Foundry Energy Recovery

Final Report

ME 450: Fall 2007
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12/11/2007

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ABSTRACT

Increasing energy costs have given a foundry reason to reduce waste energy in its plant. They manufacture their product using a series of processes that involve melting, forming, heat treating, sorting, packaging, and storage. The company has given us the task of surveying areas of energy loss, with the goal of designing a method to recover and reuse waste energy.

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INTRODUCTION

A foundry is looking to reduce energy waste in its plant. Confidentiality issues have forced us to withhold information regarding the company's identity and the specific nature of their business. The general layout of the foundry is shown in Appendix A. Their manufacturing process requires that the metal be heated multiple times. At the end of the first process, when the metal is formed into the desired shape, the water used in the cooling process drains into outdoor cooling ponds. The heat treatment line, shown in Appendix B, has high energy waste. Heated air, known as flue gas, escapes up through the stacks into the atmosphere. This area will be the main location to recover heat losses. A large portion of the foundry's operation costs go toward the consumption of natural gas and electricity. The heat treatment furnaces and dryers have high natural gas usage, and a smaller amount is consumed during the winter for heating offices and a warehouse. The warehouse is open to the outdoors and must be kept at a certain temperature to ensure the quality of the product by preventing the formation of condensation during storage, which would lead to rust.

The sponsor company has therefore tasked us with quantifying waste energy and devising methods to recover the waste heat. To accomplish this, an energy survey on their manufacturing processes was conducted. Methods were then devised to recover the waste heat and put it to use by displacing existing energy sources. They can then use the information to go forward and fully implement the proposed system.

At the very least, recovered heat energy will be used to heat the plant offices and warehouse. Any excess energy will be sold to neighboring plants. Another result of this project will be to use the recovered energy to generate electricity.

INFORMATION SEARCH

Methods for recovering waste heat energy are hardly a new idea. For example, a simple patent search yields a design of a regenerative glass-drawing furnace dating from 1913 (Patent 1,157,246). In short, this device takes the hot exhaust from a furnace and routes it into a heat exchanger to preheat the incoming air, reducing the amount of energy needed to bring the air up to the operating temperature. This is not a very elaborate system, but it has proven to be very effective. Examining modern heat recovery systems reveal remarkably similar designs. Patent 4,083,398 from 1975 for a waste heat recovery system, although more refined, still employs the same idea of using the waste heat to preheat the inlet gasses, and do so in roughly the same manner. The modern design only has three key differences. First, the exhaust airflow is adjusted with electrically controlled actuators. This allows for precise control of the amount of air entering the heat exchanger to control the amount of heat transferred and keep it at a desired amount. The second is the use of two heat exchangers. One is used to take energy from the exhaust and the other is used to preheat the inlet air. This method allows more energy to be stored in the fluid transferring heat between the heat exchangers to heat the incoming air more than would be possible directly using the exhaust air. The third is the use of blowers to improve airflow. Considering how little the process has changed over the years, it is clear that this is a mature technology, and any improvements would be minor and difficult to achieve.

In addition to using the exhaust to preheat incoming air, a number of other uses have also been devised. Another common use is to generate electricity. Such a system generally involves a boiler to create steam, which is then used to run a steam turbine (as in patent number 4,753,068). Like regenerators, this process involves routing the exhaust air through a heat exchanger to boil water. The steam is then used to run a turbine to generate power. Also like the regenerators, this technology has been around for a long time, and any improvements made are small. It is also common to find systems utilizing steam turbines and regenerators at the same time (known as cogeneration).

There are a few other techniques for recovering waste heat, but they all have the same basic concept of using a heat exchanger to transfer heat energy from one medium to another. In fact, in any of the energy recovery methods above, the biggest difference between the systems is in the details of how it is implemented. Each situation requires a different configuration, such as a different type of heat exchanger, a different heat cycle, possibly a different type of turbine. Likewise, in this project the challenge is in how to implement the system, and overcoming two key issues which have not been addressed in the designs found in the information search. First, the waste heat available is at a low temperature with a high flow rate. The highest temperature seen is only about 400°F, which limits the rate at which heat can be transferred. The high flow rate makes this problem worse because the exhaust gas would only be exposed to the heat exchanger for a short time. The other challenge is in how to integrate it into the existing system. The original plant was not designed with heat recovery in mind, so the product would need to be designed in a way that it could be retrofitted with the existing setup, without interfering with the normal operation.

CUSTOMER REQUIREMENTS AND ENGINEERING SPECIFICATIONS

In order to ensure that we meet all of our sponsor's needs, we determined customer requirements along with their individual importance and translated them into engineering specifications. In this section, the customer is considered to be our sponsor since they will be the users of our designed system. We assessed the strength of the relationship between the specifications and requirements in our Quality Function Deployment diagram (QFD) shown in Appendix C.

Customer Requirements

From our meeting with the sponsor and a tour of their foundry, we were able to gain an understanding of the requirements for this undertaking. Of course, our customer wants to reduce energy usage. Our goal for this project is to engineer a solution with the purpose of reducing energy consumption, and therefore cost, for the sponsor. This must be done in compliance with government regulations and cannot interfere with product quality. It is also important for our product to use space efficiently and to integrate easily into the existing setup. We are also required to provide a product that requires low maintenance and is highly reliable to avoid further costs. As an additional bonus, our sponsor would like for us to maintain their ISO 14000 certification, making our solution as environmentally friendly as possible. Although not a main concern, our sponsor prefers low equipment cost and minimized installation cost. These are not given a large weight on our QFD because a well-engineered, long-term solution that saves energy will pay for itself.

Engineering Specifications

Due to the fact that this project is focused on energy consumption, one of the most important engineering specifications is net energy gain, measured in BTUs. This correlates strongly to the consumer requirement of reducing energy usage. It also relates to reliability because a reliable system works consistently to reduce energy consumption.

Another important engineering specification is part selection cost, which is the direct translation of the consumer requirement of low equipment cost. If we assume that a more expensive component is more reliable and performs better than its cheaper counterpart, then the consumer requirements of high reliability and reduction of energy use have a partial impact on this specification. Additionally, part selection cost is slightly affected by a low installation cost because larger equipment tends to be more expensive and costs more to install.

In the interest of providing a cost effective solution, our sponsor requires a low installation cost, translating into an engineering specification for this requirement. Installation cost is also related to easy system integration because there are financial consequences to changing the existing set-up.

For obvious reasons, the requirement for high reliability also results in a specification concerning low maintenance cost. Since our consumer demands a low maintenance, highly reliable system, component lifetime is an important engineering specification. If we assume that more expensive components last longer, then component lifetime is also related to low equipment cost.

More expensive, larger parts are also more difficult to integrate into the existing setup. Additionally, low installation cost, easy system integration, and high reliability are the customer requirements that translate into the number of components required specification. When designing our system we must also take into account equipment volume. This is most strongly related to the requirement of efficient space usage. It also has a weaker relationship to low equipment cost and easy system integration for the same cost-size relationship discussed above. In addition, our sponsor needs to meet government regulations and ISO 14000 qualifications, so the emission quantity for our system must be measured and minimized.

