared for different concepts. The concepts were applied to some or all of the cooling needs of the system, as discussed in section 4.2, depending on their suitability for evaluation. The values of this comparison were calculated subjectively with the knowledge acquired from the literature search. Additionally which concepts were applied to which aspects of the cooling system was also selected subjectively.

The design methodology described in section 3.3 prescribes multiple iterations for the concept development; as prescribed the information gained from the first set of concept development was used to generate further concepts. These concepts were developed from combinations of the concepts from the initial iteration. These combinations, detailed in Appendix A, were completed in an attempt to remove weaknesses from the initial designs. These new more robust concepts were then evaluated using the same qualitative analysis from section 4.41 (Figure 14).

The process of combining concepts with others was then repeated. Concepts originally excluded because they fell short in certain areas were combined with ideas that were strong in other areas. These combinations were then evaluated using the same procedures as for the previous two iterations. The matrix evaluating the concepts is shown in Figure 15.

Iteration three provided no concept with an improved overall score relative to the qualitative criteria, as compared to iteration two. I therefore decided to continue with the best concept developed thus far, which was the implementation of water cooled guiding tubes, internal water channels, and a forced air system with refrigeration for the electronics. The best qualitative evaluation of the system is shown in Figure 15. The concept sketch can be found in Appendix A.

4.5. General Form Solution

The general form solution was loosely established based on the concept selected during the concept development process. Restated, the general form of the cooling solution includes the following: a water cooling loop to remove the heat absorbed via radiation and a forced air cooling system with an AC refrigeration unit to cool the air. Implemented on the RSB system the system's water cooling loop is passed through the guide tubes and internal channels. The forced air system specifically targets the two areas of interest, and the system status feedback sensors.

4.6. Layout Design

The layout design is addressed in a bi-level manner. First, the physical location of the components relative to each other is addressed and the impact on the performance. Secondly, the dimensional limits of the layout are addressed as well as the performance thresholds. Both The two stages were conducted in an iterative fashion.

Initially layouts were broken into the 4 subcomponents that have limited interaction: guide tube cooling, vertical internal channel cooling, horizontal internal channel cooling, and the air cooling system (refrigeration and forced air). The layout interactions between the systems are as follows; the first three components share a coolant cycle, and the internal channels are in close physical proximity or in contact with each other. Since the interactions are very limited from a layout perspective the division is logical at this design stage

The guide tubes as previously discussed shield the majority of the radiation. They are currently removable from the system with the interruption of the water cooling cycle. This is important for major maintenance on elements in area two. The use of quick-disconnect water connectors facilitates removal. There are concerns with the reliability of quick-disconnect connections as discussed in the previous system failures (section 2.1). The majority of the physical layout of the guide tubes is determined by the mill specifications, and the other RSB components. The range of bar sizes at the mill determines the ID of the guide tubes; in contrast, the OD of the guide tube is constrained by other components not related to cooling within the system. Given that the redesign of other components is beyond of the scope of this project only layouts that fit within the specified constraints will be considered.

The vertical interior channel is primarily for removing the energy transmitted via radiation to the system from the gap between the two guide tubes. The size constraints of this component are limited, without redesigning other components within the system. The ID of the system is constrained by the guide tube and non related components. The OD is constrained by the size of the mounting plate and the overall cage itself. The thickness is limited by the adjacent non related components which are spaced a minimum of 20 mm away.

The horizontal interior channels shields any remaining radiation and convective heat transfer from reaching the electronics in area of interest 1. It sits directly above the vertical channels and is also limited by the non cooling related components.

Finally, the AC forced air system is currently located remotely and cooled air is transported via a duct to the sensor. This has been identified as a small problem (section 2.1) since the ducts can be readily punctured in the industrial environment. The physical layout is not constrained in the current location; however, changing the location means introducing new constraints.

Ideas for possible layouts were generated based upon the working knowledge of the system, existing cooling systems, and the subjective specifications. Sketches of the derived layouts for the subsystems are shown in Appendix B. A comparison of these layouts is provided in Figure 16. The evaluation is based upon the same subjective specifications used for the concept evaluation. The concepts are evaluated with respect to others within the same sub component as comparing two layouts from different subcomponents was not useful.

The layout possibilities for the guide tube portion have a negligible impact on performance. There would be a slight additional exposure of the water tubing to thermal radiation from piping it outside the unit; however, additional shielding would eliminate this problem. Therefore the layout is established purely by virtue of the constraints. In order to give detailed specifications for the performance of the guide tube a mathematical model was developed.

Secondly, the vertical channel cooling layouts also have a negligible effect on performance. Design parameters that would have an impact on performance would be the material, the flow area, the convection coefficient, the wall thickness, and the color. None of these parameters are specific to either layout discussed in section 4.61. Similar to the guide tube a mathematical model will be developed to help determine specifications.

The horizontal channel cooling layout choice does have an impact on performance. The choice of water cooling over a simple conductor will greatly enhance performance of the system. Additional insulation as a barrier to further emission would improve the performance. Therefore a more analytical analysis will be required to choose the detailed horizontal layout. Such an analysis will develop additional specifications addressing this problem.

The refrigeration and forced air system layout also contributes to the performance of the system. Since we plan to use a commercial unit and not build a custom designed unit the main concern regarding layout is to identify an existing unit that meets the specifications. Evaluation of existing commercial refrigeration forced air systems will be required for the detailed design. Cost is a concern, and is therefore considered here since this is likely to be the single most expensive component to the RSB cooling system. The analysis required to choose the refrigeration layout will also produce additional specifications for the system.

4.6.1. Guide Tube Black Box Analysis

The guide tube absorbs energy from the steel passing through the unit. This energy absorption is through a cast iron insert and therefore is a conductive energy transfer (Figure 17). The cooled guide tube can be modeled as an annulus. Some assumptions for the following model are a steady state system, a constant cooling rate of the metal, a constant specific heat, uniform cooling of the rolled bar, and no loss in energy transfer. These assumptions are fairly conservative because there are significant losses in energy transfer, especially through air.

The cooling rate of hot rolling mills downstream of the last roller varies depending on the material, the bar size, the grade, and additional factors. The interactions between thermal, mechanical, and metallurgical processes determine the microstructure's properties, which are of significant importance for metals [28, 29]. The fastest cooling rate documented in the literature reviewed was $35^{o}C/s$ for 60Si2MnA spring steel rod, however, the highest documented heat flux for a rolled bar being air cooled was given as $74\ kW/m^2$ [28, 29, 30, 31, 32, 33].

The specific heat of the rolled material we assume to be constant, although this is known to be false given the immense variation in temperature. It provides a conservative assumption for this model. The specific heat at a temperature of 1600K was calculated to be 675 J/Kg-K based upon its composition [34]. For comparative purposes the specific heat capacity of similar metals at lower temperatures were found in additional literature to be in the range of 0.5 to 748 J/Kg-K over a temperature range of 1 to 900K [35, 36, 37, 38] the above result is therefore within an expected range.

The bar diameter varies in this system. However, the largest bar size is ~76 mm. Since the goal is a cooling system adequate for the worst scenario the analysis will be for the largest bar. This is because the larger the bar at the same temperature the more energy emitted per change in degree of the bar. This choice ensures a robust system.

Given that the goal is to design a cooling system adequate for current and future rolling parameters I will use the heat flux in cooling of a rolled bar and apply it to the largest diameter bar.) is derived from a black box energy analysis of the system with the steel energy entering the system and that same energy leaving the system via the steel, and the difference in the guide tube cooling. Using (1) the guiding tube must be able to cool 17.8 KJ/m-s at a minimum. This is an energy removal rate per unit length of the cooled guide tube.

$$\dot{E}_1\left(\frac{J}{s}\right) = \pi * D(m) * L(m) * \lambda\left(\frac{J}{m^2 s}\right) \qquad (1)$$

Given that the calculations for the minimum amount of cooling required are a mere conservative estimation, a safety factor or reserve capacity needs to be included. After reviewing safety factors used previously, I have chosen to adopt a safety factor of 1.67. This corresponds to a safety factor used for rigorous environments, including, but not exclusive to aerospace and off-shore [39, 40, 41, 42]. Applying this safety factor gives a design cooling rate of 29.7 KJ/m-s.

The ID and OD of the tube are fixed given that they are designed for the mill's rolling sizes and the non cooling related RSB components. The lengths of the two guiding tubes are also pre-determined due to the existing configuration. Therefore the sole variables of design are the internal dimensions, manufacturing, and assembly parameters.

4.6.2. Vertical Cooling Channel Black Box Analysis

The thermal energy absorbed by the vertical cooling plates is the energy emitted from the steel bar passing through the unit as shown in Figure 5. There is a gap between the guide tubes. This gap corresponds to the exposed surface area of the bar. A conservative estimate of the energy absorbed by the cooling plate can therefore be characterized by the cooling rate of the bar, the size of the cooling plate, the diameter of the bar, the bar's specific heat, the field of view or angle of radiation exposure to the bar, and the travel length of the gap between the guide tubes. (2) is a black box analysis of the vertical cooling plates and the exposed portion of the bar. Using the energy absorbed by the vertical cooling plates can be conservatively estimated and is done so in the following paragraph.

$$\dot{E}_2\left(\frac{J}{s}\right) = \pi * D(m) * F_1 * G(m) * \lambda\left(\frac{J}{m^2 s}\right) \tag{2}$$

The gap between the troughs is designed to be 37.6 mm. The previous system's guiding tube was manufactured by standard machining operations and there is no obvious benefit to changing this, the analysis will be done assuming such. Since the unit is to be made from machined parts and welding there will be some variability in dimensions. When the unit is assembled there are 11 parts that impact the gap between the troughs. Knowing that the machine shop manufactures parts using the standard system of units we shall assume the parts are within 0.254mm of the specified dimension. This is double the specified tolerance on the parts and highly conservative for the CNC machined parts, but less conservative for assemblies involving welding. The worst case scenario for the error stack up is every part at the maximum error in the same direction. For this case the error stack up is 2.794mm. Therefore I shall assume the gap between the troughs is 2.80 mm wider than designed or 40.4 mm. This is the most conservative estimate possible for a tolerance stack up.

The maximum and minimum dimensions of the vertical cooling plates are fixed because of the non cooling related components; however, the range available still permits them to be design variables. For this application the maximum dimension is 500 mm, and the minimum is 192 mm.

For determining the correction factor F_1 we shall assume a single vertical cooling plate absorbs 50% of the radiation emitted by the steel between the guide tubes. This is highly conservative given that there are two vertical cooling plates and a horizontal cooling plate all removing energy from this space and they occupy less than 100% of the volume as there are other components within this volume.

With the above assumptions and the same parameters as stated in section 4.63 the minimum energy removal rate for the cooling plate was found to be 0.6 KJ/s. We will apply the same safety factor as used for the previous section and therefore the design requirement will be a minimum energy removal rate of 1.0 KJ/s.

4.6.3. Horizontal Cooling Channel Black Box Analysis

The horizontal cooling plate is subject to similar operation as the vertical cooling plates (section 4.64). The special correction factor is different since the volume occupied by this plate is smaller.

$$\dot{E}_3\left(\frac{J}{s}\right) = \pi * D(m) * F_2 * G(m) * \lambda\left(\frac{J}{m^2 s}\right) \tag{3}$$

The area of the cooling plate exposed to absorb energy is dictated by the dimensions of non cooling related components, which are not subject to change within the scope of this project. From this fixed area the correction factor F_2 was set conservatively as 33%. The volume and two linear dimensions of the plate are not fixed, but design variables. The width of the plate is dictated by the optical cooling plates themselves as 500 mm.

From the above assumptions and parameters including the previous two sections the minimum cooling rate was estimated to be 0.4 KJ/s. By using the same safety factor as for the previous two sections the design requirement was found to be a minimum cooling rate of 0.7 KJ/s.

The optical design dictates the area exposed to the radiation is 0.0254 m^2 and therefore the heat flux will be approximated as 26.3 KW/m^2. Using a two dimensional finite element analysis the system performance of the simple plate system and a water cooled plate system were simulated. The boundary conditions were setup based upon the component interactions with other cooling devices and the radiation exposure. The water plate approximation generates a maximum temperature 26 ^oC lower than the simpler plate design. 26 degrees is significant to this application, although in reality the model is constructed in a highly conservative fashion and therefore the temperature is less. Nonetheless, a water cooled solution was selected because of its vastly superior performance.

4.6.4. Refrigeration and Forced Air Black Box Analysis

As previously stated, the forced air system must move sufficient air into the sensor enclosure to dissipate the heat generated by less than 100% efficient electronic components and remove any radiation from the bar not absorbed by the water cooling system.

The list of electronic devices within the system is lengthy and not included in this document; however, the sum of their electronic power consumption is 3000 W. The elements of interest labeled as 1 Figure 7 has the highest consumption (consumption of 1200 W) and have an efficiency of 75 %. The weighted average efficiency of all the devices is 76%, because the other components employed have a higher efficiency (~85%).

Additionally, the system must remove a small portion of the energy radiated by the bar. It would be ideal if the air system is robust enough to deliver sufficient cooling such that no device reaches a critical temperature, were the water system to fail. For the purposes of a requirement we will set the portion of the energy from the steel to be removed as 100%.

$$\begin{aligned}\dot{E}_4\left(\frac{J}{s}\right) &= (1-\varepsilon) * \sum ElectricalConsumption\left(\frac{J}{s}\right) \\ &+ \pi * D(m) * F_3 * W(m) * \lambda\left(\frac{J}{m^2 s}\right)\end{aligned} \tag{4}$$

(4) mathematically denotes the energy removal requirements of the forced air cooling system according to the above discussions. Employing the calculated numerical values, we conclude the system should be able to remove 20.7 kJ/s. Using the same safety factor as for previous sections, the engineering specification for the air system is 34.6 KJ/s.

A local system would require a packaged terminal air conditioner for which the range of cooling capacity ranges between 2.0 to 3.5 kJ/s [43]. Given the performance specification and the added robustness of a remote air system we will eliminate the local system layouts suggested in the previous sections.

The maximal dimensions of a remote system are not a primary concern in a steel mill, however, we will set a limit of 3 meters for all dimensions of the remote refrigeration and forced air system. This limit is arbitrary and it is highly unlikely it will become a limitation for the detailed design.

4.6.5. Resulting Iteration

As a result of the black box analysis done in the previous sections some additional layout concepts were generated.

First the possibility of combining the horizontal cooling plate and the vertical cooling plate for manufacturing purposes was investigated. As they are in physical contact it is possible to manufacture them as a single piece, two pieces, or three full pieces as previously discussed. Manufacturing them as a single piece constrains the non cooling related components excessively; however, manufacturing two pieces would be cost effective and maintain all degrees of freedom and performance.

In order to combine the two vertical cooling plates and single horizontal cooling plate into a single piece I have split the horizontal cooling plate into two pieces and attached these to the vertical cooling plates. This maintains the flexibility of two vertical cooling channels and minimizes manufacturing costs. Mathematically by adding the cooling rates calculated in section 4.64 and section 4.65, the new cooling rate for the combined component was arrived at. The new cooling rate specification including the safety factor prescribed is 1.35 kJ/s for each of the two cooling channels.

Secondly, the concept of eliminating the local booster and filter instead of a sensor to detect air with excessive particles was created. This is possible because the purpose of the local booster and filter is to prevent contamination of the system. A local filter would require a very large surface area to achieve a sufficient performance; however, this is not possible given the physical size constraints. The sensor has a significantly smaller format and provides an alarm for contaminated air. The cost of buying a laser based sensor to detect particles greater than a micron in size is around $2500, therefore alternative sensor types were investigated.

4.6.8. Engineering Specifications of the System

Combining the information from each model derived as well as dimensional information about the optical configuration of the system from the above sections the set of engineering specifications is specified in Table 3. The horizontal cooling plate is listed separately because although it will be integrated into the vertical cooling plates the specifications apply specifically to that section.

4.6.9. Finalized Layout

The finalized layout is shown in Figure 18; this shows the location of each component relative to the sensor frame. The details of the systems are below.

The guide tube will use the external water connection layout plan derived during the initial layout phase due to the improvement in risk of water damage to the equipment and the increased access to water tubing for inspection. The available design parameters include the internal geometry of the water passage, material, fabrication method, maximum water inlet temperature, and minimum flow rate.

The vertical cooling channel will use the water exits below the mounting plate so that the risk of water damage to the system is minimized. The remaining design parameters include the external geometry, internal water passage geometry, maximum water inlet temperature, and minimum water flow rate.

The horizontal cooling channel will be integrated into the vertical cooling channel. This will allow the water connections to be located physically below the mounting plate and thus minimize the risk of exposing electronics to water. In addition, the smaller number of parts reduces the complexity and assembly costs.

Lastly the AC system will use a remote system with a local particle sensor. The available design parameters include physical dimensions, performance, air flow rate, and particle filter size.

The three concerns for safety are high pressure, moving parts, and hot surfaces. Regarding pressure the concern can be eliminated with a simple pressure regulation system. This would ensure that pressures do not become dangerous. A hot surface remains possible on the exterior of the unit if a bar recently passed the system. Considering that employees in a mill are aware of the hot surfaces a safety warning by means of a sign would be sufficient for this application. The moving parts are all fan blades which will have appropriate guards so that body parts do not come in to contact with the blades. There is no unprotected high voltage or current source within the system.

4.7. Detailed Design

The detailed design was carried out with several numerical utilities, including the use of Fluent a computational fluid dynamics (CFD) package. The use of CFD modeling is recognized as a cost effective design tool in industry though the error in the calculations can be significant. The detailed design was done in the same subdivisions as previous sections.

4.7.1. Guide Tube Details

The internal geometry of the guiding tubes was simulated using Fluent (Figure 19) in order to improve the heat transfer. The first iteration of the models was completed using several key attributes identified in other heat transfer papers including: the surface roughness [44, 45], turbulence promoters [46], curved passages [47], number of passes in a heat exchanger [48, 49], and surface print [50]. The combinations of the different elements were investigated using FLUENT. Given that each simulation was done with the same boundary conditions and FLUENT computational models it is acceptable to use the results comparatively. The parameters were set in accordance with the software manufacturers guidelines for turbulent compressible flow [51]. The initial results indicated that a 2 pass heat exchanger was on the correct order of magnitude heat transfer. Several subsequent iterations revealed an appropriate flow rate was on the order of 0.14 kg/s of water.

The two tubes were arranged such that water flowed first through the long guide tube and subsequently through the short guide tube. The water temperature change is on the order of 30^{o}C overall from both tubes, for a water inlet temperature of 35^{o}C. One must recall that a safety factor of 1.67 is built into the energy emitted from the steel, and therefore the real temperature change is much lower.

The minimum wall thickness of the tube was determined based upon a force analysis of a rolled bar, which has the same mass as a billet, striking the guide tube at an angle of 1 degree. The normal component of the force to the wall of the guide tube was used to determine the necessary wall thickness of the material specified. This is a highly conservative assumption following the trend set forth in this paper. The material was selected based upon strength, corrosion resistance, melting temperature, conductivity, and cost. Given that stainless steel and titanium are the only common materials that satisfy the constraints [52, 53] and that titanium is orders of magnitude more expensive [54]; stainless steel was chosen for this application. Based upon the material selection the actual wall thickness was designed based upon the availability of tubes close to the necessary final dimensions.

In order to ensure the outer surface of the guiding tube does not produce condensation. In the event of an air cooling failure, an additional layer of insulation will be added. The appropriate insulation for this application is sweat-stopping pipe insulation, a thin paint like layer designed for this purpose. It is available in black, the best color to maximize radiation absorption and minimize the emission [55], from mass part suppliers such as McMaster-Carr.

A final model was simulated in the same CFD package with a much finer mesh and precise boundary layers, using the double precision mode, such that the heat transfer and flow improvements could be verified (Figure 19). The parameters for the flow setup in FLUENT are listed in Table 4. The details of the final design are shown in Appendix C. The improvement between the initial design simulated in FLUENT and the final design proposed is shown in Table 5, which shows the simulated temperatures for the guide tube without air cooling.

The construction of the design is based upon a small scale manufacturing business model. There are many manufacturing techniques readily available including: casting [56], forging [57], rapid prototyping [58], standard machining operations [59], advanced machining operations [60, 61], and abrasive operations [62]. For this model standard machining and abrasive manufacturing techniques are the most appropriate. Should metal deposition, a form of rapid prototyping, become comparable in cost and readily available this would be an alternative fabrication method. This limits the manufacturing to processes able to be performed on a 3 axis mill, a lathe, a grinder, and with welding.

4.7.2. Combined Vertical and Horizontal Channel Details

The combined cooling channel is highly constrained in terms of external geometry options. There are a number of options for tubing that can be bent, brazed, and or welded into the desired layout. For the purposes of improving heat exchange a copper tube with an integral fin was chosen [55]. The sizes available of this of style tubing were limited, however, there is still a viable cross section (20mm x 30mm) that meets the physical layout constraints and flow parameters.

With the tubing selected the channel flow and heat exchange was simulated in FLUENT. The channel was subsequently improved in design based upon the results. The design changes from the iterations include the position of the water entry and exit, and a change from a complete rectangular shape to an open rectangle.

With the final geometry established (detailed in Appendix D) a finer mesh simulation was completed using the double precision mode of FLUENT. This test verified the heat exchange and temperature change of ~5°C when positioned after the guiding tubes in the series water loop. The improvement in design between the initial concept and the final design is shown numerically in

Table **5**. The comparison is simulated in both cases without the expected air cooling discussed below.

The construction of the channel is parallel to the guiding tubes. It can be completed with the basic machining processes, for a minimum of cost compared to the other methods. The channels will also be covered with the same black condensation preventing paint as the guiding tubes. This will also ensure that shiny copper surface does not interfere with the optical components.

4.7.3. Forced Air System Details

The forced air system is comprised of a remote filter, an air conditioner, and all the subsequently required components and interfaces. The specifications of each part are interdependent; however, it is possible to start with the air conditioning unit which has the most impact on the cost and then work towards the component of least importance.

Air conditioners are classified by the tonnage, which is a measure of their capacity. The specified energy rate (section 4.67) corresponds to just under the performance of a 10-ton air conditioner. Researching manufacturers of commercial air conditioners for industrial applications yielded several units. Nordic air manufactures an abundance of 10-ton units for both air cooled and water cooled condensers. Most other manufacturers carry at least one industrial 10-ton unit. For most mills a water cooled condenser unit would be preferred.

Airflow within the sensor chassis was optimized using FLUENT. The initial flow patterns showed that some of the cool air would exit the chassis without cooling any parts. The addition of 2 dividers in critical locations, as verified in FLUENT, direct a much greater fraction of the air towards the components desired. It is difficult to quantify the exact amount of air that exits without passing near a component; however, a visual inspection of the flow paths shows significant improvement (Figure 20). Recall that the element of interest 1 is below the opening (Figure 7) and requires air to pass through the unit. In the original flow pattern pictured the air enters the chassis and passes over this area, and with the critical divider the air flows through the element of interest. The bottom portion of the chassis's flow is much more difficult to follow. By examining the right side, it can be seen that a greater portion of the air is directed over the top and then out the bottom in the final geometry (Figure 21). Again looking back to Figure 7, note that much more cool air is being directed to the second area of interest. A comparison of systems on a 2°C winter day is shown in

Table **5**. The difference in temperature reflects the addition of the dividers discussed above. Additionally, after improving the flow the energy dissipation was simulated in FLUENT. The final average air temperature exiting the chassis was simulated to be 38°C, assuming: a 46°C ambient temperature in the room, a 31.15 m^3/s airflow, a 70% efficient 10-ton air conditioner, and the water cooled channels were non functional.

The filter is a crucial component in order to prevent dirtying the optics. There are several important properties of a filter. First the efficiency of a filter increases with a decrease in the fiber radius [63]. The filter efficiency decreases over time because of particles forming agglomerates on the filter surfaces [64]. Because of the level of contamination in the ambient air in a steel mill the system will require a dual stage filtering system. This will prevent more costly filters designed for smaller particles from being clogged with the larger particles. A dual stage system helps keep the required maintenance to a minimum. The outer filter is for particles greater than 30 microns in size, and the secondary filter is for particles greater than 5 microns. The most economical choice for the outer filter is a polyester panel filter, which is disposable and costs roughly $0.50 a square foot. The most economical choice for an inner filter is a cylindrical intake filter, which typically includes a metal housing. This type of filter is for particles 5 microns in size or larger. An adequate area for filtration at each stage was determined based upon the face velocity data provided for filters of different efficiencies [63].

4.7.4. Interfaces between Components

The system requires some basic components and interfaces between them. The water system necessitates some tubing between components, hose clamps, and certain fittings and adapters. In order to decrease the risk of rupturing a water hose, from excessive pressure, a pressure release valve will be integrated. A series of motor contactors and electronic control protection circuits will control the AC system. The AC system will also require ducting between the air conditioner and the sensor chassis.

4.7.5. Sensors

In order to monitor the overall system health, several sensors were selected. The water flow is critical (see guide tube details) and will be monitored by a vortex flow meter, which is an effective low-pressure drop type flow meter [65]. The acceptable maximum operating temperature is essential to avoid damage to electronics. The air temperature is best monitored with an economical k-type thermocouple and signal conditioner. The signal conditioner is required because thermocouple outputs are non-linear, and in order to simplify interpretation the signal is conditioned to fit 1 mV/^{o}C [66]. The airflow is critical to diagnosing temperature problems and will be monitored with a simple differential pressure switch. This measures the pressure difference present because of the fast moving air entering the chassis, explained by Bernoulli's principle of incompressible flow [67].

Air particle sensors are typically based on either: lasers and photodiodes, or rupture event scanning, which involves oscillating a diaphragm that collects particles and measuring the frequency change [68]. There are no readily available commercial models taking advantage of the latter technology, which boasts an economic alternative to the laser based method. A laser based system capable of measuring particles of 5 microns and larger at concentrations up to 500,000 parts per million costs $2500. The resolution of 5 microns is not necessary for this application because only particles significantly larger than 5 microns are of interest. An alternative would be to construct a primitive system based upon a light source and photodiode. By placing a piece of glass between the light and receptor, and coating the glass with an adhesive, particles would adhere to the glass over time reducing the transmission of light. The decrease in light would be detected by the photo diode. A possible design for such a sensor is shown in Appendix E, and costs approximately $200 to build.

4.7.6. Safety

The concerns for safety are moving parts, hot surfaces, and high pressure. The possibility of elevated pressure has addressed by adding a pressure release valve, which will release excess pressure before it becomes a safety hazard. There should be no hot surfaces if the systems are working properly. The AC system is capable of cooling the system sufficiently for operation even without any water cooled channels; therefore provided one of the systems is working no surface will be hot enough to become a safety hazard. Moving parts within the system consist of fans and blowers that will be protected by fan guards.

4.7.7. Robustness

The system is highly robust with 2 systems capable of removing the energy from the steel. In addition the AC system is in fact a dual 5 ton system, which means that only half the system is likely to fail at any given time. This ensures the dissipated energy from the electronics will always be removed, even with half the AC unit malfunctioning. Therefore, any one, of the independent cooling loops can fail, and the sensor as a whole is capable of continuing operation. The overall system is also capable of identifying which system has failed. This permits for quick replacement of faulty components.

4.7.8. Required Maintenance

Maintenance is minimal for the system. The air filters for the blower will need to be replaced periodically; the frequency of replacement will depend on the ambient air quality within the mill. Additionally the new particle sensor will require cleaning. This can be completed at the same time the system's non cooling related components are cleaned. Both the new air quality sensor and the system's components will accumulate particles and therefore requiring cleaning.

4.8. General Form Solution Review

The detailed engineering design in the previous sections can help provide some specific information relevant to the general solution for other applications. There are, however, portions of the cooling system design that remain too specific for future applications.

Any electronic equipment in a steel line or caster will require a similar type of cooled guide tube. It is possible to adapt the equation derived for this particular guide tube by conducting a similar black box analysis. The CFD simulations completed are not necessary to design a working solution, but are for an optimized one. The material specifications are valid for any similar environment.

The vertical cooling channel, with an integrated horizontal piece designed specifically for this application is of little use to similar applications since the layout is likely to be different. It is however, possible to modify the design and use the concept of a cooling channel to cool radiation emitted within the chassis.

The forced air model has a simplistic black body analysis which can be carried over to other applications. It should be noted that the approach of including the water cooling load in addition to the electronics within the chassis is extremely conservative, yet robust. The CFD simulations were done to verify the optimization of the airflow, though it would have been possible to make improvements without verification based solely upon general fluid flow mechanics.

In order to validate the design a CFD simulation was simulated with all the systems working properly and not independently as originally simulated during the design phase to assure robustness. It should be noted the safety factor was retained and the simulation was for the expected heat transfer from a three inch bar. The critical property of the system is the air temperature within the chassis. A temperature in excess of 40^{o}C will result in electronic to malfunctions. The conservative model calculated an air temperature of 21^{o}C within the system. This is well below the critical limit for the air temperature. Additionally, the water does not approach a boiling temperature.

4.9. Complete Design

The design detailed components in the previous sections are shown in Figure 22 as a complete unit. The components described are called out. There are numerous other parts to the RSB system not shown, for clarity. These components are not relevant to the cooling system. The drawings of major components manufactured for this system are shown in Appendix C, Appendix D, and Appendix E. The part cost of the new design relative to the old one results in a

30% increase. It is not possible, at this time, to determine the cost for an overall unit. It is estimated, however, the assembly costs will be significantly lower for the new system. This is because there are fewer components in the new design, which require assembly. The assembly costs of the old design are also unknown. It should be noted that the assembly costs are believed to represent a significant portion of the total cost of the system.

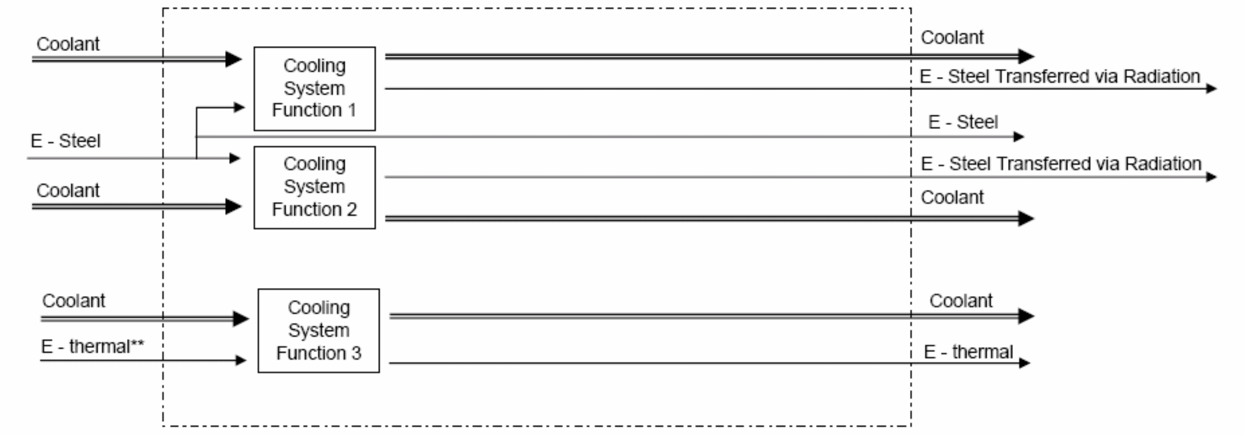


Figure 11. Hoteye^{TM} RSB Sub-level Cooling Functional Diagram

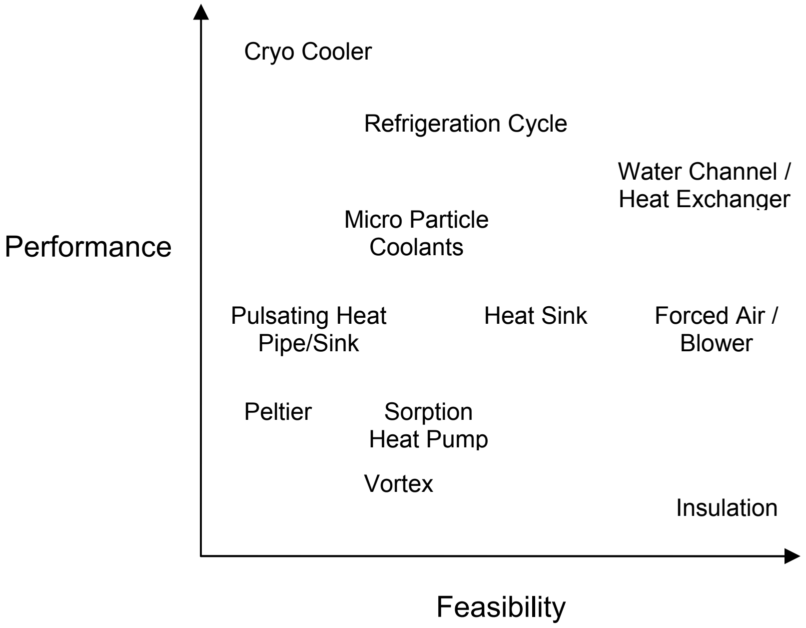
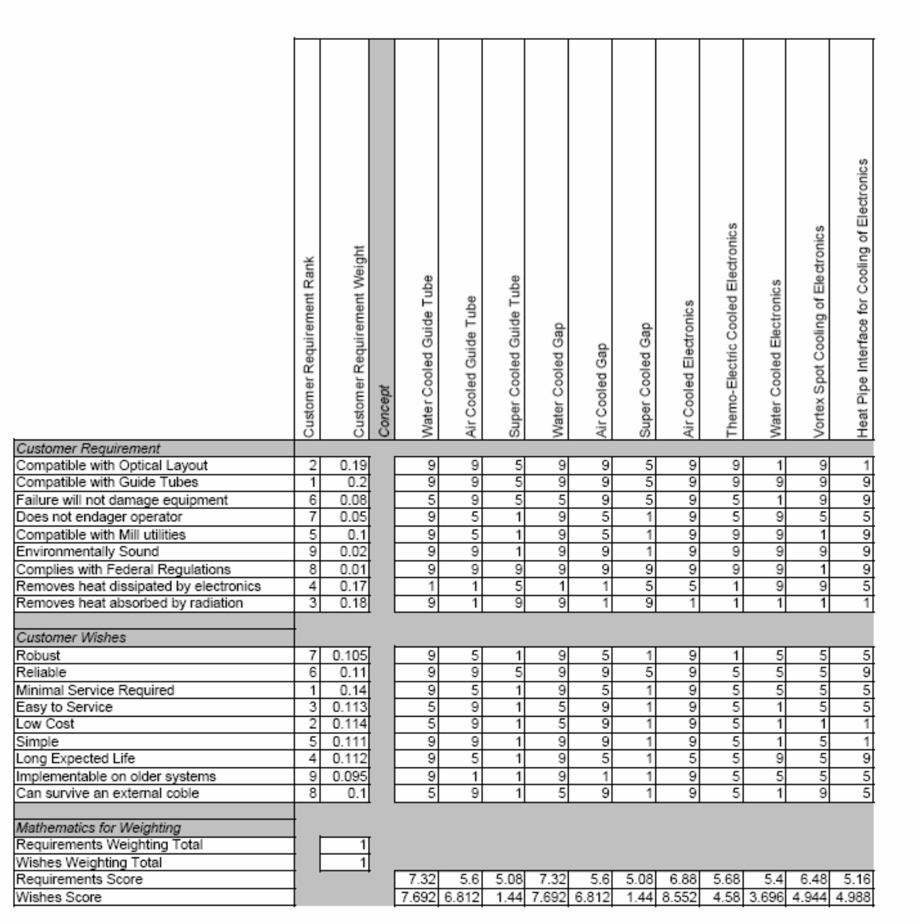
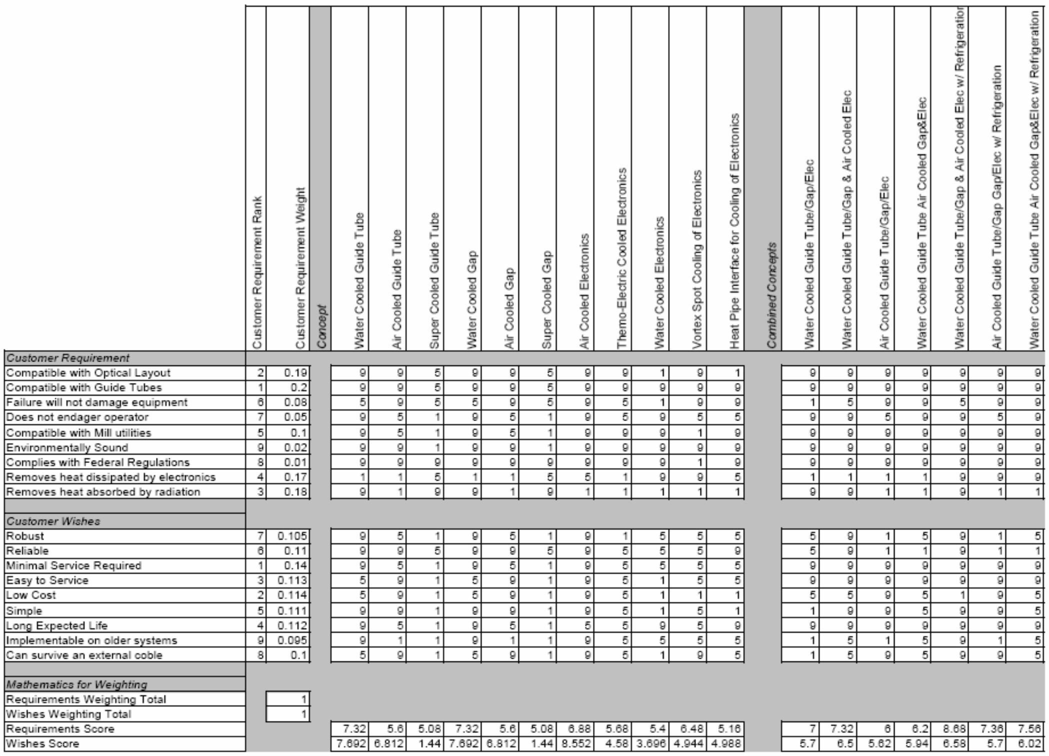