Target Values

Once we translated consumer requirements into engineering specifications, we quantified them by estimating target values. Based on discussions with the sponsor and quantities measured, we calculated our target values. Our target for net energy gain is 15 MMBTU/HR, obtained by assuming we can recover ten percent of the natural gas consumed in the heat treatment lines, heated offices, and warehouse. Although our sponsor did not give us a specific budget, we estimated part selection cost to be approximately $1.1 million. This figure was calculated based on a five year payback and current energy costs. We roughly estimate 2000 cubic feet to be the maximum equipment volume that can be used without hindering overall operations. Equipment volume limitations will be highly dependent on its location. For instance, equipment on the roof is much less invasive than equipment on the foundry floor. We are looking to design a system with a 20 year lifetime with an installation cost of $600,000. Since our sponsor would like to spend no more than 5% on maintenance per year, we estimated maintenance cost to be $1600 per month. With our current design, we do not anticipate any emissions, and hope to use no more than ten components.

To summarize, here is our list of engineering specifications with our target values:

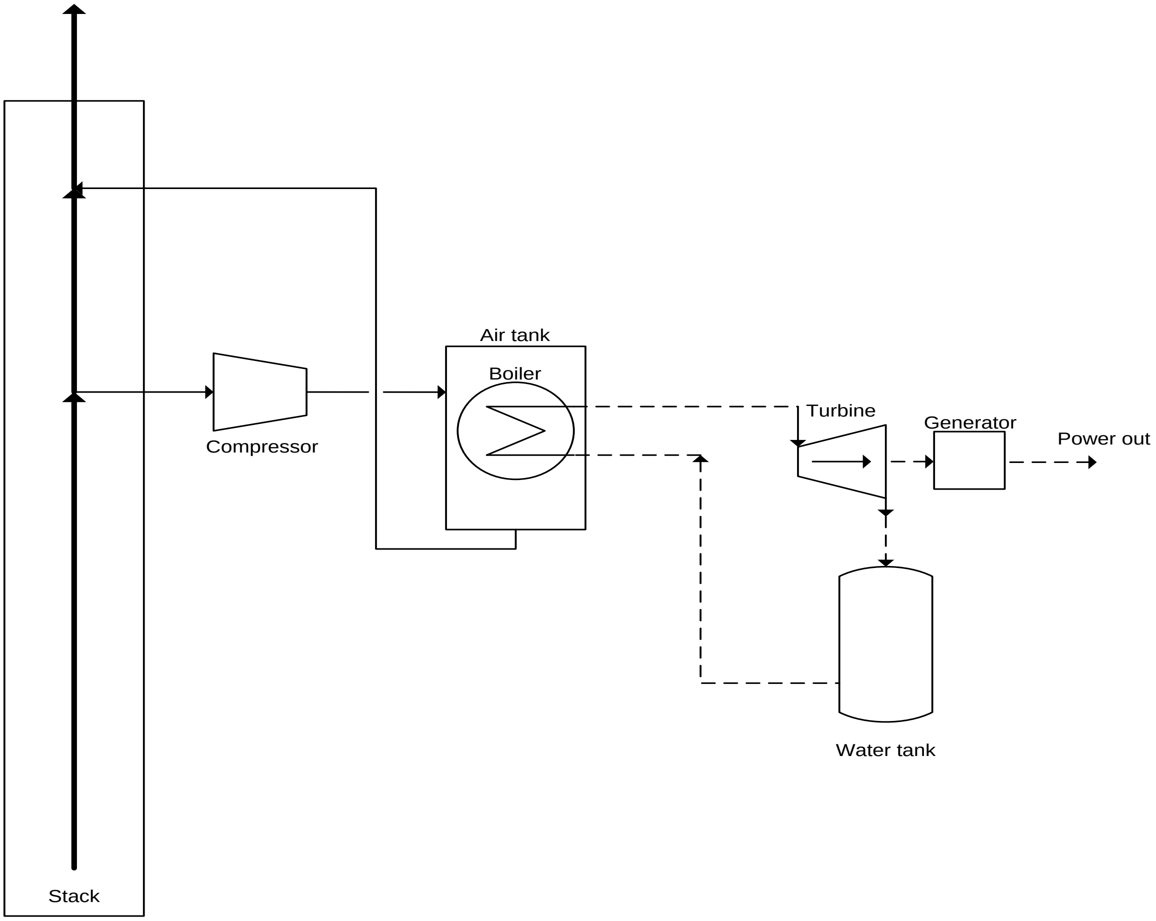
Engineering specification	Target value
Net energy gain	15 MMBTU/HR
Part selection cost	$ 1.1 million
Equipment volume	2000 ft^3
Component lifetime	20 years

Engineering specification	Target value
Installation cost	$ 600,000
Maintenance cost	$ 1600/ month
Emission quantity	0 tons
Number of components required	10

CONCEPT GENERATION

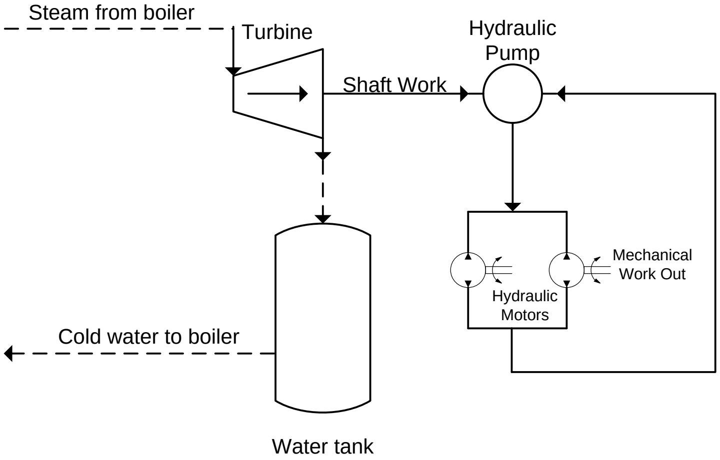
The goal of the design is to reduce the energy used in a foundry through waste heat recovery. This design requires two clear primary functions: recovery of waste heat and use of recovered heat. These represent the beginning and end of the process, so a number of subsidiary functions naturally arise to accomplish this. These include transferring energy, moving fluids, controlling the fluid flow, containing the fluids, monitoring the process, and ensuring safety. The functions were put into a morphological chart (Appendix D) and the team generated concepts that would accomplish the functions. These high-level concepts were combined into multiple designs as needed to achieve our goal of energy recovery. Appendix E shows drawings of all the concepts we considered. A number of the concepts are specific to the energy use, so it would be reasonable to categorize concepts by how the recovered energy is used. An example concept from each category is described below.