Figure 12. Initial Concept Performance and Feasibility Chart



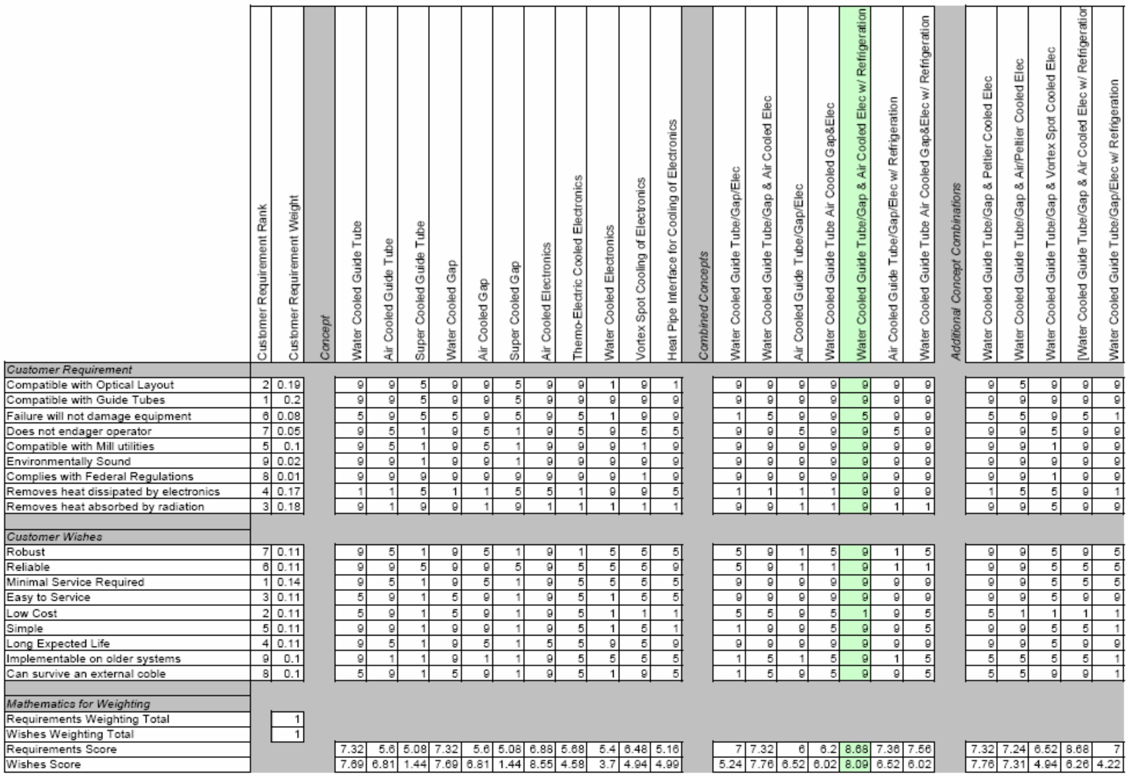
	Customer Requirement Rank	Customer Requirement Weight	*Concept*	Water Cooled Guide Tube	Air Cooled Guide Tube	Super Cooled Guide Tube	Water Cooled Gap	Air Cooled Gap	Super Cooled Gap	Air Cooled Electronics	Themo-Electric Cooled Electronics	Water Cooled Electronics	Vortex Spot Cooling of Electronics	Heat Pipe Interface for Cooling of Electronics
Customer Requirement														
Compatible with Optical Layout	2	0.19		9	9	5	9	9	5	9	9	1	9	1
Compatible with Guide Tubes	1	0.2		9	9	5	9	9	5	9	9	9	9	9
Failure will not damage equipment	6	0.08		5	9	5	5	9	5	9	5	1	9	9
Does not endager operator	7	0.05		9	5	1	9	5	1	9	5	9	5	5
Compatible with Mill utilities	5	0.1		9	5	1	9	5	1	9	9	9	1	9
Environmentally Sound	9	0.02		9	9	1	9	9	1	9	9	9	9	9
Complies with Federal Regulations	8	0.01		9	9	9	9	9	9	9	9	9	1	9
Removes heat dissipated by electronics	4	0.17		1	1	5	1	1	5	5	1	9	9	5
Removes heat absorbed by radiation	3	0.18		9	1	9	9	1	9	1	1	1	1	1
Customer Wishes														
Robust	7	0.105		9	5	1	9	5	1	9	1	5	5	5
Reliable	6	0.11		9	9	5	9	9	5	9	5	5	5	9
Minimal Service Required	1	0.14		9	5	1	9	5	1	9	5	5	5	5
Easy to Service	3	0.113		5	9	1	5	9	1	9	5	1	5	5
Low Cost	2	0.114		5	9	1	5	9	1	9	5	1	1	1
Simple	5	0.111		9	9	1	9	9	1	9	5	1	5	1
Long Expected Life	4	0.112		9	5	1	9	5	1	5	5	9	5	9
Implementable on older systems	9	0.095		9	1	1	9	1	1	9	5	5	5	5
Can survive an external coble	8	0.1		5	9	1	5	9	1	9	5	1	9	5
Mathematics for Weighting														
Requirements Weighting Total		1												
Wishes Weighting Total		1												
Requirements Score				7.32	5.6	5.08	7.32	5.6	5.08	6.88	5.68	5.4	6.48	5.16
Wishes Score				7.692	6.812	1.44	7.692	6.812	1.44	8.552	4.58	3.696	4.944	4.988

Figure 13. Matrix Comparison of Initial Concepts



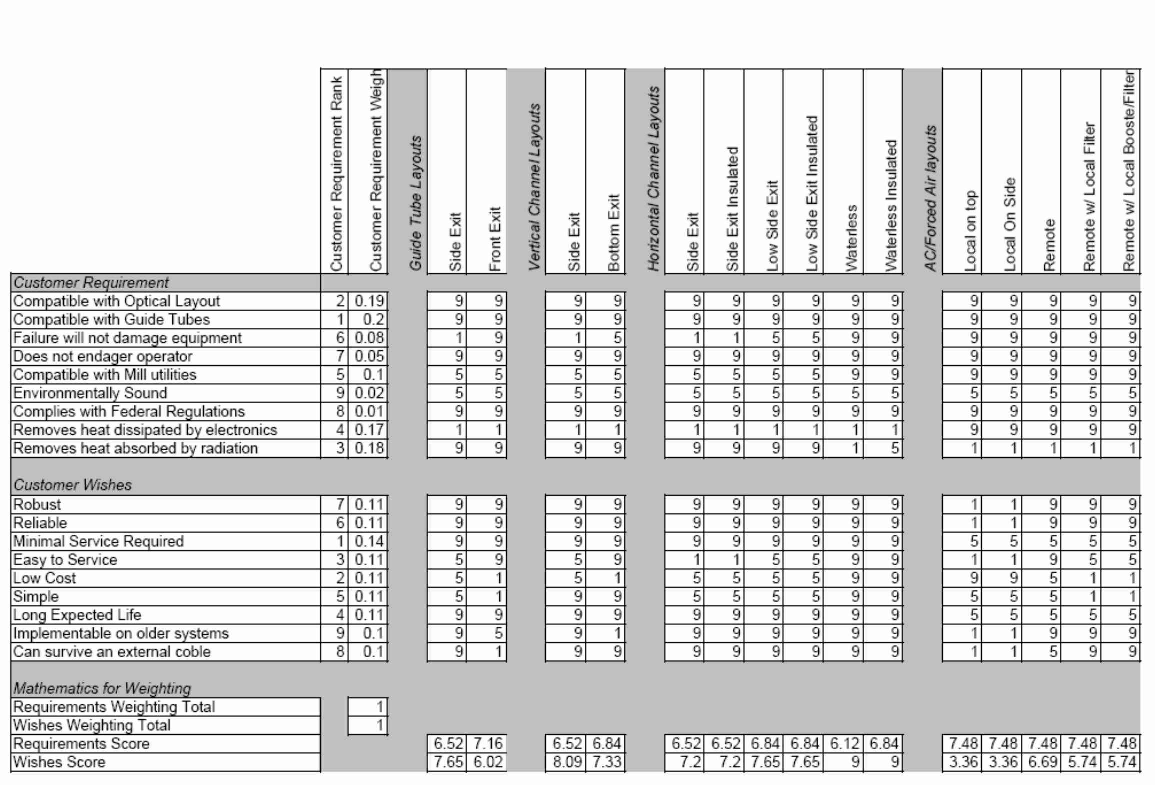
	Customer Requirement Rank	Customer Requirement Weight	*Concept*	Water Cooled Guide Tube	Air Cooled Guide Tube	Super Cooled Guide Tube	Water Cooled Gap	Air Cooled Gap	Super Cooled Gap	Air Cooled Electronics	Themo-Electric Cooled Electronics	Water Cooled Electronics	Vortex Spot Cooling of Electronics	Heat Pipe Interface for Cooling of Electronics	*Combined Concepts*	Water Cooled Guide Tube/Gap/Elec	Water Cooled Guide Tube/Gap & Air Cooled Elec	Air Cooled Guide Tube/Gap/Elec	Water Cooled Guide Tube Air Cooled Gap&Elec	Water Cooled Guide Tube/Gap & Air Cooled Elec w/ Refrigeratio	Air Cooled Guide Tube/Gap Gap/Elec w/ Refrigeration	Water Cooled Guide Tube Air Cooled Gap&Elec w/ Refrigeration
Customer Requirement																						
Compatible with Optical Layout	2	0.19		9	9	5	9	9	5	9	9	1	9	1		9	9	9	9	9	9	9
Compatible with Guide Tubes	1	0.2		9	9	5	9	9	5	9	9	9	9	9		9	9	9	9	9	9	9
Failure will not damage equipment	6	0.08		5	9	5	5	9	5	9	5	1	9	9		1	5	9	9	5	9	9
Does not endager operator	7	0.05		9	5	1	9	5	1	9	5	9	5	5		9	9	5	9	9	5	9
Compatible with Mill utilities	5	0.1		9	5	1	9	5	1	9	9	9	1	9		9	9	9	9	9	9	9
Environmentally Sound	9	0.02		9	9	1	9	9	1	9	9	9	9	9		9	9	9	9	9	9	9
Complies with Federal Regulations	8	0.01		9	9	9	9	9	9	9	9	9	1	9		9	9	9	9	9	9	9
Removes heat dissipated by electronics	4	0.17		1	1	5	1	1	5	5	1	9	9	5		1	1	1	1	9	9	9
Removes heat absorbed by radiation	3	0.18		9	1	9	9	1	9	1	1	1	1	1		9	9	1	1	9	1	1
Customer Wishes																						
Robust	7	0.105		9	5	1	9	5	1	9	1	5	5	5		5	9	1	5	9	1	5
Reliable	6	0.11		9	9	5	9	9	5	9	5	5	5	9		5	9	1	1	9	1	1
Minimal Service Required	1	0.14		9	5	1	9	5	1	9	5	5	5	5		9	9	9	9	9	9	9
Easy to Service	3	0.113		5	9	1	5	9	1	9	5	1	5	5		9	9	9	9	9	9	9
Low Cost	2	0.114		5	9	1	5	9	1	9	5	1	1	1		5	5	9	5	1	9	5
Simple	5	0.111		9	9	1	9	9	1	9	5	1	5	1		1	9	9	5	9	9	5
Long Expected Life	4	0.112		9	5	1	9	5	1	5	5	9	5	9		9	9	9	9	9	9	9
Implementable on older systems	9	0.095		9	1	1	9	1	1	9	5	5	5	5		1	5	1	5	9	1	5
Can survive an external coble	8	0.1		5	9	1	5	9	1	9	5	1	9	5		1	5	9	5	9	9	5
Mathematics for Weighting																						
Requirements Weighting Total		1																				
Wishes Weighting Total		1																				
Requirements Score				7.32	5.6	5.08	7.32	5.6	5.08	6.88	5.68	5.4	6.48	5.16		7	7.32	6	6.2	8.68	7.36	7.56
Wishes Score				7.692	6.812	1.44	7.692	6.812	1.44	8.552	4.58	3.696	4.944	4.988		5.7	6.5	5.62	5.94	6.58	5.7	6.02

Figure 14. Iteration Two Concept Evaluation



	Customer Requirement Rank	Customer Requirement Weight	*Concept*	Water Cooled Guide Tube	Air Cooled Guide Tube	Super Cooled Guide Tube	Water Cooled Gap	Air Cooled Gap	Super Cooled Gap	Air Cooled Electronics	Themo-Electric Cooled Electronics	Water Cooled Electronics	Vortex Spot Cooling of Electronics	Heat Pipe Interface for Cooling of Electronics	*Combined Concepts*	Water Cooled Guide Tube/Gap/Elec	Water Cooled Guide Tube/Gap & Air Cooled Elec	Air Cooled Guide Tube/Gap/Elec	Water Cooled Guide Tube Air Cooled Gap&Elec	Water Cooled Guide Tube/Gap & Air Cooled Elec w/ Refrigeration	Air Cooled Guide Tube/Gap/Elec w/ Refrigeration	Water Cooled Guide Tube Air Cooled Gap&Elec w/ Refrigeration	*Additional Concept Combinations*	Water Cooled Guide Tube/Gap & Peltier Cooled Elec	Water Cooled Guide Tube/Gap & Air/Peltier Cooled Elec	Water Cooled Guide Tube/Gap & Vortex Spot Cooled Elec	[Water Cooled Guide Tube/Gap & Air Cooled Elec w/ Refrigeratior	Water Cooled Guide Tube/Gap/Elec w/ Refrigeration
Customer Requirement																												
Compatible with Optical Layout	2	0.19		9	9	5	9	9	5	9	9	1	9	1		9	9	9	9	9	9	9		9	5	9	9	9
Compatible with Guide Tubes	1	0.2		9	9	5	9	9	5	9	9	9	9	9		9	9	9	9	9	9	9		9	9	9	9	9
Failure will not damage equipment	6	0.08		5	9	5	5	9	5	9	5	1	9	9		1	5	9	9	5	9	9		5	5	9	5	1
Does not endager operator	7	0.05		9	5	1	9	5	1	9	5	9	5	5		9	9	5	9	9	5	9		9	9	5	9	9
Compatible with Mill utilities	5	0.1		9	5	1	9	5	1	9	9	9	1	9		9	9	9	9	9	9	9		9	9	1	9	9
Environmentally Sound	9	0.02		9	9	1	9	9	1	9	9	9	9	9		9	9	9	9	9	9	9		9	9	9	9	9
Complies with Federal Regulations	8	0.01		9	9	9	9	9	9	9	9	9	1	9		9	9	9	9	9	9	9		9	9	1	9	9
Removes heat dissipated by electronics	4	0.17		1	1	5	1	1	5	5	1	9	9	5		1	1	1	1	9	9	9		1	5	5	9	1
Removes heat absorbed by radiation	3	0.18		9	1	9	9	1	9	1	1	1	1	1		9	9	1	1	9	1	1		9	9	5	9	9
Customer Wishes																												
Robust	7	0.11		9	5	1	9	5	1	9	1	5	5	5		5	9	1	5	9	1	5		9	9	5	9	5
Reliable	6	0.11		9	9	5	9	9	5	9	5	5	5	9		5	9	1	1	9	1	1		9	9	5	5	5
Minimal Service Required	1	0.14		9	5	1	9	5	1	9	5	5	5	5		9	9	9	9	9	9	9		9	9	5	5	5
Easy to Service	3	0.11		5	9	1	5	9	1	9	5	1	5	5		9	9	9	9	9	9	9		9	9	5	9	9
Low Cost	2	0.11		5	9	1	5	9	1	9	5	1	1	1		5	5	9	5	1	9	5		5	1	1	1	1
Simple	5	0.11		9	9	1	9	9	1	9	5	1	5	1		1	9	9	5	9	9	5		9	9	5	5	1
Long Expected Life	4	0.11		9	5	1	9	5	1	5	5	9	5	9		9	9	9	9	9	9	9		9	9	5	9	9
Implementable on older systems	9	0.1		9	1	1	9	1	1	9	5	5	5	5		1	5	1	5	9	1	5		5	5	5	5	1
Can survive an external coble	8	0.1		5	9	1	5	9	1	9	5	1	9	5		1	5	9	5	9	9	5		5	5	9	9	1
Mathematics for Weighting																												
Requirements Weighting Total		1																										
Wishes Weighting Total		1																										
Requirements Score				7.32	5.6	5.08	7.32	5.6	5.08	6.88	5.68	5.4	6.48	5.16		7	7.32	6	6.2	8.68	7.36	7.56		7.32	7.24	6.52	8.68	7
Wishes Score				7.69	6.81	1.44	7.69	6.81	1.44	8.55	4.58	3.7	4.94	4.99		5.24	7.76	6.52	6.02	8.09	6.52	6.02		7.76	7.31	4.94	6.26	4.22

Figure 15. Iteration Three Concept Evaluation



	Customer Requirement Rank	Customer Requirement Weigh	*Guide Tube Layouts*	Side Exit	Front Exit	*Vertical Channel Layouts*	Side Exit	Bottom Exit	*Horizontal Channel Layouts*	Side Exit	Side Exit Insulated	Low Side Exit	Low Side Exit Insulated	Waterless	Waterless Insulated	*AC/Forced Air layouts*	Local on top	Local On Side	Remote	Remote w/ Local Filter	Remote w/ Local Booste/Filter
Customer Requirement																					
Compatible with Optical Layout	2	0.19		9	9		9	9		9	9	9	9	9	9		9	9	9	9	9
Compatible with Guide Tubes	1	0.2		9	9		9	9		9	9	9	9	9	9		9	9	9	9	9
Failure will not damage equipment	6	0.08		1	9		1	5		1	1	5	5	9	9		9	9	9	9	9
Does not endager operator	7	0.05		9	9		9	9		9	9	9	9	9	9		9	9	9	9	9
Compatible with Mill utilities	5	0.1		5	5		5	5		5	5	5	5	9	9		9	9	9	9	9
Environmentally Sound	9	0.02		5	5		5	5		5	5	5	5	5	5		5	5	5	5	5
Complies with Federal Regulations	8	0.01		9	9		9	9		9	9	9	9	9	9		9	9	9	9	9
Removes heat dissipated by electronics	4	0.17		1	1		1	1		1	1	1	1	1	1		9	9	9	9	9
Removes heat absorbed by radiation	3	0.18		9	9		9	9		9	9	9	9	1	5		1	1	1	1	1
Customer Wishes																					
Robust	7	0.11		9	9		9	9		9	9	9	9	9	9		1	1	9	9	9
Reliable	6	0.11		9	9		9	9		9	9	9	9	9	9		1	1	9	9	9
Minimal Service Required	1	0.14		9	9		9	9		9	9	9	9	9	9		5	5	5	5	5
Easy to Service	3	0.11		5	9		5	9		1	1	5	5	9	9		1	1	9	5	5
Low Cost	2	0.11		5	1		5	1		5	5	5	5	9	9		9	9	5	1	1
Simple	5	0.11		5	1		9	9		5	5	5	5	9	9		5	5	5	1	1
Long Expected Life	4	0.11		9	9		9	9		9	9	9	9	9	9		5	5	5	5	5
Implementable on older systems	9	0.1		9	5		9	1		9	9	9	9	9	9		1	1	9	9	9
Can survive an external coble	8	0.1		9	1		9	9		9	9	9	9	9	9		1	1	5	9	9
Mathematics for Weighting																					
Requirements Weighting Total		1																			
Wishes Weighting Total		1																			
Requirements Score				6.52	7.16		6.52	6.84		6.52	6.52	6.84	6.84	6.12	6.84		7.48	7.48	7.48	7.48	7.48
Wishes Score				7.65	6.02		8.09	7.33		7.2	7.2	7.65	7.65	9	9		3.36	3.36	6.69	5.74	5.74

Figure 16. Initial Layout Subjective Comparison

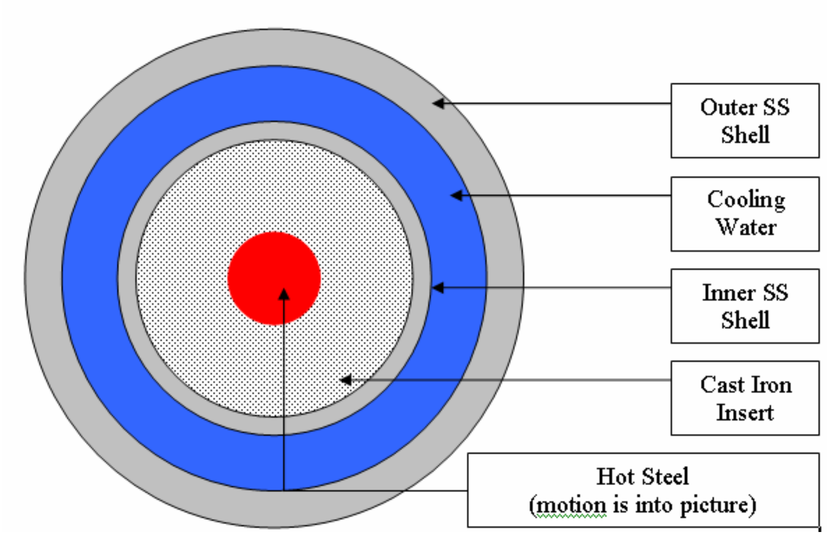


Figure 17. Cooled Guiding Tube Cross Section

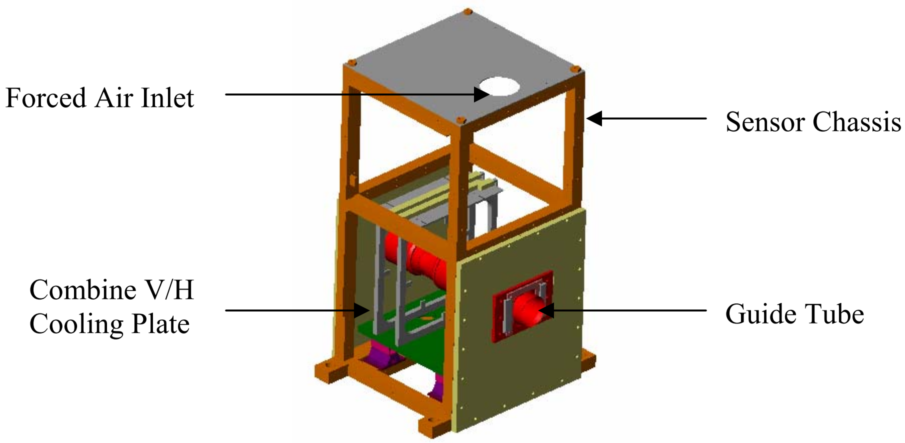


Figure 18. Finalized Local Cooling Layout

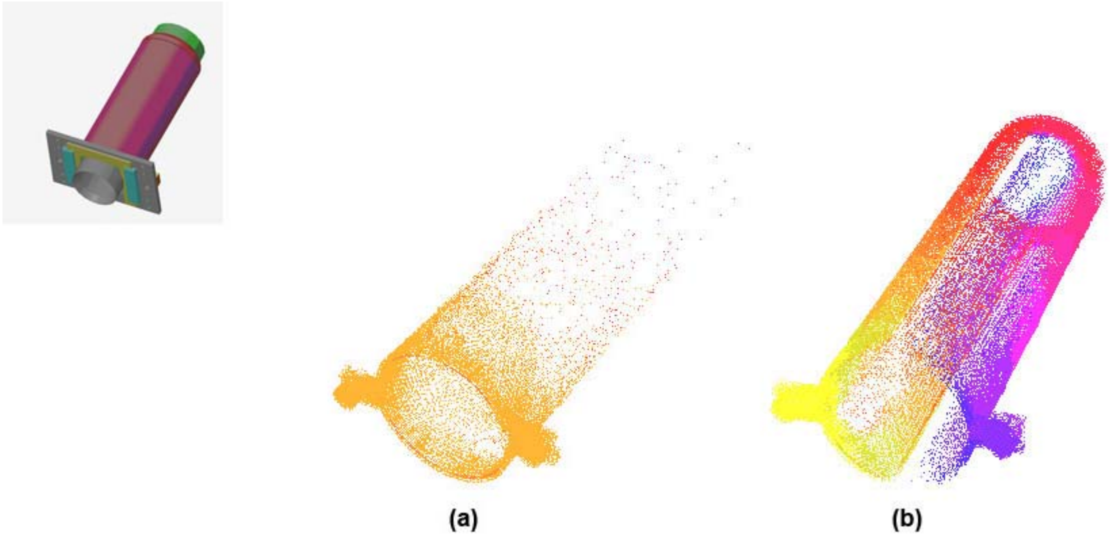


Figure 19. FLUENT Guide Tube Velocity Vector (a) Initial Geometry, (b) Final Geometry

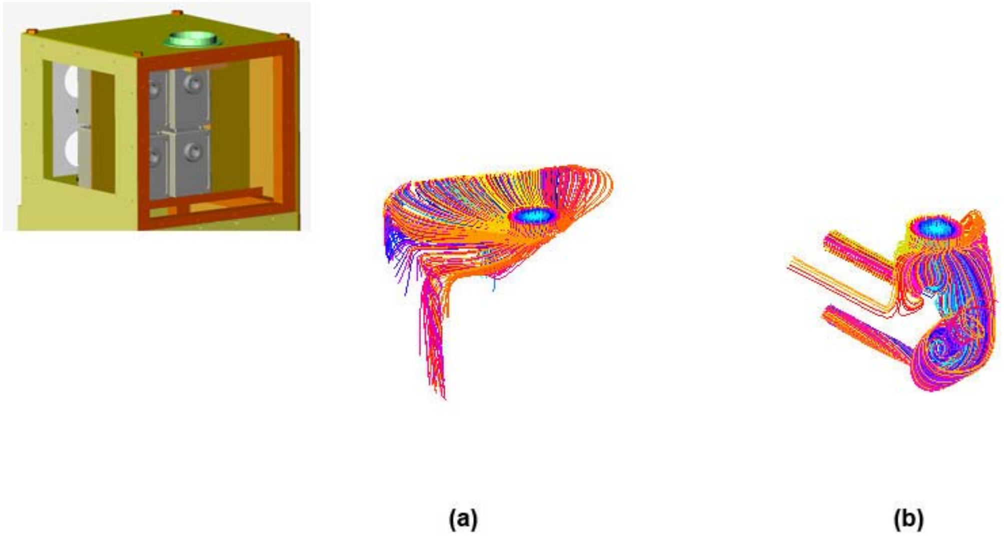


Figure 20. FLUENT Sensor Chassis (Top Portion) Airflow (a) Initial Geometry (b) Final Geometry

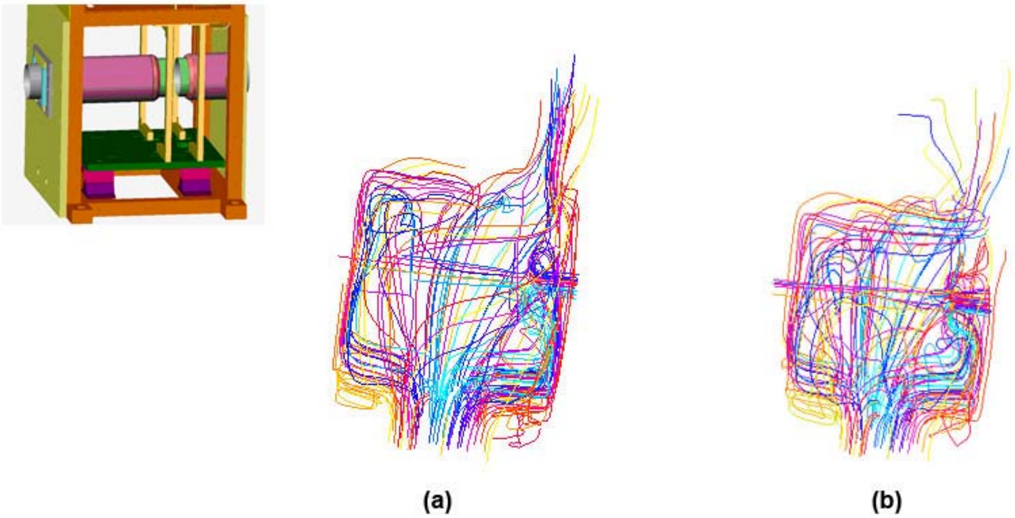


Figure 21. FLUENT Sensor Chassis (Bottom Portion) Airflow (a) Initial Geometry (b) Final Geometry

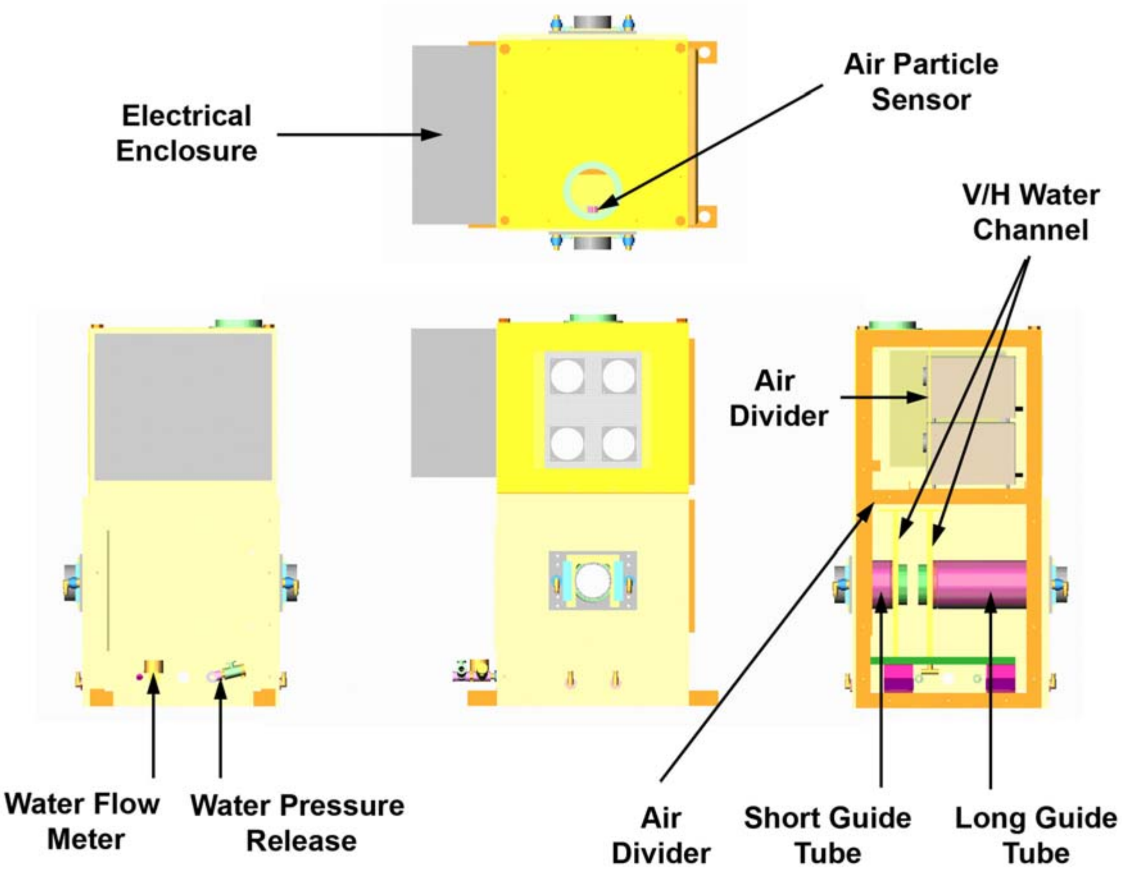


Figure 22. RSB Cooling System CAD Drawing

Design Requirements	Design Wishes
Compatible with Optical Layout	Robust
Compatible with Guide Tubes	Reliable
Failure will not damage equipment	Minimal Service Required
Meets Safety Standards	Easy to Service
Compatible with Mill Utilities	Low Cost
Environmentally Conscience	Simple
Removes Heat Dissipated by Electronics	Long Expected Life
Removes Heat Absorbed Via Radiation	Upgradeable on Older Systems
Can Survive a Coble	

Table 1. Hoteye^{TM} RSB Cooling System Qualitative Requirements

	Concepts	
Forced Air	Thermo-Electric/Peltier	Closed loop/Open Loop
Refrigeration Cycle	Cooling Channel	Micro Particle Coolants
Heat Pump	Radiator/Heat Exchanger	Black Body Effect
Vortex Principle	Blower/Fan	Insulation
Heat Pump	Cryo Cooler	Thermal Resistance
Heat Pipe	Oscillating Heat Sink	Thermal Conductor
Heat Sink	Sorption Heat Pump	
Pulsating Heat Pipe	Contact Resistance	

Table 2. Initial Concepts Developed

Detail	Spec	Units
Guide Tube ID	115	mm
Guide Tube OD	168.28	mm
Guide Tube Length 1	510	mm
Guide Tube Length 2	250	mm
Guide Tube Energy Removal Rate	29.7	KJ/m-s
Max Vertical Cooling Plate Height	500	mm
Min Vertical Cooling Plate Height	192	mm
Max Vertical Cooling Plate Width	500	mm
Min Vertical Cooling Plate Width	192	mm
Max Vertical Cooling Plate Thickness	25.4	mm
Vertical Cooling Plate Energy Removal Rate	1.0	KJ/s
Horizontal Cooling Plate Width	500	mm
Max Horizontal Cooling Plate Length	350	mm
Min Horizontal Cooling Plate Length	76.2	mm
Max Horizontal Cooling Plate Thickness	38.1	Mm
Horizontal Cooling Plate Energy Removal Rate	0.7	KJ/s
Refrigeration/Forced Air Max Width	3	m
Refrigeration/Forced Air Max Height	3	m
Refrigeration/Forced Air Max Length	3	m
Refrigeration/Forced Air Performance	34.6	KJ/s

Table 3. Engineering Specifications

Parameter	Value
Wall Material	Stainless Steel
Water Flow Rate (kg/s)	0.139
Water Inlet Temp (K)	308
Surface Roughness	0.01
Turbulence	k-epsilon model
Energy Equation	Yes
Compressible	Yes
Turbulence Intensity	0.02
Turbulence Diameter (mm)	25.4

Table 4. Guide Tube FLUENT Parameters

Component (location)	Initial Design Temp (^oC)	Final Design Temp (^oC)
Guide Tube (inlet)	35	35
Guide Tube (outlet)	48	62
Guide Tube (surface)	87	82
V/H Cooling Channel (inlet)	75	75
V/H Cooling Channel (outlet)	78	81
V/H Cooling Channel (surface)	87	85
Chassis (inlet)	-9	-9
Chassis (light box air intake)	10	-8
Chassis (lower base plate)	15	6

Table 5. Numerical Design Improvement Comparisons

CHAPTER 5

DISCUSSION

The design detailed in chapter 4 was directed to solve the defined problems in a cooling system. The problems consist of several recognized incidences of failure, a high number of components, access difficulty for service of other sensor systems, and an imposed risk to electronic components due to water cooling. Additionally there was a desire to reduce the amount of redesign work needed to develop similar cooling systems for new applications. A standardized approach and base level design was needed to modify the practice of starting new designs from a conceptual level.

5.1. Benefits of Methodology Examination

The goal of the work thesis was to solve these problems cited; not only technically and theoretically but also efficiently and practically. In order to increase the efficiency of solving this problem, a significant amount of time was spent developing an initial plan to reach the solution. The plan developed was followed with the sole exception of implementing the layout design before introducing the engineering specifications. This reversal was done due to the inefficiency of developing quantifiable specifications for each layout. This plan allowed for one person to work in a methodical manner in what was a large project spread out over significant time. For, the work to be completed in a timely manner required such a guide.

There are always improvements and additional details that could be added to expand the methodology. Safety elements and environmental concerns should be listed explicitly in the methodology. In this project these concerns are limited and mainly intuitive. For some projects detailing and following the implementation related to each hazard may not be as simplistic. Environmental concerns vary greatly; however, a similar practice should be employed. Specifically Restrictions on Hazardous Substances (RoHS) compliance should be addressed in the initial stages, as requirements continually become more restrictive and may be limiting. All necessary compliance codes need to be included in the development plan. Most commercial users require systems be UL approved or listed, CSA certified, or CE approved depending on the location.

5.2. A Comparison of Designs

Three specific incidences of failure were addressed in the new design. These include the set of recognized failures, a large number of components, and difficulty in access to service components. With each attempt to correct a recognized failure, the methodology employed led to a decrease in parts, and facilitated service access where possible.

The wire failure due to radiation was resolved with the corrected airflow pattern and specific routing for wires. The part count has also been reduced slightly; specifically the horizontal water cooler was eliminated. The elimination of the horizontal water cooler also increases the room for servicing since there is no longer a water tube running up from the base plate.

The guide tube water connections were moved outside which eliminates the problem associated with water leaking from the quick-disconnect connector. Additionally, this makes them easier to access and provides even more room inside for reach.

The overall risk of damage to electronics was lowered significantly by moving all water connections below the base plate or outside the chassis; this ensures the base plate will shield any leaking water. This relocation of tubing also creates additional space where needed for access.

The air quality sensor was added to detect contaminated air entering the system. By locating the sensor near the air inlet it can be assured that contamination in the incoming air will collect on the sensor. This additional component is small relative to other components and it is placed where access is easy and there is no interference with access to other components. The new solution clearly addresses all the documented incidences of failure of the old design.

By using the qualitative criteria established originally for concept reviewing, the new system scores as well or better in the system requirements, and far exceeds the old system’s ability to meet additional design wishes. Specifically the system is significantly more robust, at the expense of additional component costs. The new design takes far less room inside the chassis allowing more room to service other components, and is easier to disassemble should this be necessary. The new parts of the system would also be easy to implement on older systems as it requires only the modification of existing guide tubes and the replacement of the inner water channels. This improvement was expected as the design was selected based upon the same criteria.

There are significant physical design similarities between the existing design and the one presented in this paper. The water cooling channels all have the same basic dimensions since the non cooling related component design was not changed and the same cooling method was retained. The differences are much more subtle than the obvious similarities. First the guide tubes have a different location for the water connection, and a slightly different internal design. Secondly the vertical cooling channels and horizontal channel were combined into two pieces instead of the original three. Third the water connections were moved to a better location. Lastly the custom air system has been replaced with a complete commercial unit requiring no modification or further assembly.

Piping the water outside the unit may not initially appear ideal; however, with the addition of secondary guiding elements outside the unit, for specific customers, it becomes and advantage. By integrating the additional water cooling circuits into one, the total flow can be monitored at no additional cost. An additional advantage of this layout is that it requires much less piping to hook up the entire system. The only new risk with piping the water outside of the unit is physical damage from a cobble. Repairing the unit would be easy requiring simply a new piece of water tubing.

5.3. Quantification of Differences

In order to quantify a difference between the old system and the new system a FLUENT analysis approximating that of a system in service was simulated using a very fine mesh including the appropriate boundary layers. This simulation varied from the other chassis simulations performed. The safety factor was eliminated, the bar size was significantly smaller than three inches, and the air conditioner's capacity was changed to the old system's capacity. The air conditioner capacity was changed because comparing a 10-ton unit and a 2-ton unit is purposeless since the result is obvious without any simulation. The result of the above comparison was a 3^{o}C difference in temperature, at a point slightly below the front area of interest 1, in favor of the new design. This difference should be even higher in service as the model is still fairly conservative for the simulation.

FLUENT inherently has some error in calculating complex flows. The error associated with CFD estimation of heat transfer is reported to be less than 25%, however, for some experiments the error has been found to be less than 4.5% [69]. Since the safety factor used (1.67) is in excess of the maximum 25% error, associated with FLUENT turbulent energy calculations, it is safe to conclude the design is capable of providing the necessary cooling. As to the comparison between the existing unit and the simulation of the new design the difference is within the possible error. Therefore, there is not necessarily any improvement in cooling performance with the 2-ton unit. It is, however, obvious that the proposed 10-ton unit would provide a much lower operating temperature under the same conditions.

The cost difference between the two designs is significant only because of the 10-ton air conditioner. The 10-ton unit is three times the cost of the 2-ton unit. There is an undetermined cost savings in assembly of the new design, since the 2-ton unit required a supplemental blower and significant man hours for assembly. The new system costs roughly 30% more in part costs. This increase is smaller than the difference in the increased price of the new air conditioner because a set of parts supporting the smaller 2-ton unit were removed. Note this price increase does not take into account the decrease in assembly costs. The majority of assembly savings is achieved with many fewer parts in the forced air system. The previous design used two blowers and a two piece air conditioner. This required three motor starters and all the appropriate system controls. By replacing all of these components with one unit the wiring and physical assembly between them were eliminated. If the additional cost is still deemed significant there are alternatives to be considered.

5.4. Possible Variations

The obvious added benefit of the 10-ton unit is additional cooling. But additionally most system failures will only result in a loss of half the cooling capacity and not the entire system. I would suggest the 10-ton unit be used, especially in mills located in warmer climates.

Eliminating the 10-ton air conditioner in favor of the previous 2-ton unit, in exchange for a lower robustness there would still be a functioning system; as proven in the simulation discussed in section 5.3. This alternative choice retaining the rest of the design changes provides only a lower robustness from an engineering standpoint; this however, may be negligible as the mill's water utility is typically more reliable than the electrical utility. The business argument for this reduced setup appears initially strong as the overall part cost would be slightly below the previous system. However, a detailed examination of assembly costs would need to be conducted to verify the attractiveness. The new system would still benefit from all the new design improvements except for the additional robustness of the new air conditioner. With the use of a 2-ton unit the new system would cost less in parts than the old system, however the assembly costs would be on the closer to the old system. This is achieved by using one less custom made cooling channel, and lower cost alternatives for other parts.

The second alternative possibility would be to use the new type of air conditioner but instead of the 10-ton unit a smaller 5-ton unit could be used. It would be possible to obtain a smaller unit that is still a two phase unit, which means only half of the system is likely to fail at once as there are two independent cycles within the single unit. This design would retain the added benefit of the new air conditioner, and cut some of the part costs, while maintaining lower assembly costs. At this time it is unknown what a 5 ton unit would cost of the same series from Nordic Air.