Generate electricity



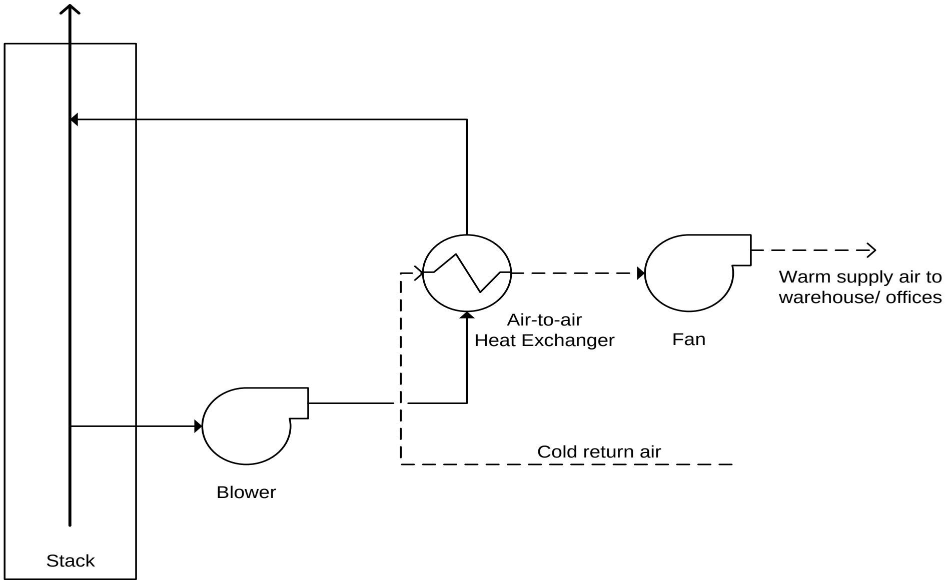
To generate electricity, a generator attached to a steam turbine is used. Flue gas is split off into a separate duct. To increase the air temperature it is compressed, and then passed through a large compressed air tank with a boiler inside it. This slows the air velocity as it heats up the water in the boiler. The temperature of the steam should be increased to the temperature needed for the turbine, which should be around 700 °F. The cold air is returned to the exhaust stack and the steam goes to the turbine. The turbine exhaust water is returned to a water tank to be used again. The power generated can be used at the facility, stored in batteries until needed, or returned to the power grid.

Hydraulic motor



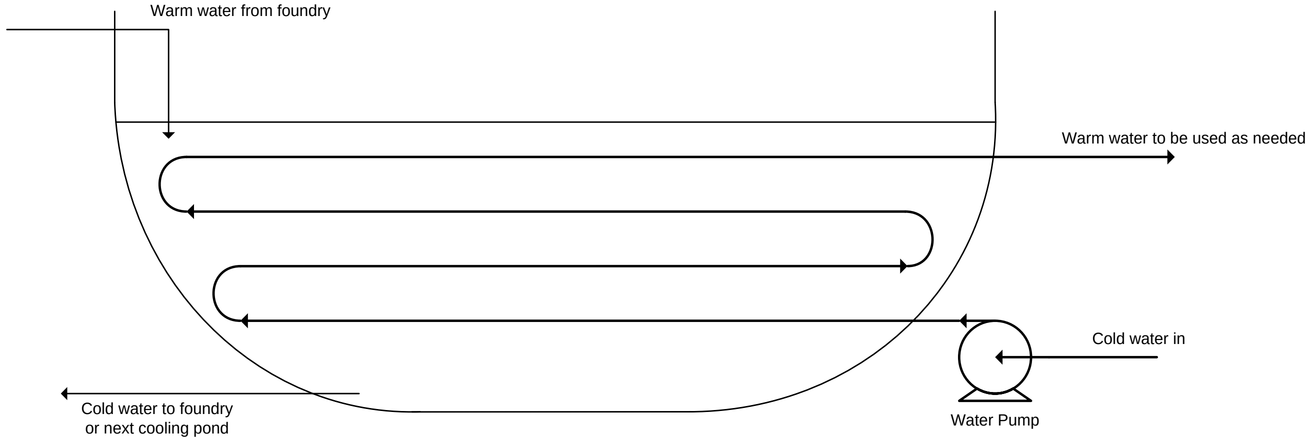
Running a hydraulic motor would be a similar process to generating electricity. However, because there is less power required for hydraulic motors, not as much energy would need to be extracted from the stacks. However, the hydraulic pump could be used in conjunction with electricity generation. The hydraulic pump would run the motors used to turn the furnaces and dryers.

Heat offices and warehouse



Heat for the offices and warehouse could be provided through a simple air-to-air heat exchanger. The flue gas passes through a cross-flow heat exchanger. The flow rate would be controlled to reach the temperature needed to heat the buildings. Blowers would be needed to overcome the pressure losses introduced by the system.

Provide hot water for facility



Hot water for use in the facility could be produced from the water in the cooling ponds. To accomplish this, water lines would be run through the cooling ponds with a pump. The hot water would be routed to the existing water heaters, where it would be stored and available to be used as needed. The cold water in the pond would be sent to the next cooling pond or to the foundry, depending on its temperature.

CONCEPT EVALUATION AND SELECTION

In order to select a concept system we first looked at the merits and limitations of each design. The results of this evaluation are shown in Table 1 and described in more detail in this section. In order to also keep our focus on customer requirements, a Pugh chart evaluation was performed and is described in this section.

Table 1: Merits and limitations of each energy recovery concept.

Concept	Merit	Limitation
#1: Air-air heat exchanger (Appendix E.1)	Simple, low maintenance	High volume ductwork needed, risk of CO exposure, only useful during heating months
#2: Air convection to boiler: steam powered turbine (Appendix E.2)	Recovers natural gas loads by displacing electric loads, simple on air side, relies on convection or blower, low maintenance	Insufficient amounts of heat available for steam generation
#3: Air-condensate heat exchanger (Appendix E.3)	Single HX unit for multiple stacks, low maintenance, easily retrofit to heat offices/warehouse	Requires plumbing to be run across ceiling, only useful during heating months
#4: Steam-condensate heat exchanger (Appendix E.4)	Single HX unit for multiple stacks, low maintenance, easy retrofit to heat areas, high heat recovery	Requires plumbing to be run across ceiling, only useful during heating months

Concept	**Merit**	**Limitation**
#5: Cooling pond heat exchanger (Appendix E.5)	Simple, low maintenance	Low amounts of energy available for recovery, plumbing travels long distances, pond dredging becomes difficult
#6: Heat exchanger in each stack (Appendix E.6)	Less duct material, no losses associated with separate duct system	Cannot control air flow, a separate HX unit is needed for each stack
#7: Hydraulic motor (Appendix E.7)	Eliminates electric motor loads	Plumbing clutters heat treatment lines, a separate system for each motor is needed
#8: Turbine steam generation (Appendix E.8)	Recovers natural gas loads by significantly displacing electric loads	Expensive, large system

Waste heat recovery systems

Air-air heat exchanger (Appendix E.1)

Merit: The air-air heat exchanger is a relatively simple system capable of routing air heated from flue gas waste heat to heated rooms via ductwork. The system would be low maintenance and only a few centrifugal fans would require significant electricity.

Limitation: Since this system recovers energy through the heating of rooms, it is only effective during the few heating months. A large network of ducts would take up high volumes of space. Also, there is a significant safety risk associated with sending air to an occupied environment with an air-air heat exchanger. A heat exchanger crack would send potentially lethal amounts of carbon monoxide into occupied areas. Therefore, an air quality monitoring system in the ductwork would be required.