5.5. Implementation

In order to implement the new design the armor plating on the sensor chassis will require a modification for the new guide tubes. The previous design allows for the connector to pass through; however the new design requires a larger cutout for it to mount flush with the armor plates. Additionally four new holes will be required in the base mounting plate, which will require a minimal amount additional machining. These are the only two changes in existing parts and not a significant one, there is no impact on the cost as it will require the same amount of machining time. To achieve the new air flow pattern in the chassis two new dividers will need to be added to the system. These two additions can be welded in new systems and bolted in place in existing systems. Additionally a test of the particle sensor’s design would be required before implementing it in a commercial product. The only other step necessary for implementation is to manufacture the parts designed.

5.6. General Form Solution

The cooling of different systems for similar applications has previously been designed from the conceptual level up. The generation of the general form solution in section 4.8 provides a concept for a cooling system and the analytical approach to providing the specifications to the system. The information detailed is broad enough to be applied to other applications. A new application will still require substantial work in generating a new design. However, it will avoid the immense amount of time spent researching alternative concepts and deciding upon on analytical approach.

The system proposed is conservative and it is possible some applications cannot afford such measures because of existing constraints, such as cost or size. There are certainly other solutions to new applications. This concept may not be optimal for other applications; however, implementing this concept will be substantially easier given the information documented in this report.

5.7. Possible Future Solutions

The cooling system design was highly constrained by co- existing systems within the unit, specifically the optical system and the chassis. Should the entire unit be redesigned it may be possible to further improve the cooling system both in performance and cost. Because of the interdependence of systems a redesign of the entire system with the simplest cooling system possible might further complicate other systems and inflate other costs. The current design is costly for such a simple function; however the robustness is necessary since there are much greater consequences from failure should an inadequate system be installed.

CHAPTER 6

CONCLUSION

The problem defined as a cooling system plagued by several documented incidences of failure, a high number of components, access difficulty to service, and an imposed risk to electronic components from water leakage. The solution presented solves the problem in a manner that is worthy of implementation. The solution was arrived at using a carefully designed plan. There are similarities between the new design and the old design. The new design benefits from operating knowledge of the current system, and boasts several improvements like improved access to all components and decreased risk of water contacting electronic components in the event of a failure. Additionally the problem of generating new designs for future applications of the system was radically simplified with a general form solution. This solution provides the basic toolbox needed to adapt the current design concept to new ideas and future applications.

The choice between a 2-ton, 5-ton, or 10-ton air conditioner will have to be based upon finances. However, the remaining changes are negligible in cost and would provide improvements for the identified weaknesses, serviceability, and robustness, regardless of the choice of air conditioner. The new suggested design is a marked improvement and worthy of implementation, however, design improvements are continuous and future improvements must be incorporated.

CHAPTER 7

FUTURE WORK

The future work necessary at this time is to first construct a prototype of the air quality sensor and test such a unit. It is anticipated that possible improvements will be made on the prototype. Secondly a business argument would need to be developed for each of the three possible choices of air conditioners based upon labor costs, specific to the operating business for assembly costs. The labor cost associated with such manufacturing also varies, depending on whether the product is manufactured in house or outsourced. An additional component to the business case is whether the added robustness adds commercial value to the customer and can justify an increase in commercial value. A complete business argument might vary greatly depending on the customer but it would facilitate the choice of designs. I would product that a choice would be made and standardized for future customers.

As a separate note no design is ever perfect or without need of further improvement. Improvements will be made based upon future working knowledge of the system, new technologies, lower cost alternative technologies, alternative manufacturing methods, new materials, and other advancements in knowledge. These changes should be incorporated into the design or provide a new design as necessary.

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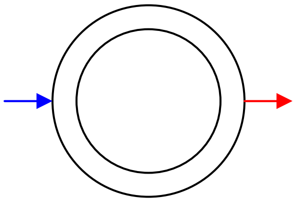
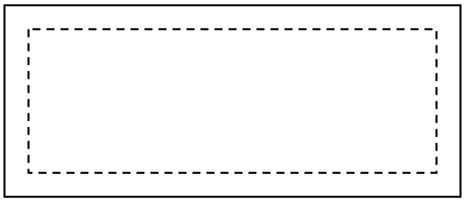
Appendix A: Concept Sketches

Concept: Water Cooled Guide Tube



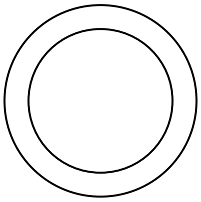


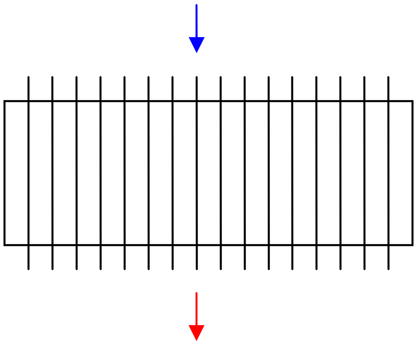
Advantages:
High level of thermal protection

Disadvantages:
Water is a danger to electronic components

Layout Comments:
Connectors outside armor
QD connector
Insulation around trough

Concept: Air Cooled Guide Tube



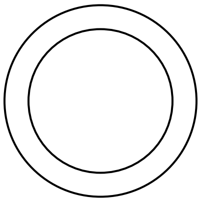


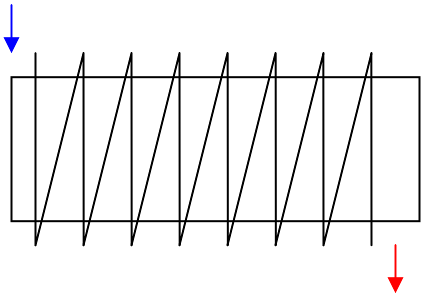
Advantages:
No Water
Forced Air System could be used for entire cooling system

Disadvantages:
Low level of thermal protection

Layout Comments:
Direction of fins

Concept: Super Cooled Guide Tube



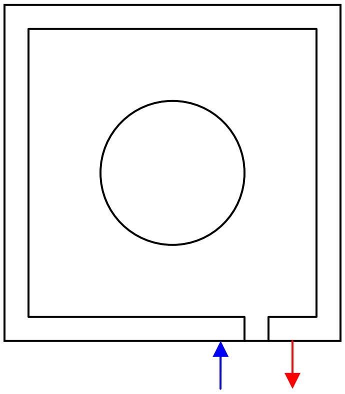


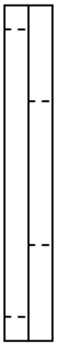
Advantages:
Extremely high heat capacity

Disadvantages:
Requires refrigerant
System could easily be damaged
Tubing is difficult to pipe outside system

Layout Comments:
Where to locate refrigeration cycle

Concept: Water Cooled Gap



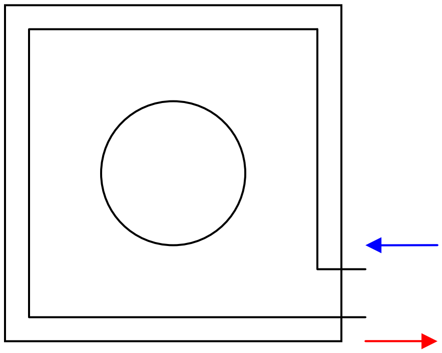
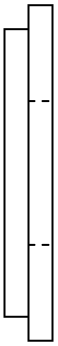


Advantages:
High level of thermal protection

Disadvantages:
Water is a danger to electronic components
Limits access to Machine Vision systems

Layout Comments:
Connectors below base plate

Concept: Super Cooled Gap

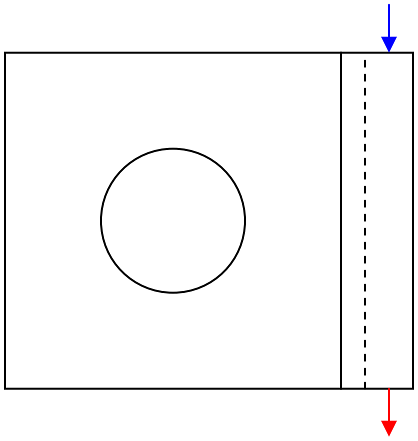
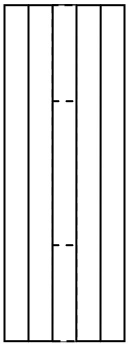



Advantages:
Extremely high level of thermal protection
Smaller size than water channel

Disadvantages:
Refrigerant is needed
Piping is difficult

Layout Comments:
Connectors below base plate

Concept: Air Cooled Gap

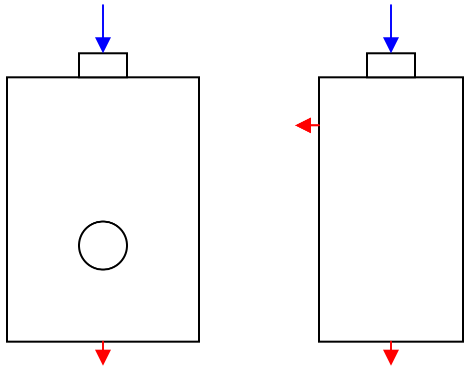



Advantages:
Easily removable for full access to machine vision systems
Cheap
No need for water

Disadvantages:
Low level of thermal protection
Shields radiation excellently

Layout Comments:
Removable heat sink

Concept: Air Cooled Electronics

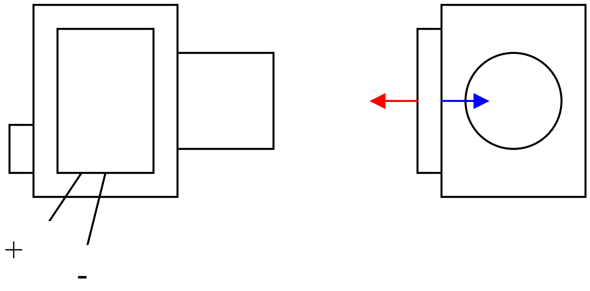


Advantages:
No Internal components required
Simple
Can be combined with other concepts easily

Disadvantages:
Low level of thermal protection
Debris
Some refrigeration of air required

Layout Comments:
Local/Remote blower
Local/Remote AC unit

Concept: Thermo-Electric Cooled Electronic Components

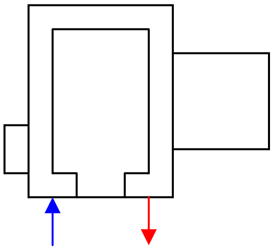


Advantages:
Very Small
Simple

Disadvantages:
Low level of thermal protection
Would require a large number of individual elements

Layout Comments:

Concept: Water Cooled Electronic Components

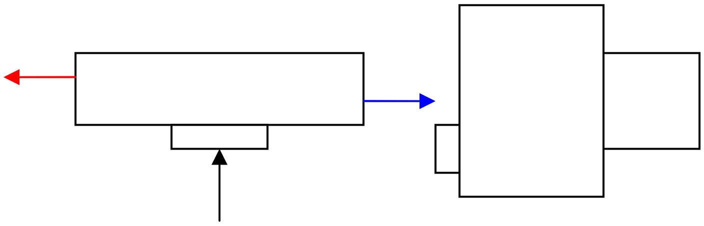


Advantages:
High level of thermal protection

Disadvantages:
Water tubing is difficult to pipe
Would require a large number of individual elements
Severe risk of water damaging components

Layout Comments:

Concept: Vortex Spot Cooler

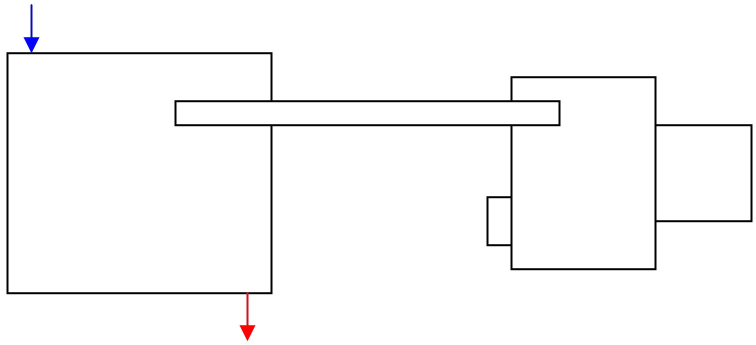


Advantages:
Small size
Direct cooling of electronic components

Disadvantages:
Relies on mill utilities, unless a separate compressor is provided
Extremely low level of thermal protection for components without direct flow
Relatively low cost, not including a separate compressor

Layout Comments:

Concept: Heat Pipe Interface to Coolant Heat Exchanger

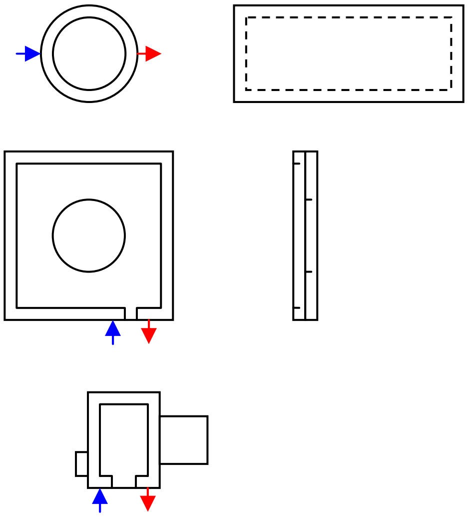


Advantages:
Moves heat exchanger away from components
Do not need as many heat exchangers

Disadvantages:
Costly
Flexible heat pipe would be necessary

Layout Comments:

Concept: Water Cooled Guide Tube, Water Cooled Gap, Water Cooled Electronics

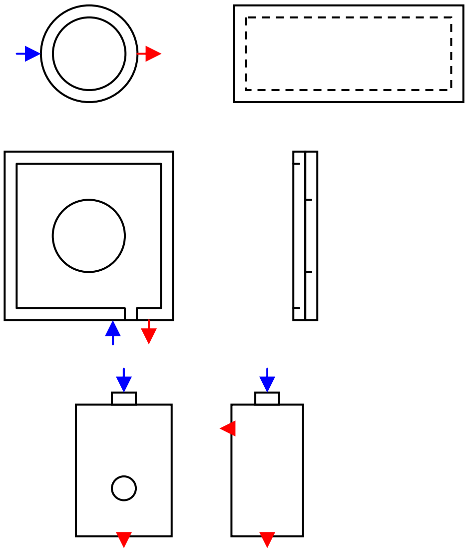


Advantages:
Extremely High level of thermal protection

Disadvantages:
Water is a danger to electronic components
Water cooling on each and every electronic component is difficult

Layout Comments:
Connectors outside armor
QD connector
Insulation around trough

Concept: Water Cooled Guide Tube, Water Cooled Gap, Air Cooled Electronics

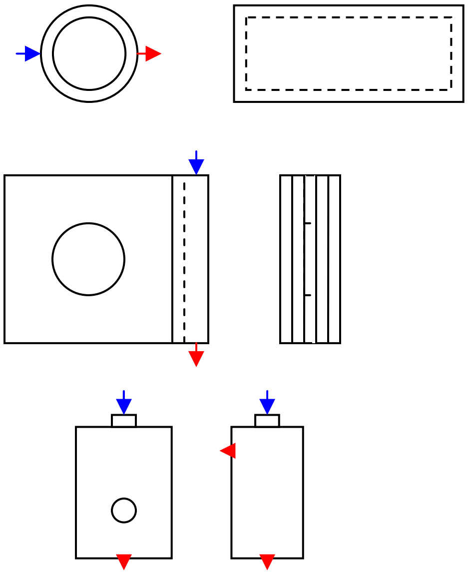


Advantages:
High level of thermal protection
Water Risks can be managed

Disadvantages:
Air and Water system required

Layout Comments:
Connectors outside armor
QD connector
Insulation around trough

Concept: Water Cooled Guide Tube, Air Cooled Gap, Air Cooled Electronics

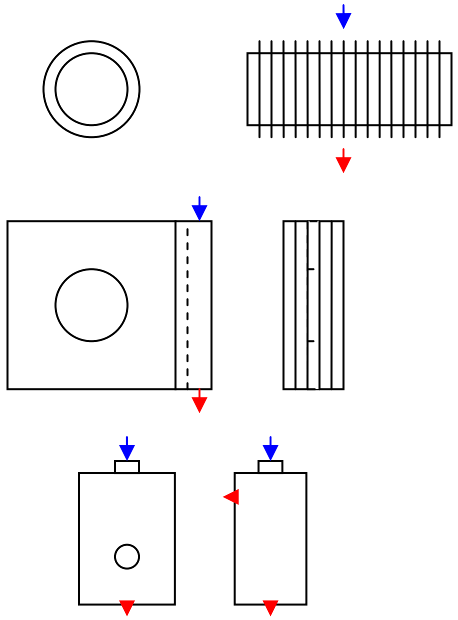


Advantages:
Water Risks can be managed

Disadvantages:
Moderate level of thermal protection
Air and Water system required

Layout Comments:
Connectors outside armor
QD connector
Insulation around trough

Concept: Air Cooled Guide Tube, Air Cooled Gap, Air Cooled Electronics

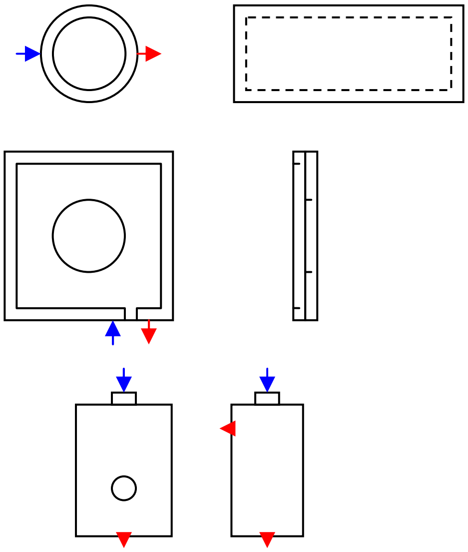


Advantages:
No water risks

Disadvantages:
Low level of thermal protection

Layout Comments:

Concept: Water Cooled Guide Tube, Water Cooled Gap, Air/Refrigeration Cooled Electronics

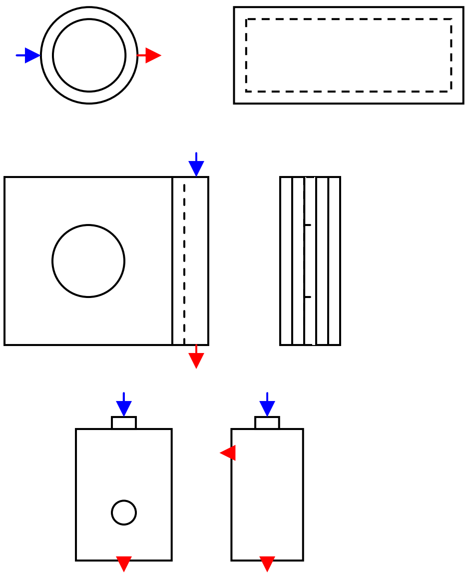


Advantages:
High level of thermal protection
Water Risks can be managed
Refrigeration Cycle for Forced Air ensures air cools equipment sufficiently

Disadvantages:
3 Systems required

Layout Comments:
Connectors outside armor
QD connector
Insulation around trough
Possibility of using forced air to cool top of Gap
AC system can be located in variety of locations and layouts

Concept: Water Cooled Guide Tube, Air Cooled Gap, Air Cooled Electronics with Refrigeration Cycle Cooled Air

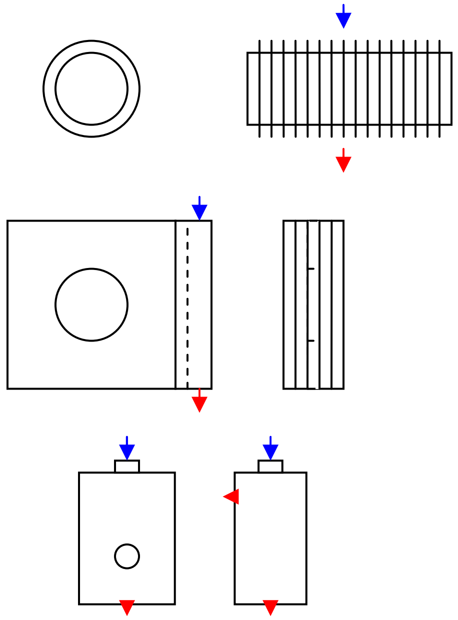


Advantages:
Water Risks can be managed

Disadvantages:
Moderate level of thermal protection
Air and Water system required
3 Systems required