Air convection to boiler (Appendix E.2)

Merit: Steam generation running a generator could significantly reduce purchased electric loads. Routing high temperature flue gas to heat a boiler is a simple, low maintenance method of steam generation.

Limitation: The heat recovered from flue gas may be insufficient for producing steam to optimally run a generator. Costs to implement the system will be high. The equipment will most likely take up large amounts of roof space.

Air-condensate heat exchanger (Appendix E.3)

Merit: The air-condensate heat exchanger is a relatively simple system capable of sending air heated from flue gas waste heat to heated rooms via a closed-loop condensate system. An air-condensate heat exchanger is a much better choice than air-air for several reasons. First, there is no risk of air quality issues in the heated areas. Additionally, the plumbing that transports the condensate to furnaces is much less intrusive in comparison to ductwork. The system would be low maintenance and only a few centrifugal fans and pumps would require electricity usage. Limitation: Since this system recovers energy through heating offices, it is only effective during the few heating months during the year.

Condensate loop off steam line (Appendix E.4)

Merit: The steam-condensate heat exchanger is a relatively simple system. The steam-condensate system will produce higher temperature condensate in comparison to the proposed air-condensate system. There is no risk of air quality issues in the heated areas. Plumbing that transports the condensate to furnaces is much less intrusive in comparison to ductwork. The system would be low maintenance and only a few centrifugal fans and pumps would require electricity usage.

Limitation: Since this system recovers energy through heating offices, it is only effective during the few heating months during the year.

Cooling pond heat exchanger (Appendix E.5)

Merit: A heat exchanging system in the cooling ponds is an easy opportunity to recover waste heat from the pond water.

Limitation: The low amounts of heat available for recovery in the pond water limit the opportunities to reuse the recovered heat. Dredging will be made extremely difficult due to pipes running through the pond.

Heat exchanger in each stack (Appendix E.6)

Merit: A heat exchanger in each stack instead of centralized heat exchangers using flue gas from multiple stacks would reduce losses associated with ductwork, while providing the same office heating performance.

Limitation: An individual heat exchanger unit would be required for each exhaust stack causing much higher costs compared to a centralized heat exchanger design. Air flow through the heat exchanger cannot be controlled causing a less than optimal heat transfer. Redesigns to the stack would potentially be needed to assure flue gas is exhausting properly. This could involve widen the stack and may require the implementation of exhaust fans. Since this system recovers energy through heating offices, it is only effective during the few heating months of the year.

Power generation systems

Hydraulic motor (Appendix E.7)

Merit: Hydraulic motors replacing the electric motors that turn furnaces and dryers could be an effective method of reducing purchased electricity usage through recovery of natural gas waste energy.

Limitation: Pipes needed around the heat treatment lines are much more intrusive compared to the electrical wiring that runs electric motors. Each replaced motor would require its own tertiary water loop.

Turbine steam generation (Appendix E.8)

Merit: Steam generation running a generator could significantly reduce purchased electric loads. Running the heated flue gas through a compressor before entering the boiler allows significant amounts of heat to be gained. This results in better steam generation capabilities to run the generator at optimal output.

Limitations: The system requires electricity to run the compressor and pumps. Costs to implement the system will be high. Additionally, the equipment will most likely take up large amounts of roof space.

Pugh chart evaluation

To be certain our selected concept will best suit our customer, all concepts were evaluated using a Pugh Chart (Appendix F). Each concept was checked for a positive or negative correlation against each weighted customer specification. A summation of the positive or negative correlations was used as a method of rating each concept. We allowed energy reduction to have a double positive correlation since we feel that its importance as a customer specification far exceeds that of any other specification. This method determined our turbine steam generation system to best meet our customer requirements.

Concept selection

Using our evaluation of each concept's merits and limitations, as well as our Pugh evaluation, we were able to move ahead with selecting a concept. It is possible and beneficial for some concepts to operate concurrently. The risks associated with the air-air heat exchanger and large amounts of duct work make it inferior to the safer, more compact air-condensate heat exchanger. Air-condensate heat exchanger is an inferior choice compared to a steam-condensate heat exchanger since it has lower levels of available heat recovery. Lower equipment costs make a centralized heat exchanger design more cost effective than installing a heat exchanger in each stack. Hydraulic motors replacing electric could prove to be an effective method of reducing purchased electricity and could be considered in the future, however we feel there will not be enough time to develop such a system. Finally, the turbine steam generation concept with an axial flow fan is a more capable system. We do not see the pond heat exchanger as an effective solution at this time due to the low levels of heat available for recovery. Considering all the aforementioned factors, a combination of a steam powered turbine and steam-condensate heat exchanger system is our best concept.

SELECTED CONCEPT

An early schematic drawing of our final concept is shown in Appendix G. It consists of three major loops: a flue gas loop, a steam loop, and a condensate loop. A majority of the system is likely to be installed on the roof where space should be ample and there is less exposure to oxides.

Flue gas loop

Flue gas from several stacks is redirected into duct that branches off the main stacks and enters a common plenum. It is routed to a compressor, and the compressed gas enters a tank containing a boiler. The gas heats the steam loop and exits through a duct and is exhausted. Damper valves, sensors, and other components will be installed as needed.

Steam loop

A boiler generates steam which is distributed through pipes to turn a turbine. The turbine runs a generator to supply electricity to various foundry electric loads. The steam exits the turbine and enters a condenser to heat condensate. The lower temperature water enters a storage tank and exits to a centrifugal pump which sends it back to the boiler. Check valves, isolation valves, flow meters, pressure gauges, and temperature sensors will be installed as needed.

Condensate loop

Water is heated in a condenser and distributed to various furnaces. The furnaces are used to heat offices and the warehouse as needed. A pump returns the cool water to the condenser. Temperature sensors, valves, flow meters, and pressure gauges will be installed as needed.

ENGINEERING ANALYSIS

There are four critical areas of the design that need to be considered: the generator power output, the heat recovery steam generator, the condenser, and the pumps and blower. The amount of power that can be extracted determines the sizes and capacities of all the other components. There will also be additional losses to components such as the pumps and blower.

Generator power output

The first step of the engineering analysis is to determine approximately how much energy we can expect to extract from the system. Our initial analysis is based simply on the steady flow energy equation $(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_e - h_i$, where q is the heat energy, w is the work, and h is the enthalpy. We are assuming the flue gas to have to properties of air and Δq and w_{in} to be 0. Combined with property tables for water, steam, and air, it is possible to determine the approximate power output of the system.

Our engineering specifications had a 10% energy recovery, which works out to 15 MMBTU/hr. For now, an ideal Rankine cycle will be used for the steam loop. The steam input was assumed to be at saturation temperature at 116 psi so the steam is at approximately 338 °F, which is nearly as hot as it can get from the flue gas. Its enthalpy is 1190 BTU/lb, and its entropy is 1.591 BTU/(lbs · R). If the turbine backpressure, is 7.25 psi, then the outlet enthalpy (assuming constant entropy), is 995.3 BTU/lb. This is a difference of 194.8 BTU/lb. To get 15 MMBTU/hr would require 19.46 lbs/s of steam. Converting water to steam starting at atmospheric pressure and at the saturation temperature requires 1010 BTU/lb of energy, so producing enough steam would require 70.73 MMBTU/hr. If the air is cooled from 392 °F to 212 °F, it releases 43.73 BTU/lb of energy. Therefore, it would take 449.3 lbs/s of air to produce the steam. Using an air density of 0.04596 lbs/ft^3, this works out to 9775 ft^3/s, or 586,590 CFM, which is much more than is available, and does not take into consideration the inefficiencies of the turbine and generator.