Layout Comments:
Connectors outside armor
QD connector
Insulation around trough
AC system can be located in variety of locations and layouts

Concept: Air Cooled Guide Tube, Air Cooled Gap, Air Cooled Electronics with Refrigeration Cycle Cooled Air

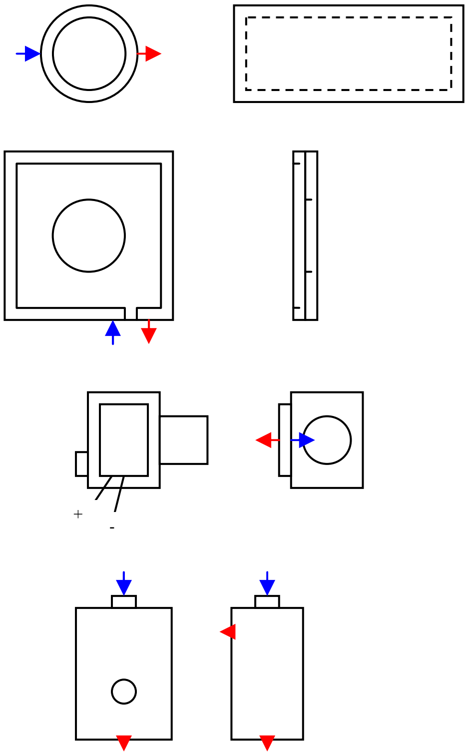


Advantages:
No water risks
Increased thermal protection vs only forced air
Only 2 systems required still

Disadvantages:
Low level of thermal protection

Layout Comments:
AC system can be located in variety of locations and layouts

Concept: Water Cooled Guide Tube and Gap & Air/Peltier Cooled Electronics

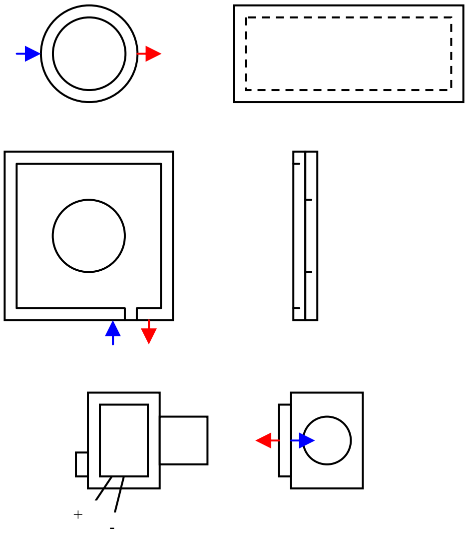


Advantages:
Thermal Radiation is heavily protected
Provides excellent thermal protection to specific electronic components

Disadvantages:
More expensive than a forced air cooling of electronics

Layout Comments:
Difficult to implement the Peltier on all electronics

Concept: Water Cooled Guide Tube and Gap & Peltier Cooled Electronics

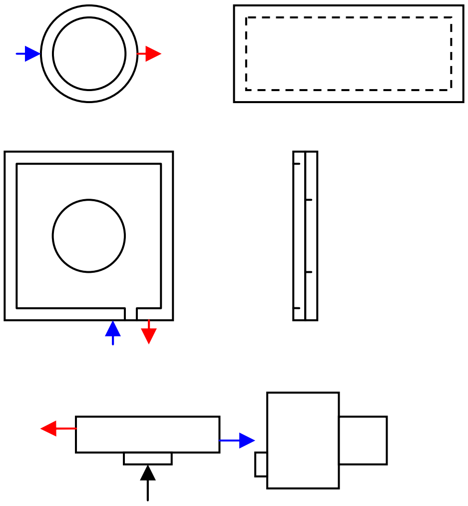


Advantages:
Thermal Radiation is heavily protected
Cheaper than forced air/refrigeration systems

Disadvantages:
Low level of thermal protection for electronics

Layout Comments:
Difficult to implement on every electronic component

Concept: Water Cooled Guide Tube and Gap & Vortex Spot Cooled Electronics

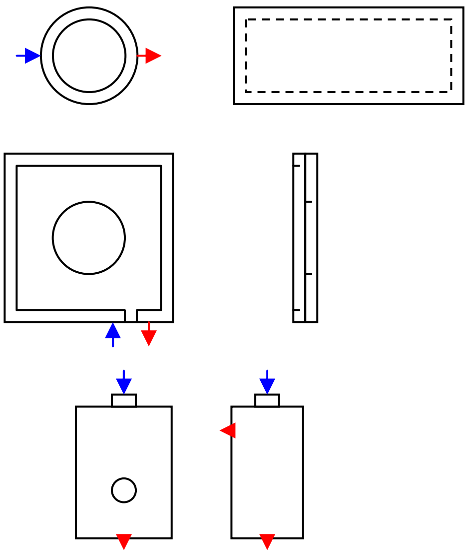


Advantages:
Easy to implement
Minimal space required

Disadvantages:
Air is a mill utility with very low reliability
A suitable compressor is more expensive than a refrigeration unit

Layout Comments:
Directing air to every location necessary can be difficult

Concept: Water Cooled Guide Tube and Gap w/ Refrigeration & Air Cooled Electronics w/ Refrigeration

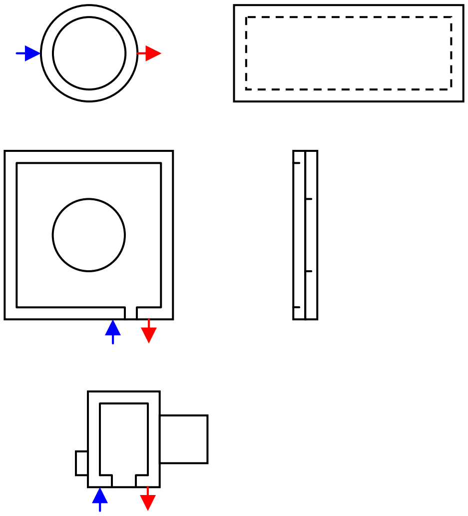


Advantages:
Cooled water can remove more heat
Electronics can be cooled without additional equipment within the sensor

Disadvantages:
Cooling the water in addition to the air costs more with minimal gains

Layout Comments:
Large AC unit may not be located directly at sensor

Concept: Water Cooled Guide Tube, Gap, and Electronics w/ Refrigeration

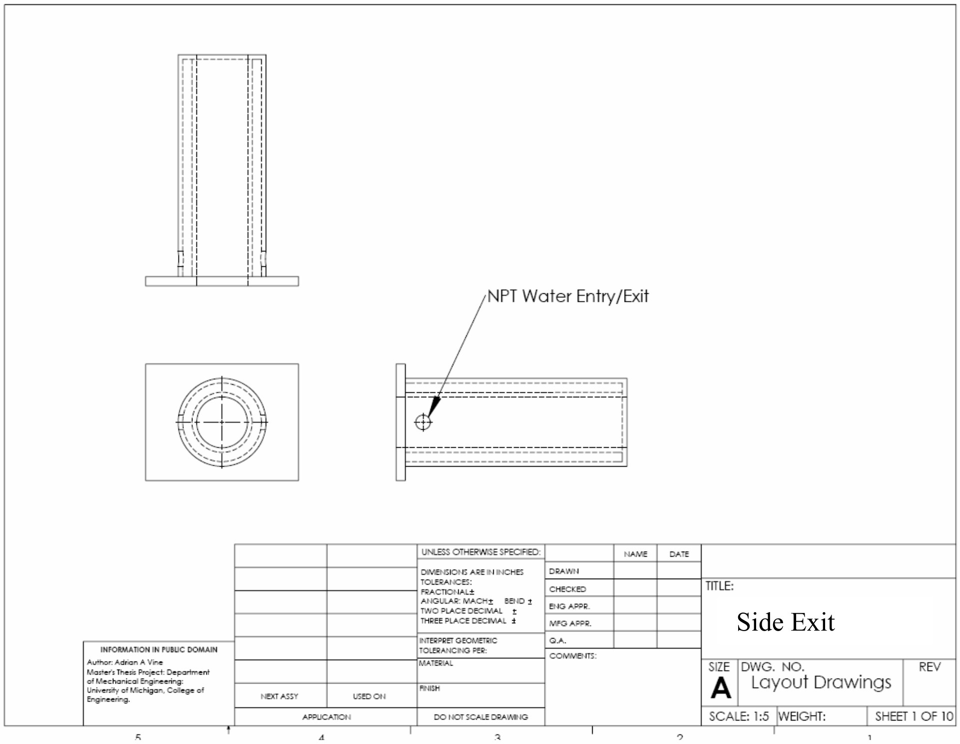


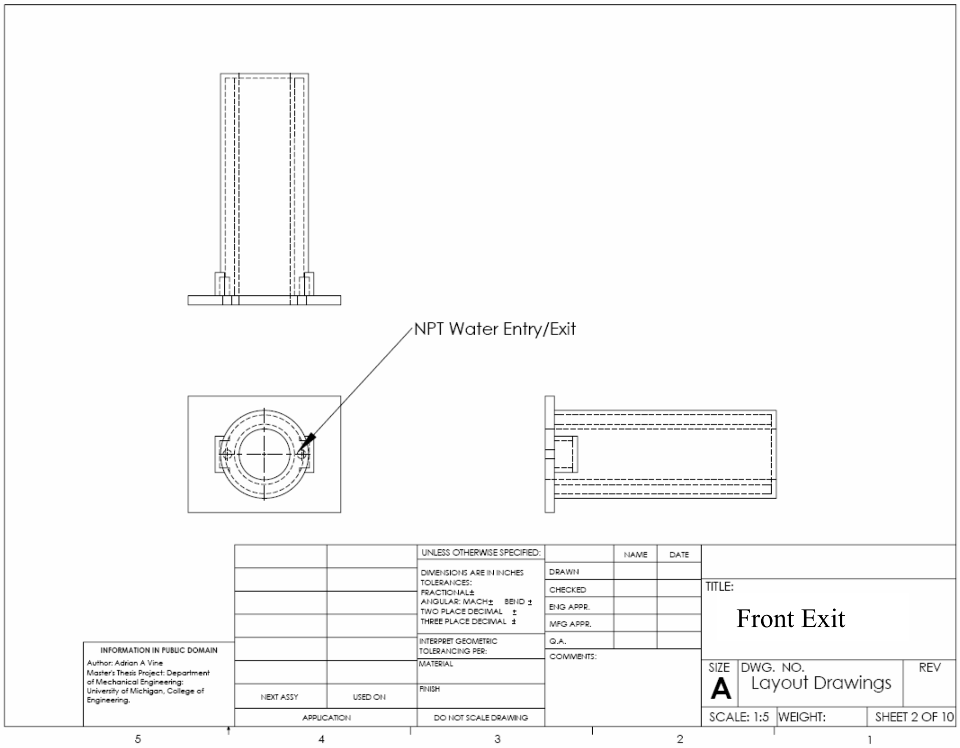
Advantages:
Water and AC systems only
Immense cooling capacity

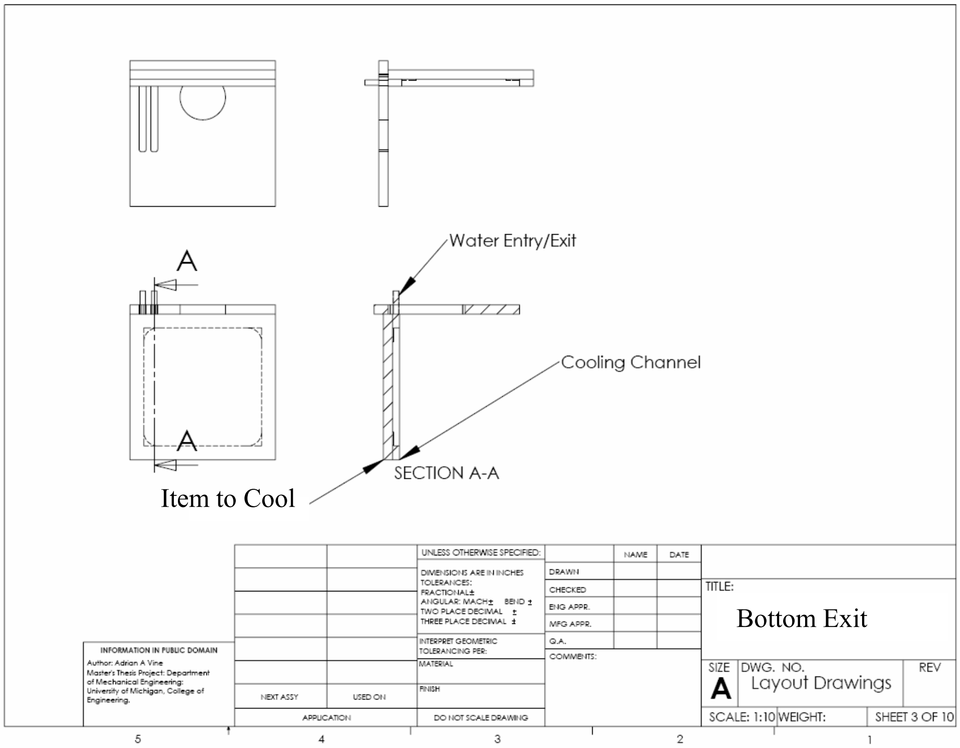
Disadvantages:
Cooling the water provides minimal gains

Layout Comments:
Difficult to provide heat exchanger for each individual electronic component

Appendix B: Initial Layout Sketches






A
Water Entry/Exit
Cooling Channel
A
SECTION A-A
Item to Cool
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DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Bottom Exit
SIZE
A
DWG. NO.
Layout Drawings
REV
SCALE: 1:10
WEIGHT:
SHEET 3 OF 10
INFORMATION IN PUBLIC DOMAIN
Author: Adrian A Vine
Master's Thesis Project: Department of Mechanical Engineering; University of Michigan, College of Engineering.
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4
3
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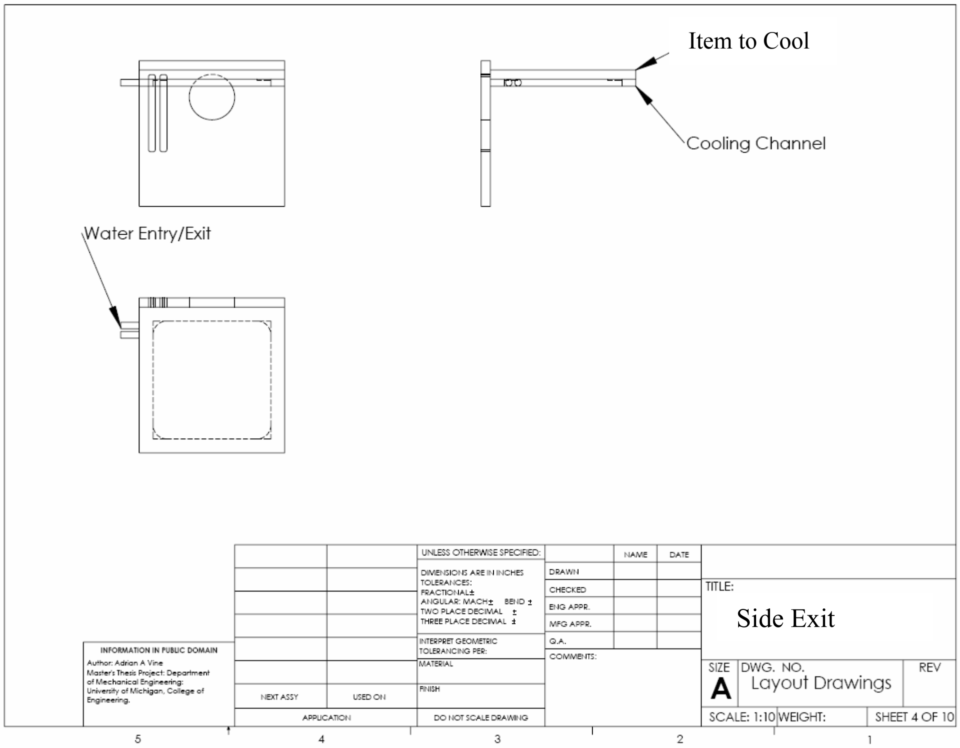
1


Item to Cool
Cooling Channel
Water Entry/Exit
UNLESS OTHERWISE SPECIFIED:
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FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
NAME
DATE
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CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Side Exit
SIZE
A
DWG. NO.
Layout Drawings
REV
SCALE: 1:10
WEIGHT:
SHEET 4 OF 10
INFORMATION IN PUBLIC DOMAIN
Author: Adrian A Vine
Master's Thesis Project: Department of Mechanical Engineering; University of Michigan, College of Engineering.
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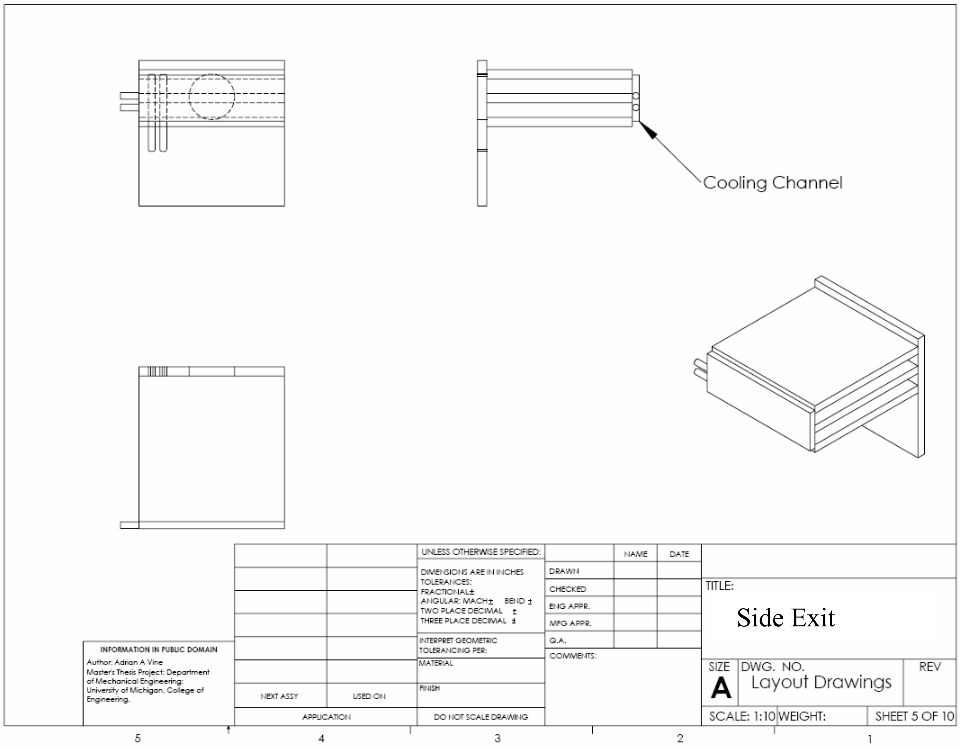

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TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

NEXT ASSY
USED ON
APPLICATION

	NAME	DATE
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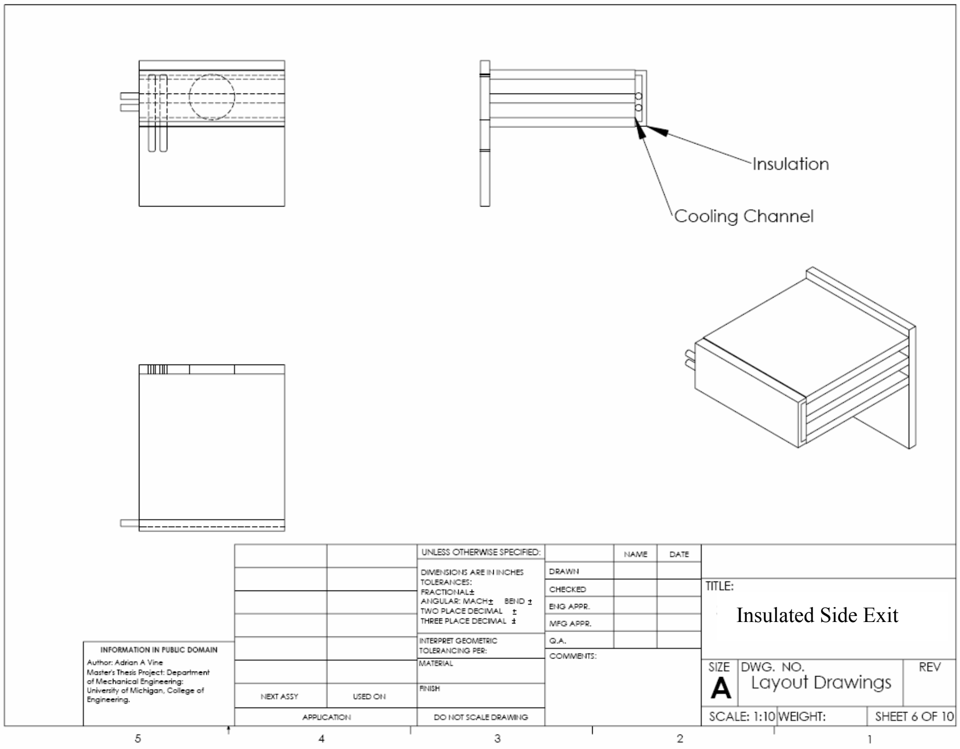
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

INFORMATION IN PUBLIC DOMAIN
Author: Adrian A Vine
Master's Thesis Project: Department of Mechanical Engineering: University of Michigan, College of Engineering.