Even with the many approximations made with the calculations, it is clear that achieving this 15 MMBTU/hr of power output is not feasible. Going through the same set calculations, under more realistic operating conditions, but starting with 30,000 CFM of flue gas and working towards power output, we arrived at a power output of 1.7 MMBTU/hr. At this power output, however, the system would not be cost effective.

It is clear that another source of energy is needed to make an effective design. The solution is to use the air directly above the furnaces to superheat the steam. This air is at a much higher temperature than the flue gas coming out of the stacks, so it would be an effective way to increase the temperature and pressure of the steam. Another set of calculations was done, starting with another approach. This time, a performance estimation calculator from a turbine manufacturer was used. This tool accounted for several losses that were not considered in the previous calculations, which worked out to about a 60% efficiency for the turbine and generator. It was determined that with inlet conditions of 870 psi and 660 °F, an exhaust pressure of 0.725 psi, and a mass flow rate of 3.062 lbs/s, a power output 3.22 MMBTU/hr could be achieved. Because the flue gas would only need to boil the water, which takes the majority of the energy, the heat recovery steam generator would only need to extract 970.1 BTU/lb from the flue gas. At 3.062 lbs/s of steam, this is 10.69 MMBTU/hr of energy to extract from the air. This could be done with 43,650 CFM, which is a reasonable value for the system. The superheating process would require 1.746 MMBTU/hr of energy, which is also achievable.

Heat recovery steam generator

The next step was to determine the size of the heat recovery steam generator. This was treated as a heat exchanger design problem, which can be solved using the Effectiveness-NTU method. In this case, the equation takes the form $\frac{1}{UA} = -\ln\left(1 - \frac{q}{q_{max}}\right)$, where U is the heat transfer coefficient, A is the surface area, and q is the heat transfer rate. This equation applies to the case where one of the fluids is undergoing a phase change.

Additional calculations were needed to determine U and q. U is simply the total thermal resistance, which is determined by material properties and the fluid flow around it. The heat transfer rate is the product of the mass flow rate, the specific heat, and the temperature difference, or $q = \dot{m}c_p\Delta T$. It was determined that the heat transfer coefficient was 9.710 BTU/(hr · ft^2 · R). The required q is 10.69 MMBTU/hr and q_{max} is 30.26 MMBTU/hr. The area required would be 7007 ft^2 of a staggered finned tube assembly. This could be achieved with 378 tubes 12 ft long.

Condenser

The condenser was sized in the same manner as the heat recovery steam generator, only using different values for U and q. In this case, the heat transfer coefficient is 872.3 BTU/(hr · ft^2 · R), the heat transfer rate is 8.503 MMBTU/hr, and the maximum heat transfer rate is 12.19 MMBTU/hr. The result is 1160 ft^2 of surface area. The required flow rate is 227.2 CFM of condensate. The system was designed to have two condensers, with different systems being used depending on the heating requirements of the building, so each condenser system needs to be capable of providing all of the cooling. As a result, both condensers will be the same. During the heating season, this will provide a savings of 7.8 MMBTU/hr, which will offset a significant amount of natural gas load used to heat offices and the warehouse.

Pumps and blower capacity

With all of the major components sized, it is possible to determine the pressure drop across them and therefore what the capacities of the pumps and blower. For the blower, we calculated the pressure drop across the heat recovery steam generator. The other parts of the flue gas loop were neglected since there is a minimal amount of ducts used. The equation is

$$\Delta p = \frac{(\rho V)^2 v_i}{2}\left[\left(1 + \left(\frac{A_{\text{ff}}}{A}\right)^2\right) \cdot \left(\frac{v_o}{v_i} - 1\right) + f\frac{A}{A_{\text{ff}}}\frac{v_m}{v_i}\right],$$

where ρ is the fluid density, V is the maximum velocity, v is the specific volume, A_{ff} is the free-flow area, A is the total area, and f is the friction factor. Using the values for the steam generator calculated earlier, the pressure drop is 0.1 psi.

The boiler feed pump and condensate pumps are calculated with the equation for pressure drop in a pipe, which is $\Delta p = f\frac{l}{D}\frac{\rho V^2}{2} + \rho g(\Delta h)$. In this equation, f is the friction factor, l is the density, D is the pipe diameter, ρ is the fluid density, V is the velocity, g is the gravitational constant, and h is the change in height. Using this equation, we calculated a 1.13 psi drop in moving the water from the boiler feed pump to the steam generator and a 120 psi drop in the condenser tubes. The condenser centrifugal pump will also have to overcome the line losses in moving the condensate to the cooling tower or furnaces, which will be dependent on the positioning which is not known at this time. However, it should be relatively small compared to the pressure drop in the condenser.

Power losses

Of course, all these gains suffer losses due to electricity used by our exhauster, pumps, and the cooling tower fan. Looking at equipment in the ballpark of our needed performance, we predict these loads could reduce our recovered energy by 15%. However, we feel that the overall energy reduction justifies these losses.

FINAL DESIGN

The final design is shown in a schematic in Appendix H and a possible equipment layout is shown in Appendix I. The layout is only semi to scale, meaning all equipment is in the area of actual proportion to the roof, however, since we are not dealing with tight tolerances, it was not necessary to take care to present a perfectly dimensioned layout.

Alterations to selected concept

Several changes were necessary in bringing our selected concept to the point of final design. We learned that the proper nomenclature for a boiler that is fueled by flue gas is a heat recovery steam generator (HRSG). We also decided to reroute the newly generated steam directly over the heat treatment line for superheating. Since the temperature of the air directly above the furnaces is 400°F warmer than the flue gas temperature, routing the steam through highly conductive plumbing over the furnaces brings a higher temperature steam flowing into the turbine. Another necessary alteration is the inclusion of a cooling tower. A cooling tower loop will reject the residual heat from the steam loop to allow the Rankine cycle completion. During months when the offices and warehouse do not need to be heated, the original condensate loop will be bypassed and the cooling tower will have to make up for lost heat rejection. The cooling tower will increase electrical loads in the forms of fan and pump motors. Both condensate systems will require water treatment to prevent pipe freezing during shutdown periods. Another small change to the final design also includes an industrial blower to achieve desired flow into the HRSG because no air compressor is capable of dealing with such large volumes of air. We also determined the proper pump for the steam system is a boiler feed pump. Boiler feed pumps are multistage and ideal for the low flows associated with our system.

Bill of materials

All system components and other miscellaneous materials needed for purchase are shown below in Table 2, our bill of materials. We also list manufacturers that were highly regarded during a consultation with a UofM plant engineer. All manufacturers produce models that are capable of being custom tailored to fit the requirements of our system. We will leave specifics regarding sensors, gauges, controls, ductwork, plumbing, valves, and insulation to be determined by the party implementing the actual design.

Table 2: Bill of Materials

Component	Manufacturer	Model	Estimated Cost
Flue gas loop			
Industrial exhauster	Hartzell	Series 3 Size 49 A03-9-49	$4,200
Heat recovery steam generator	Foster Wheeler	Custom tailored	$60,000

Component	**Manufacturer**	**Model**	**Estimated Cost**
Steam loop			
Steam turbine & generator	Dresser-Rand	Custom tailored	$200,000
Boiler feed pump	Sterling	503200-JF	$3,000
Office heating condensate loop			
Centrifugal pump	Bell & Gossett	HSCS-8x12x22M	$8,900
Condenser (shell & tube HX)	ITT Standard	S1000R	$2,350
Cooling tower condensate loop			
Centrifugal pump	Bell & Gossett	HSCS-8x12x22M	$8,900
Cooling tower	Baltimore Air Coil	Custom tailored	$60,000
Condenser (shell & tube HX)	ITT Standard	S1000R	$2350
Miscellaneous			
Insulated ductwork	TBD	Custom tailored	$3,500
Plumbing	TBD	Custom tailored	$32,000
Valves	TBD	Custom tailored	$500
Temperature gauges & sensors	TBD	Custom tailored	$300
Pressure gauges & sensors	TBD	Custom tailored	$200
Flow meters	TBD	Custom tailored	$250

Budget savings

Our year round electrical savings of 3.22 MMBTU/hr translates to a cost reduction of $120,000 per year. This was determined assuming an electricity cost of $0.03/kWh and the generator providing electricity for 5000 hr/year. Our natural gas savings of 7.8 MMBTU/hr translates to a cost reduction of $93,000 per year. This was determines assuming a fixed natural gas cost of $9.15/MMBTU and the office heating operating only during around 3 months of the year (1300 hours).

Since we expect a combined yearly savings of $210,000 and assuming we are looking for a five year payback, multiplying our yearly savings by five gives us a budget for implementation of $1,050,000. This is far below our initial implementation cost target of $1.7 million. We will from now on assume $1,050,000 to be our new target implementation cost, and we have adjusted all other costs by the same factor. These new target values are shown below in Table 3.

Budget expenditures

In order to determine cost information, we mainly used the RSMeans Mechanical Cost Data 2007 Edition book. We found the price of the system components listed individually in Table 2 (above). We then found estimates of the installation and maintenance costs, listed in Table 3 below. These costs were estimated by finding components of similar performances and sizes in the cost data book and rounding up values whenever possible to cushion any error. In total, we estimate component pricing to be $390,000, 40% less than our target value of $645,000. We estimate installation cost to be $47,000, the target value, 87% less than our target value of $350,000. Our estimated maintenance cost is $820/month, which is 12% under our target value of $930/month. Our estimated total implementation cost over five years comes out to $494,000 which is 53% lower than our estimate of $1,050,000. This will result in just under a three year payback.

Table 3: Summary of Yearly Savings and Costs

Savings	Target value	Estimated value
Electric	-	$120,000
Natural gas	-	$ 38,000
Net savings	-	$158,000
Cost		
Component	$645,000	$390,000
Installation	$350,000	$ 56,000
Maintenance	$930/month	$820/month
Total implementation*	$1,050,000	$494,000

*based on a five year payback

Prototype

We do not plan to manufacture a functional prototype of our system. The large number of high complexity components causes delivery of a functional system in the allotted time to be impossible and impractical. Our sponsor is requesting our delivery of a capable design with drawings and values. A contractor capable of performing a final design will bring our system to fruition if our sponsor decides to move forward in implementation. Our Expo presentation will rely on a schematics, figures, simulations, and analysis data.

MANUFACTURING AND TESTING PLAN

The primary design goal was to determine what components are necessary for the selected concept. Thus, a significant amount of engineering analysis was required to determine what the operating conditions and requirements are for each component. It was necessary to verify the calculations with a prototype. A scale physical prototype would be nearly impossible to construct and provide no usable data. Even with dimensional analysis, the large difference in size would alter the fluid dynamics too significantly to extract information on the full-scale product.

To perform testing, the system was modeled in SolidWorks® with analysis done using COSMOSFloWorks™ software. This approach had several technical limitations. For example, it was not possible to run the entire system in a single analysis. Instead, it was split into many small sections. It was also impossible to model the turbine due to the complexity. Likewise, without information on the inner-workings of the pumps, they were also impossible to model. In these cases, it was necessary to use the manufacturer's data. By simply entering the known boundary conditions, the software was used to simulate the fluid and thermal dynamics of the system.

Still pictures of the results can be found in Appendix J. The analysis of the flue gas showed that the design draws air evenly from all of the exhaust stacks, as expected. From the heat recovery steam generator analysis, shown in Appendix J.2, we discovered that the flue gas flow was not evenly distributed along the length of the HRSG. This means that additional flow mixing is required inside the HRSG, which will also increase the pressure drop slightly. Additionally, because the fine details of the heat exchanger surface could not be modeled, this simulation cannot accurately show heat transfer rates. The analysis of the superheater system, seen in Appendix J.3, proved that while the design does heat the steam and increase the pressure as expected, additional development is needed to ensure that the steam flow is distributed evenly between the coils. Finally, our model of the condenser, seen in Appendix J.4, showed that this system also performed as expected, with pressure drop values in line with the calculated values.

PROJECT PLAN

The design process involved constant communication of the design group with the sponsor and regular group meetings. A chart detailing our plan can be viewed in Appendix K. Four design reviews and a final Design Expo are considered milestones where most preceding tasks are performed with the overarching goal of completing the design review and progressing toward producing the sponsor company's deliverables.

Completed tasks

We surveyed the foundry's energy waste and researched relevant energy recovery systems. We used this information to develop some rough ideas of systems that could be effective for energy recovery. During a meeting with the foundry's plant manager, plant engineer, and office services manager, we discussed our ideas and gained approval to move forward with conceptual design. We developed our concepts, evaluated them, and selected a final concept. Then, we consulted University of Michigan plant engineers to get a wide range of useful advice regarding the needed components, calculations, literature, and recommended manufacturers. We performed analysis to determine the capabilities and performance of our system. In the final phase of this project, we made last minute design improvements, performed tasks associated with the final Design Review and the Design Expo. We ran a computer simulation of various aspects of our system to verify the validity of our design, reported our deliverables to the sponsor and presented at the Design Expo.

Future improvement

Unfortunately, it is highly unlikely that our early design could be directly implemented at this point. Our payback of less than three years seems to be on the optimistic side for a system of this size. It is likely that our lack of expertise in industrial system design has caused errors in our system design. Therefore, steps should be taken adapt our current design into an efficiently operating system. A more experienced contractor would be able to use their field experience to use more proven engineering analysis, and component selection methods. They will be able to call out anything details that we overlooked. Also, it will be necessary to analyze the foundry vicinity to design the optimal equipment layout. The goal of this optimization would be to find a balance between the least intrusive design and the one requiring the least amount of ductwork and piping, thus reducing cost. After the contractor makes needed changes, if the system performs at a level that meets our sponsor's approval, it will be implemented.