TITLE:
Side Exit

SIZE A
DWG. NO. Layout Drawings
REV
SCALE: 1:10
WEIGHT:
SHEET 5 OF 10



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TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

NEXT ASSY
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APPLICATION

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ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

INFORMATION IN PUBLIC DOMAIN
Author: Adrian A Vine
Master's Thesis Project: Department of Mechanical Engineering: University of Michigan, College of Engineering.

TITLE:
Insulated Side Exit

SIZE A
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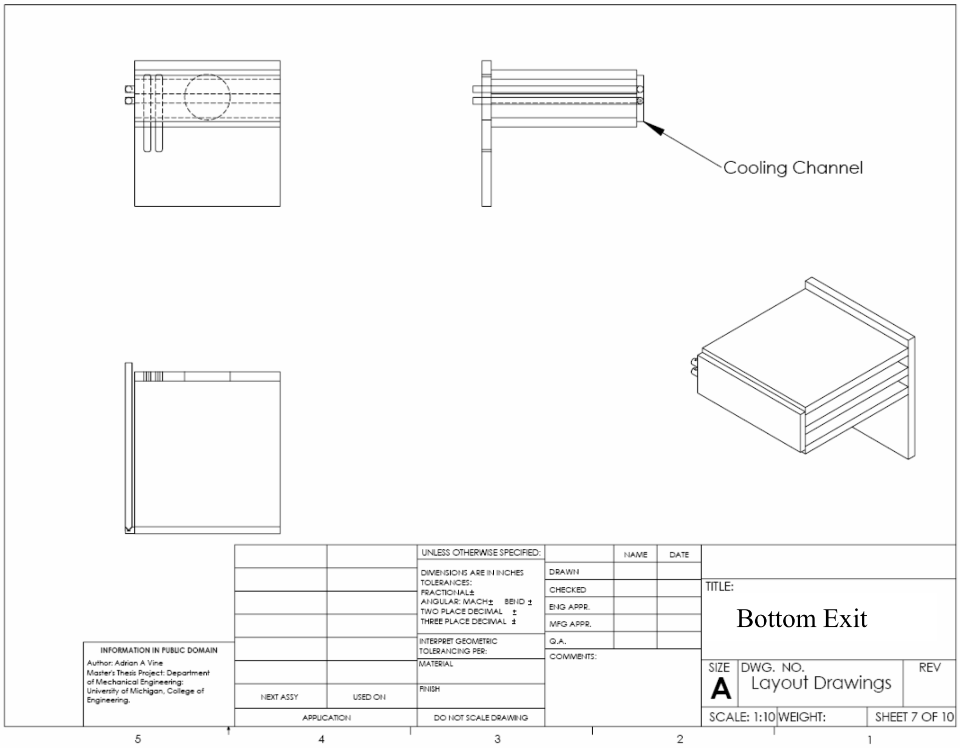
REV
SCALE: 1:10
WEIGHT:
SHEET 6 OF 10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INTERPRET GEOMETRIC TOLERANCING PER:
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NAME
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ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
INFORMATION IN PUBLIC DOMAIN
Author: Adrian A Vine
Master's Thesis Project: Department of Mechanical Engineering; University of Michigan, College of Engineering.
TITLE:
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Layout Drawings
REV
SCALE: 1:10
WEIGHT:
SHEET 7 OF 10
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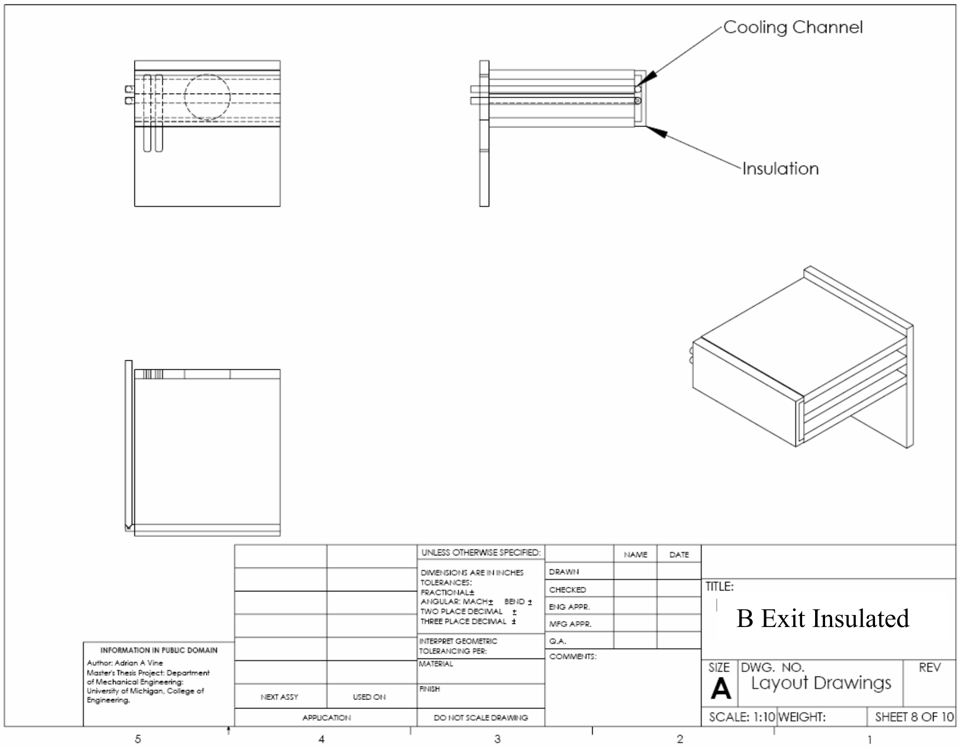
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Insulation
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ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
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NAME
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MFG APPR.
Q.A.
COMMENTS:
INFORMATION IN PUBLIC DOMAIN
Author: Adrian A Vine
Master's Thesis Project: Department of Mechanical Engineering; University of Michigan, College of Engineering.
TITLE:
B Exit Insulated
SIZE
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Layout Drawings
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SCALE: 1:10
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SHEET 8 OF 10
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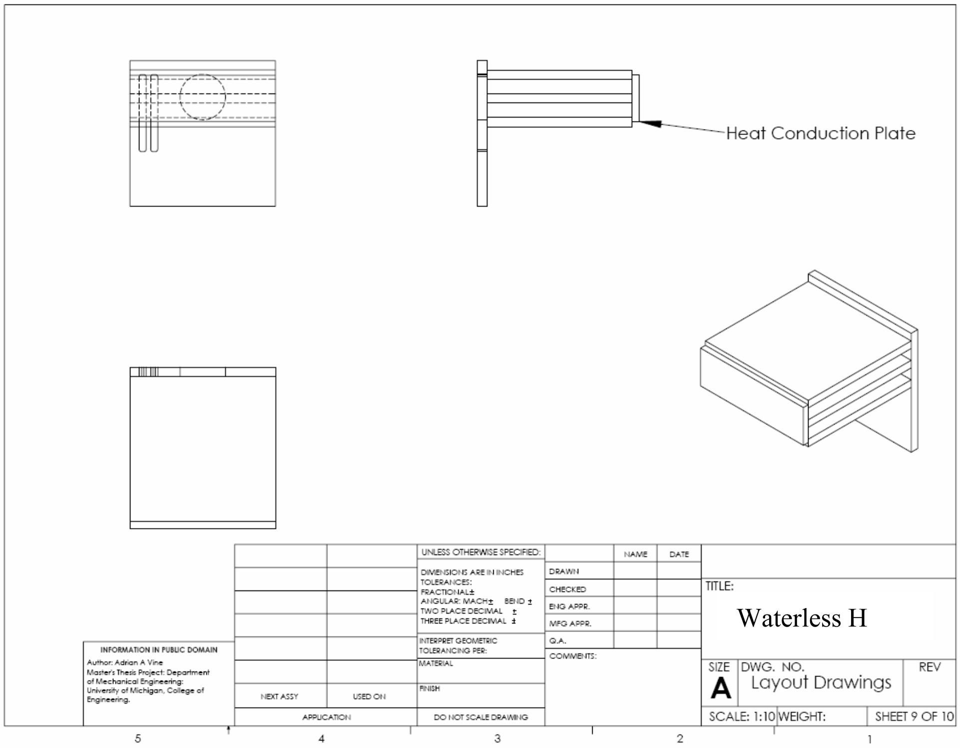
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THREE PLACE DECIMAL ±
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MATERIAL
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MFG APPR.
Q.A.
COMMENTS:
INFORMATION IN PUBLIC DOMAIN
Author: Adrian A Vine
Master's Thesis Project: Department of Mechanical Engineering; University of Michigan, College of Engineering.
TITLE:
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Layout Drawings
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SCALE: 1:10
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SHEET 9 OF 10
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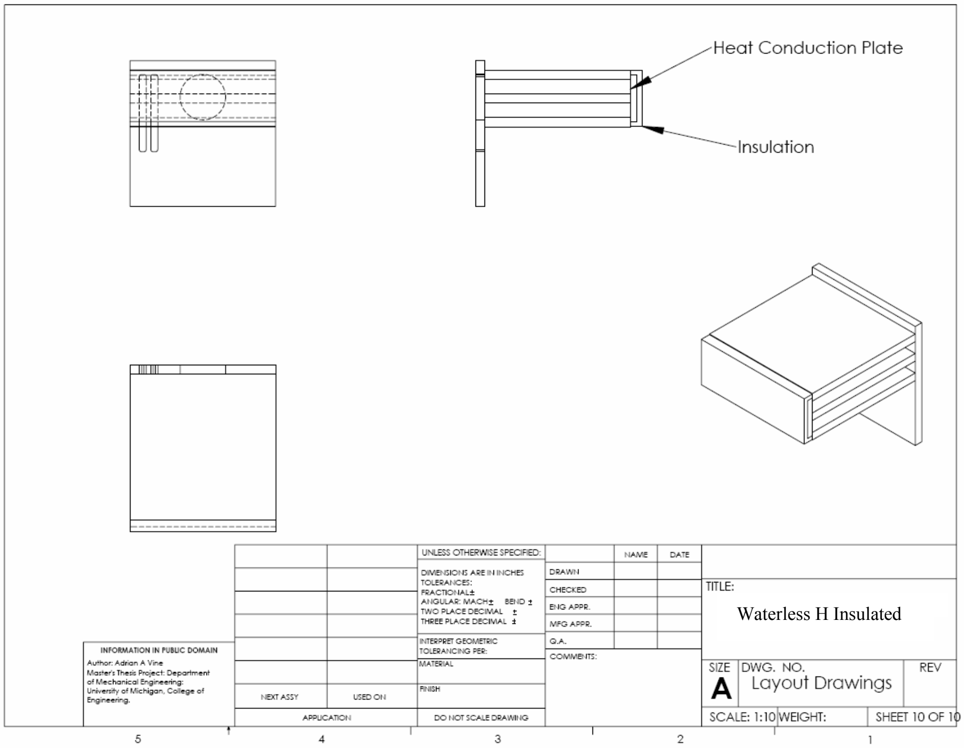
Heat Conduction Plate
Insulation
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Master's Thesis Project: Department of Mechanical Engineering; University of Michigan, College of Engineering.
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Layout Drawings
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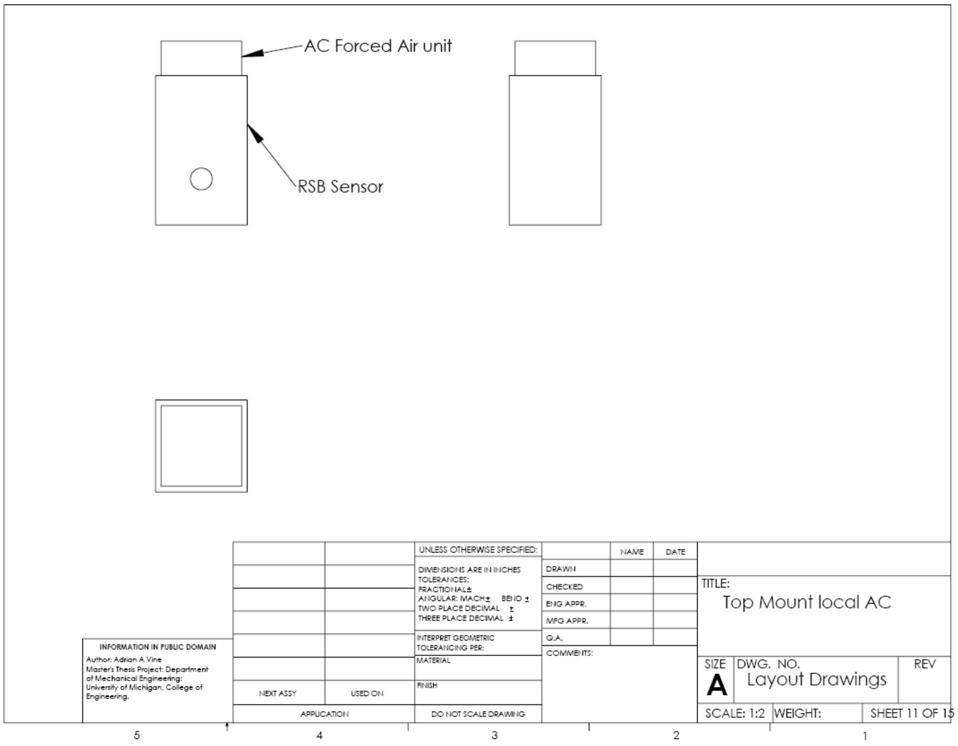
AC Forced Air unit
RSB Sensor
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TWO PLACE DECIMAL ±
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MFG APPR.
Q.A.
COMMENTS:
TITLE:
Top Mount local AC
SIZE
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DWG. NO.
Layout Drawings
REV
SCALE: 1:2
WEIGHT:
SHEET 11 OF 15
INFORMATION IN PUBLIC DOMAIN
Author: Adrian A Vine
Master's Thesis Project: Department of Mechanical Engineering: University of Michigan, College of Engineering.
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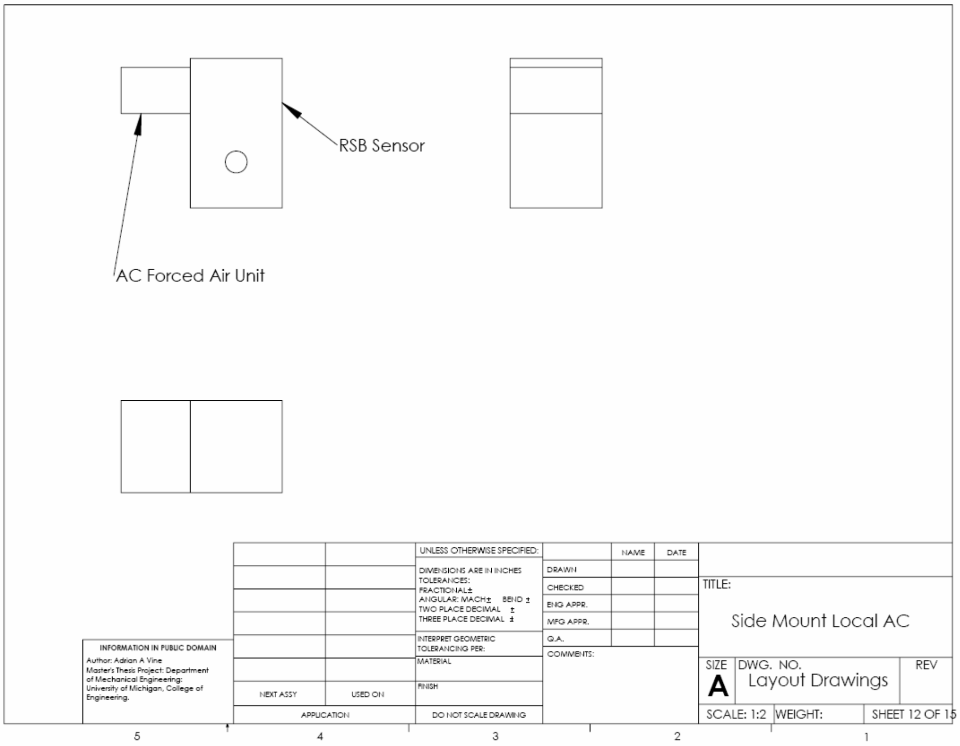
RSB Sensor
AC Forced Air Unit
UNLESS OTHERWISE SPECIFIED:
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ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
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MFG APPR.
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COMMENTS:
TITLE:
Side Mount Local AC
SIZE
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DWG. NO.
Layout Drawings
REV
SCALE: 1:2
WEIGHT:
SHEET 12 OF 15
INFORMATION IN PUBLIC DOMAIN
Author: Adrian A Vine
Master's Thesis Project: Department of Mechanical Engineering: University of Michigan, College of Engineering.
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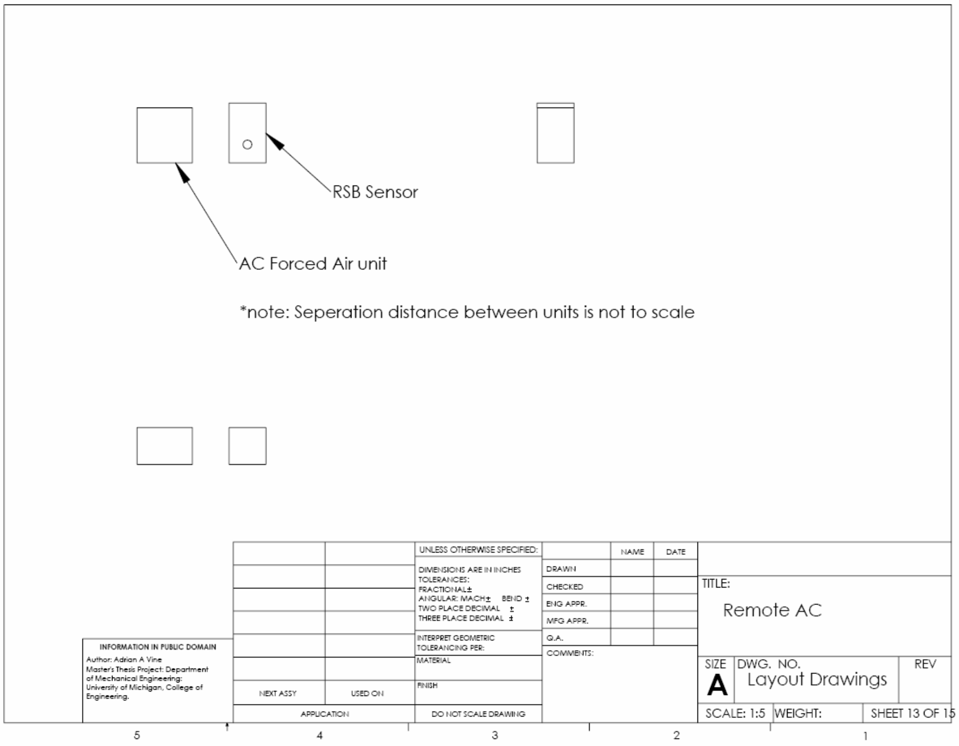