CONCLUSIONS

We have successfully designed a method of reusing waste energy to reduce energy costs in our sponsor's foundry. Our design attempts to optimize energy gain, minimizes space usage, and is relatively easy to maintain. Discussions with the sponsor and research on relevant systems allowed us to develop several concepts that recover energy from flue gas. We evaluated the concepts, and selected a steam powered turbine and steam-condensate heat exchanger system that reuses energy for electrical loads and heating occupied spaces. We designed a system that is potentially capable of reducing electric loads by 3.22 MMBTU/hr year round and 7.8 MMBTU/hr more during the heating season. Assuming 2007 fuel costs, this translates to annual cost savings of $210,000 a year, which will fully pay for the system in less than three years. Our sponsor must now take our findings to an expert industrial system contractor to use their expertise to correct our errors and proceed to fully designing our system.

ACKNOWLEDGEMENTS

We first would like to thank Dr. Katsuo Kurabayashi for his feedback and guidance. Thanks are also in order to Dr. Kazuhiro Saitou, Dr. Bogdan Epureanu, Dr. Yoram Koren, Dr. Jwo Pan, and Mr. Mohammed Shalaby. We would also like to acknowledge our sponsor’s office services manager, plant engineer, and foundry manager for their efforts to aid in our in the progress of our design.

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BIOS

Maryam Amr

Maryam graduated from Cairo American College in Egypt in 2004. Before living in Cairo for eight years, she spent time in Milan, Italy and was raised mostly in Syracuse, New York. Four months before graduation from high school, Maryam had applied to and been accepted by Columbia University’s journalism program. Although always interested in mathematics, it took one semester of high school physics to convince her to pursue a degree in mechanical engineering—a drastic career shift. This December, she hopes to graduate with a mechanical engineering BSE and to continue on for a Masters degree. Her previous internship experience includes a summer with Whirlpool Corporation as a project manager and time with BMW as a process engineer. Upon graduation, she hopes to work for an

American company with training abroad. Among her many interests are Model United Nations, learning languages, and travel.

Charles Eichhorst

Charles grew up in Grand Rapids, Michigan. From a young age, he wanted to be an engineer with the encouragement of his grandfather, who graduated from the University of Michigan with a degree in mechanical engineering in the 1950's. At the time, he wanted to know how everything worked and learned by taking apart anything he could. However, putting it back together was usually an afterthought, making it a rather expensive way to learn. He is now in his last year at UofM where he splits his time between classes and working as mechanical engineering director for the solar car team here. After graduating with a BSE in mechanical engineering, he wants to pursue a career in the automotive field and possibly returning for a Masters degree someday.

John Gilmore

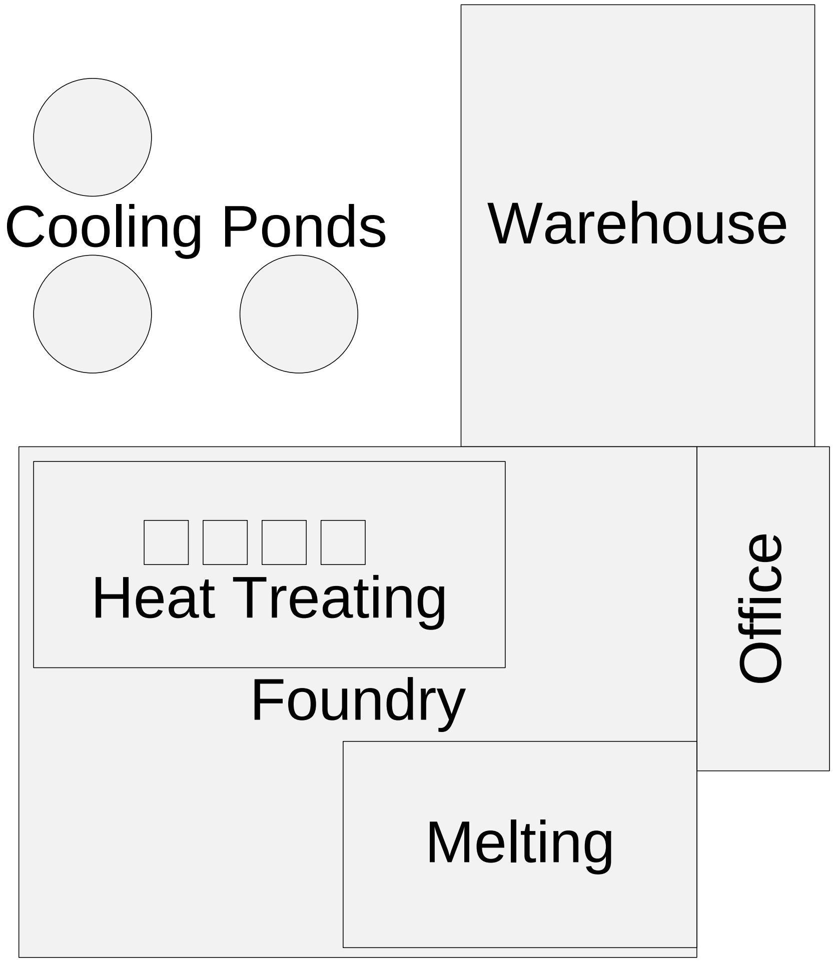
John grew up in Detroit, Michigan on a steady diet of Transformers, Voltron, and old Godzilla movies as a child – which goes a long way to explaining the way he is now. His interest in engineering goes all the way back to the age of five, when he became curious about how things work and he officially chose the career of astronaut for the future. Currently, he is in his final semester at the University of Michigan and looking forward to graduation and the pursuit of a career in an interesting field.