RSB Sensor
AC Forced Air unit
*note: Seperation distance between units is not to scale
INFORMATION IN PUBLIC DOMAIN
Author: Adrian A Vine
Master's Thesis Project: Department of Mechanical Engineering: University of Michigan, College of Engineering.
NEXT ASSY
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APPLICATION
UNLESS OTHERWISE SPECIFIED:
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TOLERANCES:
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ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
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Layout Drawings
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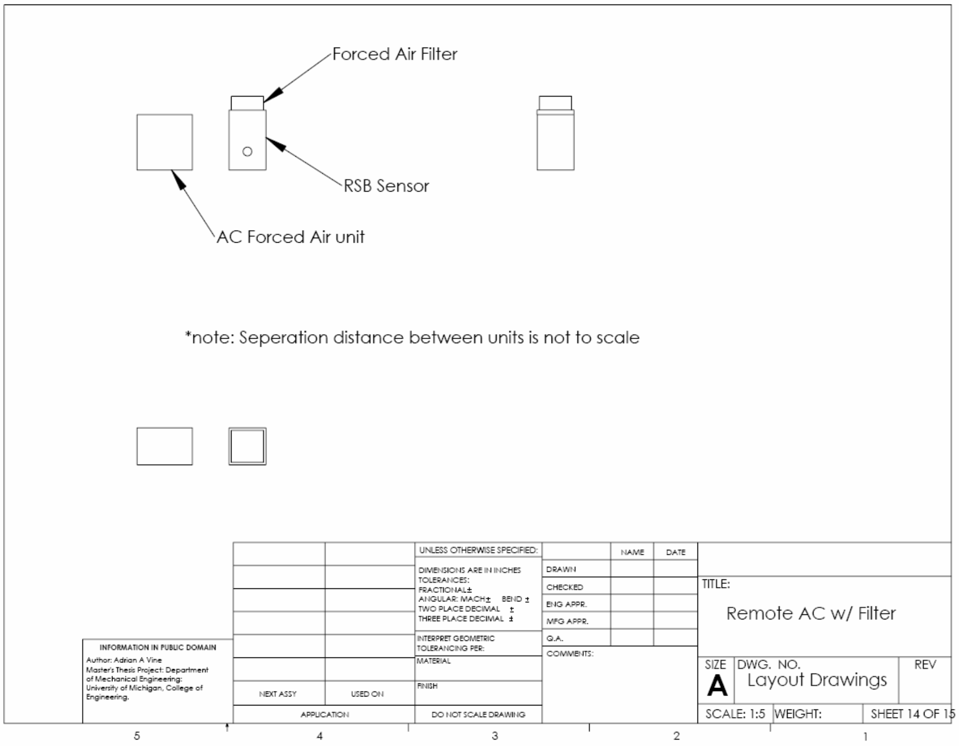

Forced Air Filter
RSB Sensor
AC Forced Air unit
*note: Seperation distance between units is not to scale
INFORMATION IN PUBLIC DOMAIN
Author: Adrian A Vine
Master's Thesis Project: Department of Mechanical Engineering: University of Michigan, College of Engineering.
NEXT ASSY
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APPLICATION
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FINISH
DO NOT SCALE DRAWING
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ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Remote AC w/ Filter
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Layout Drawings
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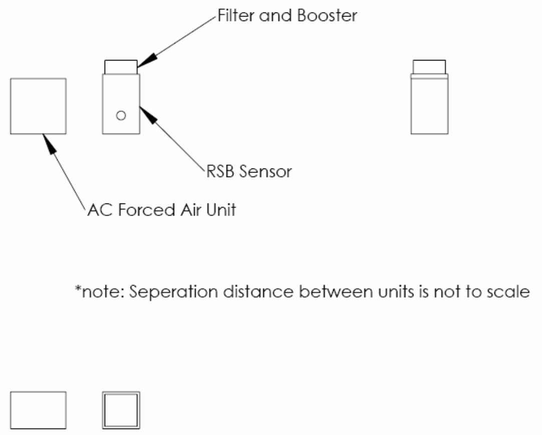

*note: Seperation distance between units is not to scale

INFORMATION IN PUBLIC DOMAIN
Author: Adrian A Vine
Master's Thesis Project: Department of Mechanical Engineering: University of Michigan, College of Engineering.

NEXT ASSY	USED ON
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UNLESS OTHERWISE SPECIFIED:
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TOLERANCES:
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ANGULAR: MACH± BEND ±
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THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:
Remote AC w/ Filter & Boost

SIZE A
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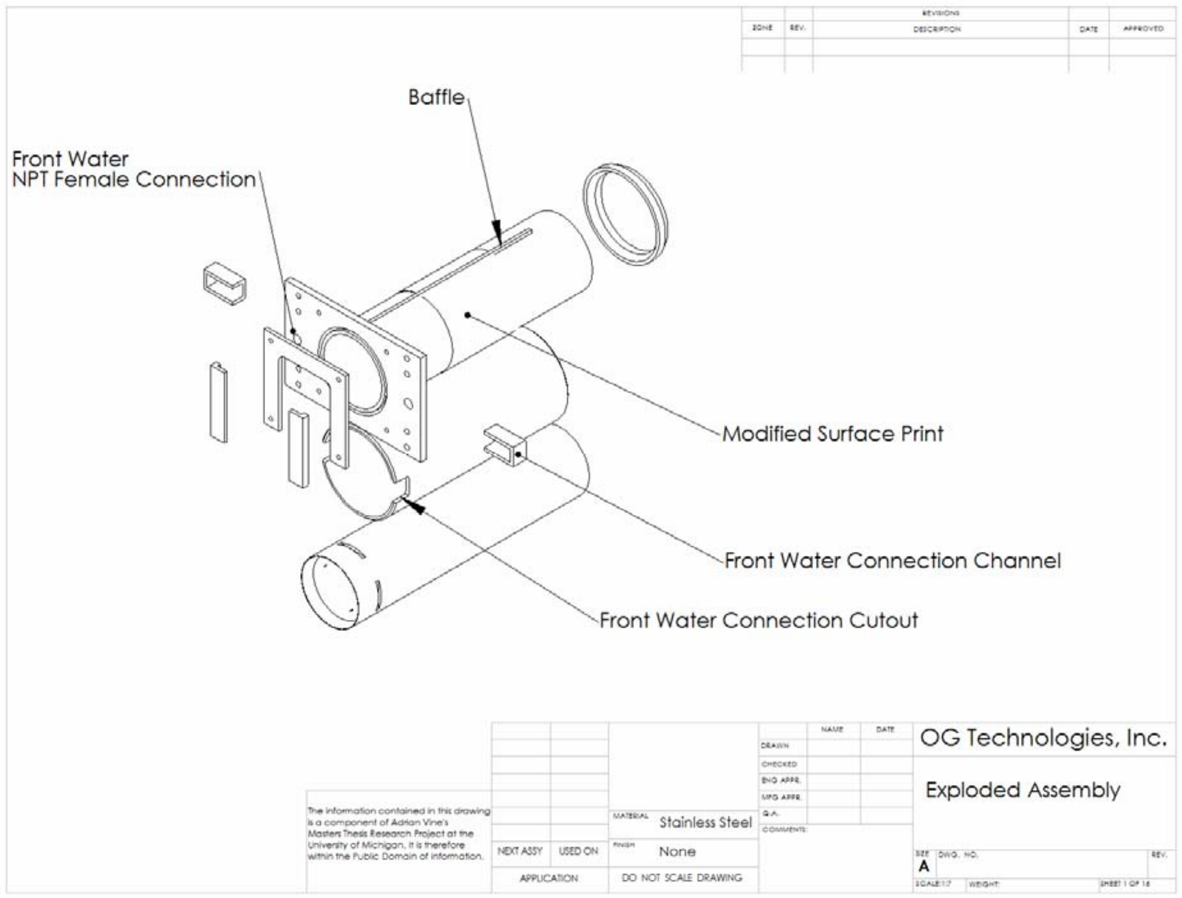
REV

SCALE: 1:5
WEIGHT:
SHEET 15 OF 15

5 4 3 2 1

Appendix C: Guide Tube Final Design Details



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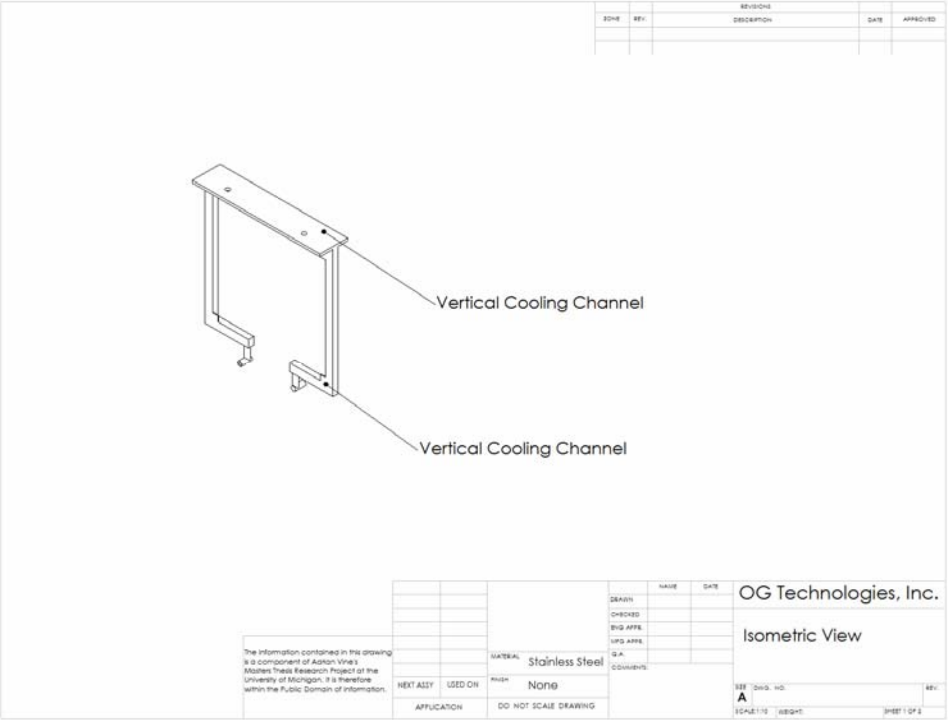
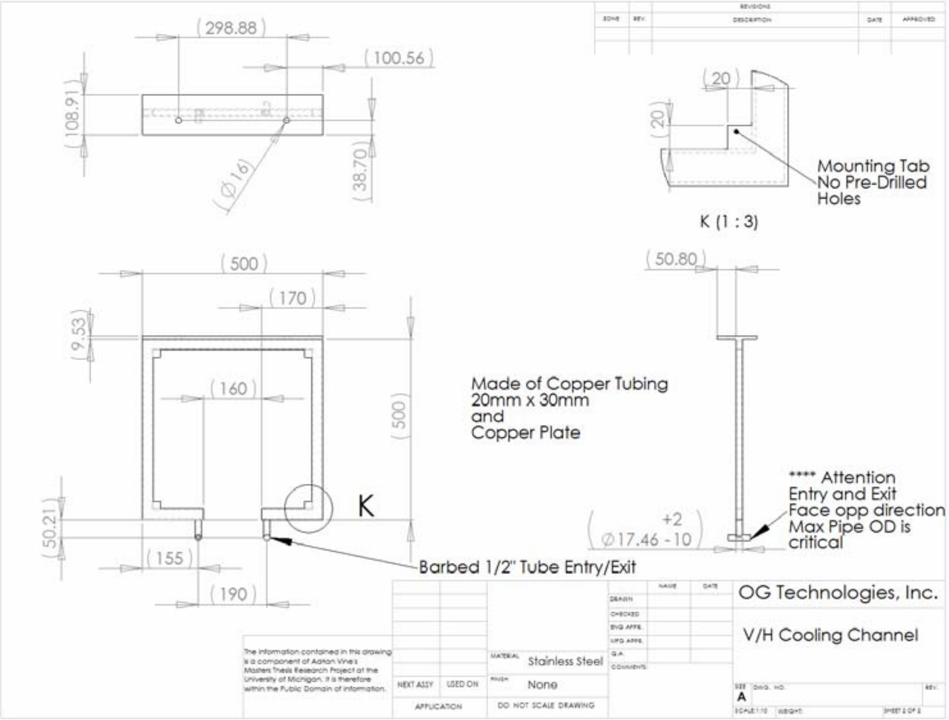
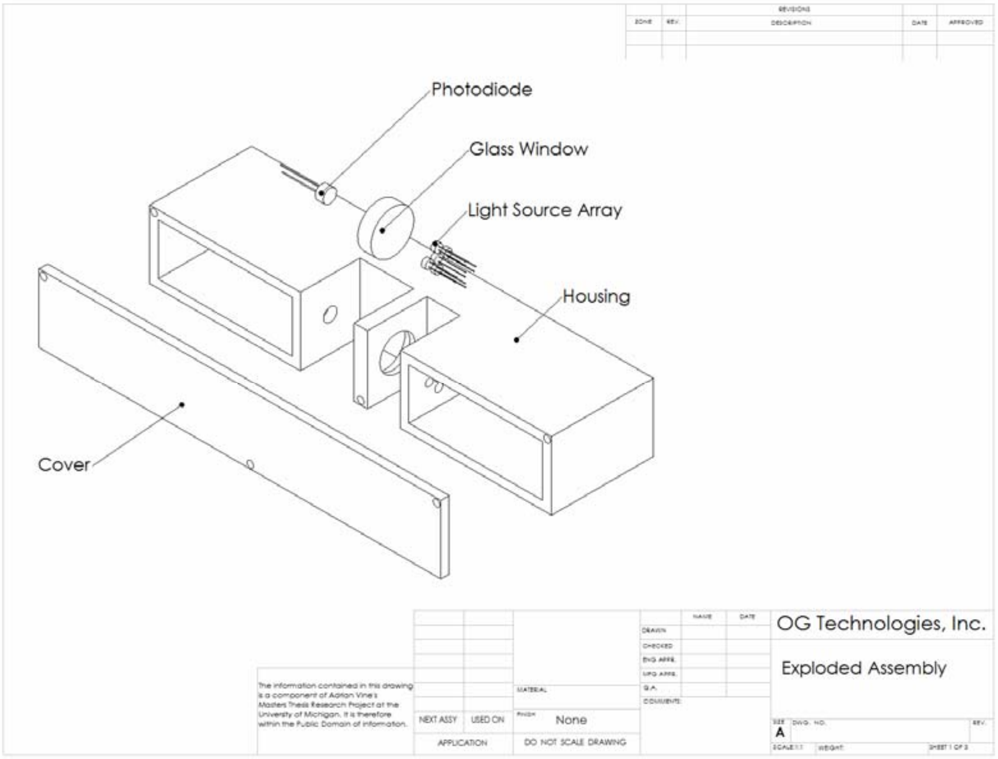
Appendix D: Combined Vertical/Horizontal Channel Final Design Details

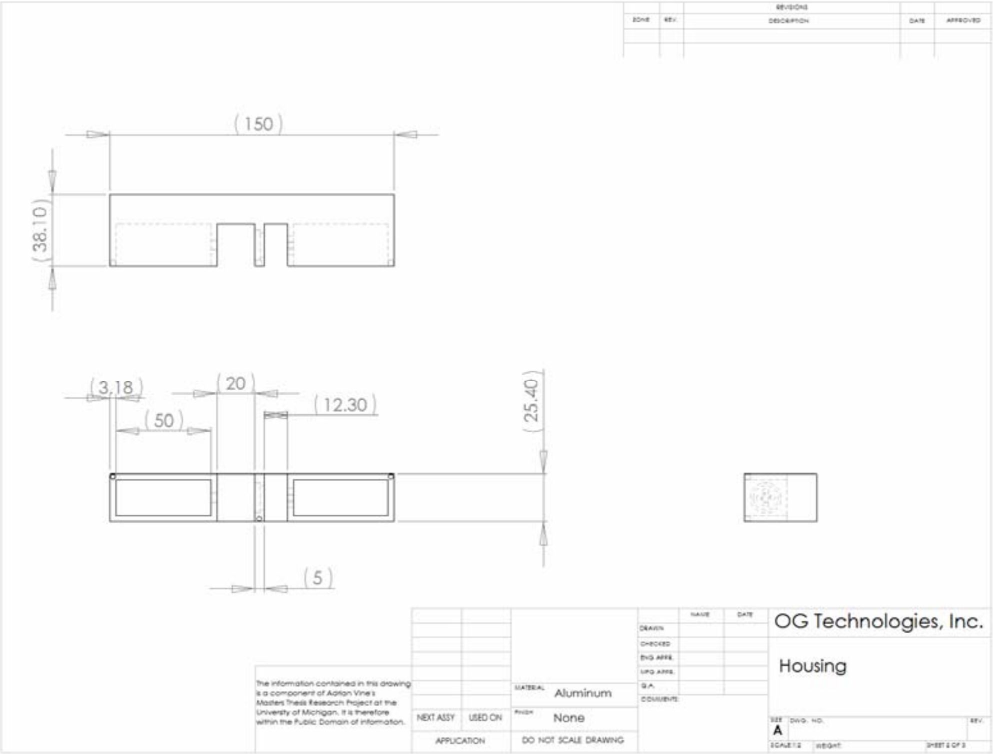




Appendix E: Particle Sensor Design



The information contained in this drawing is a component of Adrian Vine's Masters Thesis Research Project at the University of Michigan. It is therefore within the Public Domain of information.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MFG APPR.
Q.A.
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Housing
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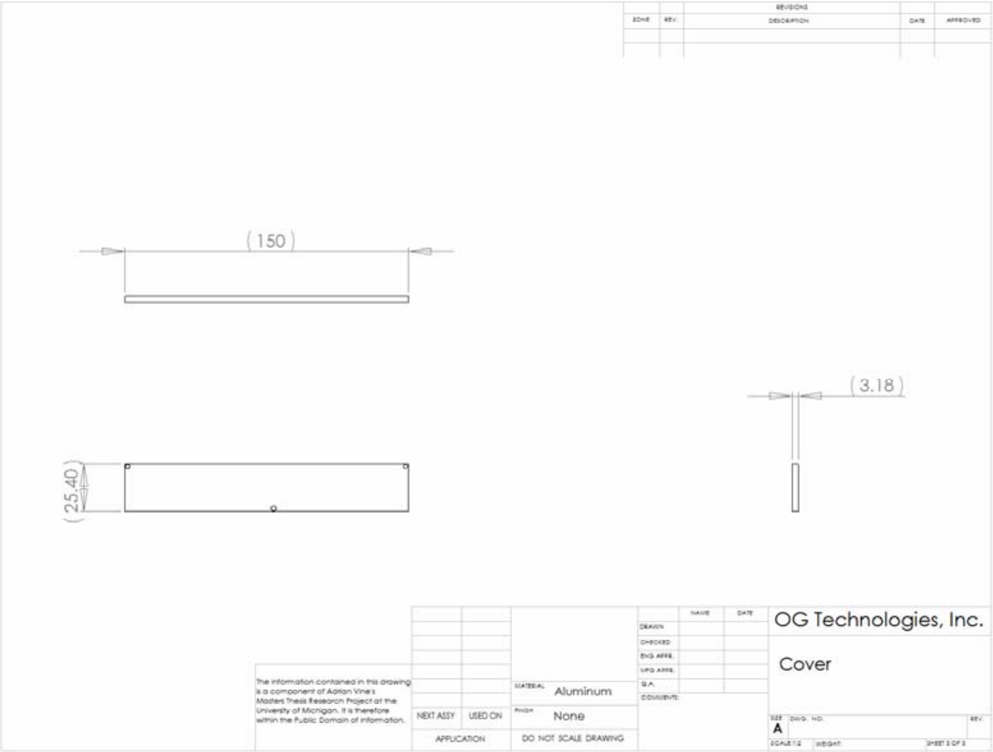
SHEET 2 OF 3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MFG APPR.
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COMMENTS:
OG Technologies, Inc.
Cover
The information contained in this drawing is a component of Adrian Vine's Masters Thesis Research Project at the University of Michigan. It is therefore within the Public Domain of information.
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WEIGHT:
SHEET 3 OF 3