Eric Romain

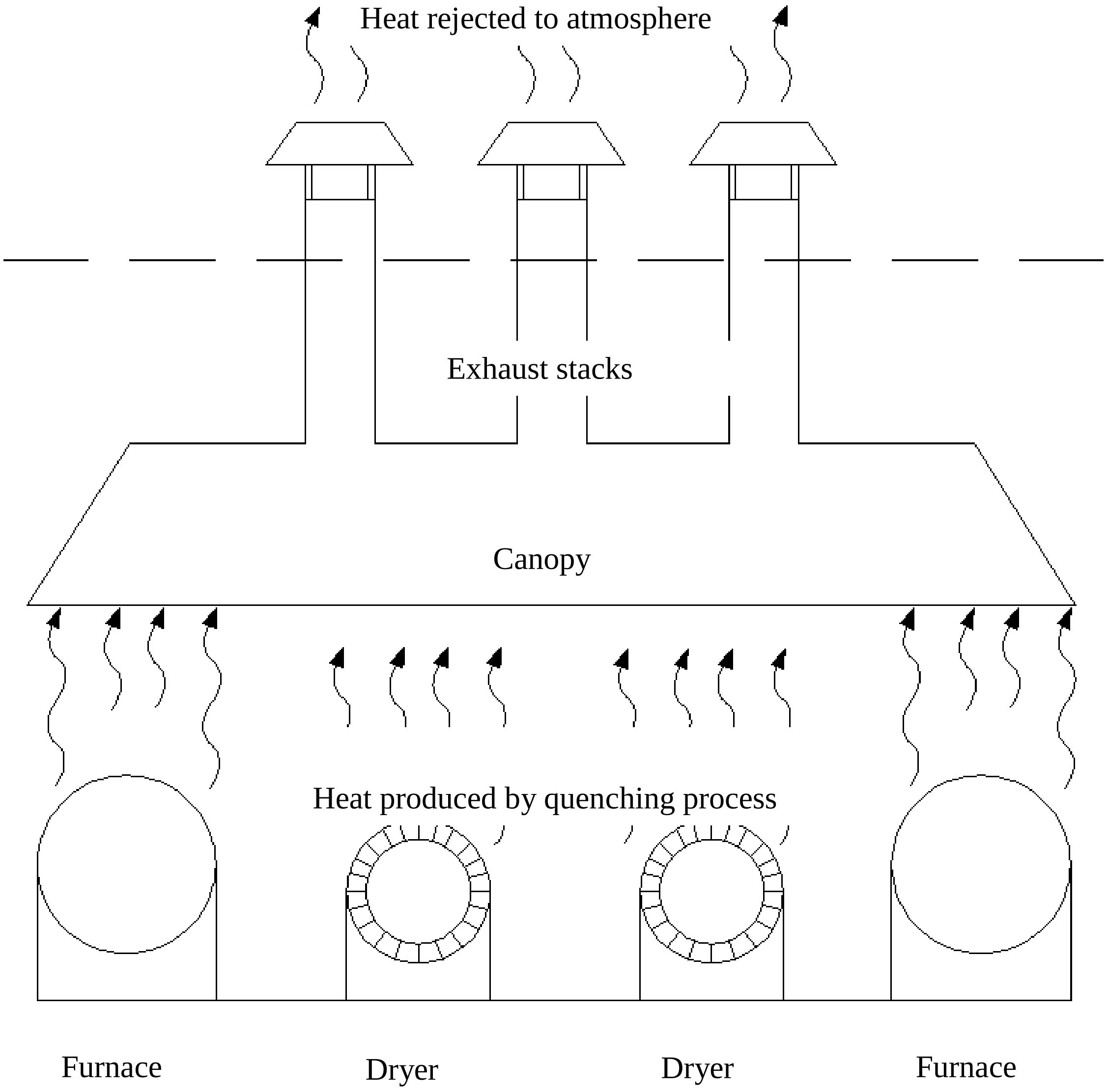
Eric grew up in Saginaw, Michigan graduating from Heritage High School in 2003. He has always had an interest in technology and automobiles that lead him to pursue mechanical engineering. He has over a year experience interning in the University of Michigan Plant Engineering & Energy Management Department working in the field of HVAC engineering and on various energy conservation measures. He is currently finishing his final semester as a mechanical engineering BSE student at UofM. After graduating, Eric hopes to work in state, but is open to any location. He is interested in a number of diverse fields and eventually plans to pursue his MBA. He has played ice hockey for 14 years and enjoys running.

APPENDICES

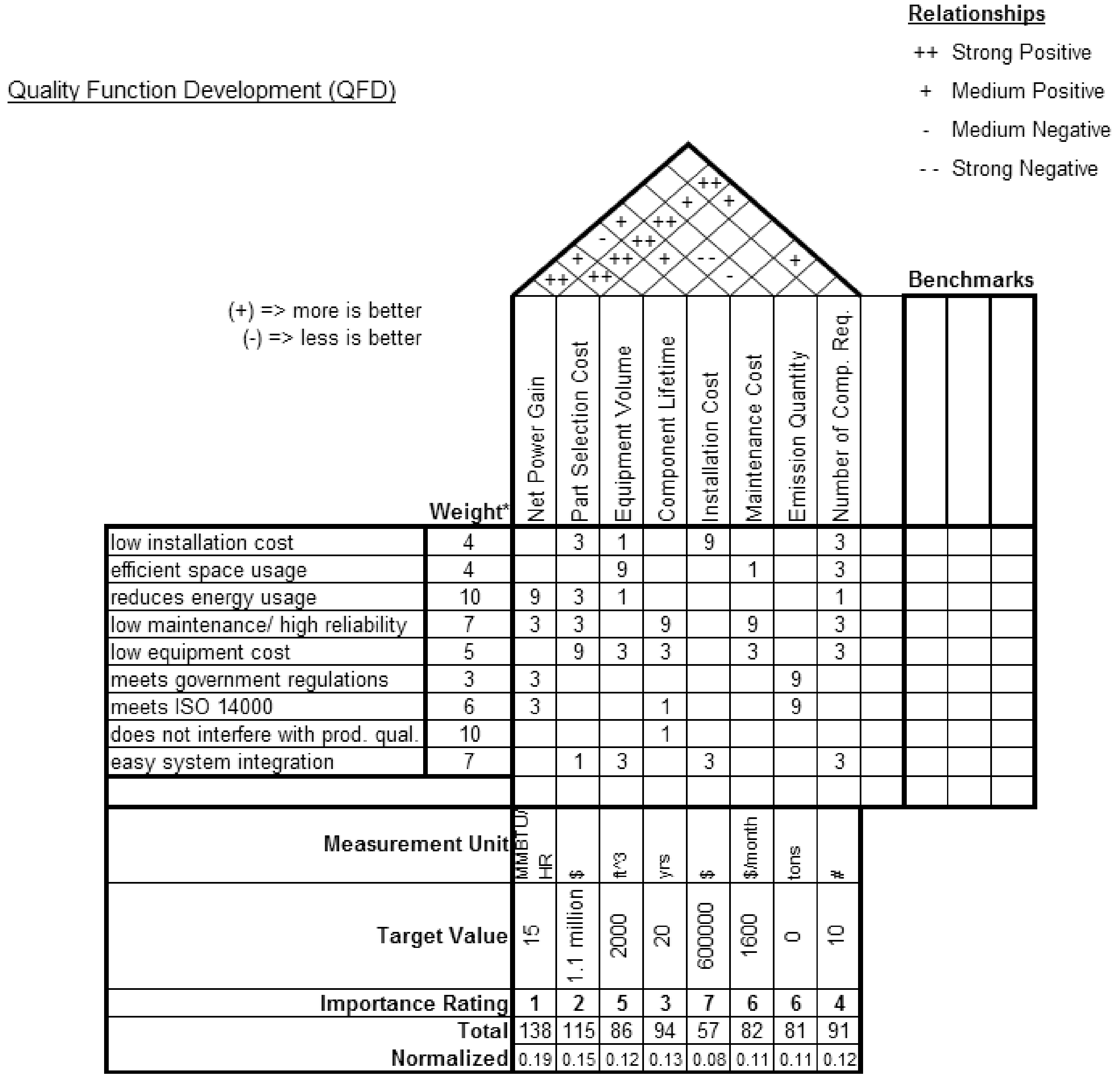
Appendix A: Foundry Facility Floor Layout (not to scale)



Appendix B: Heat Treating Process Heat Flow Diagram (not to scale)



Appendix C: Quality Function Deployment Diagram (QFD)



Quality Function Development (QFD)

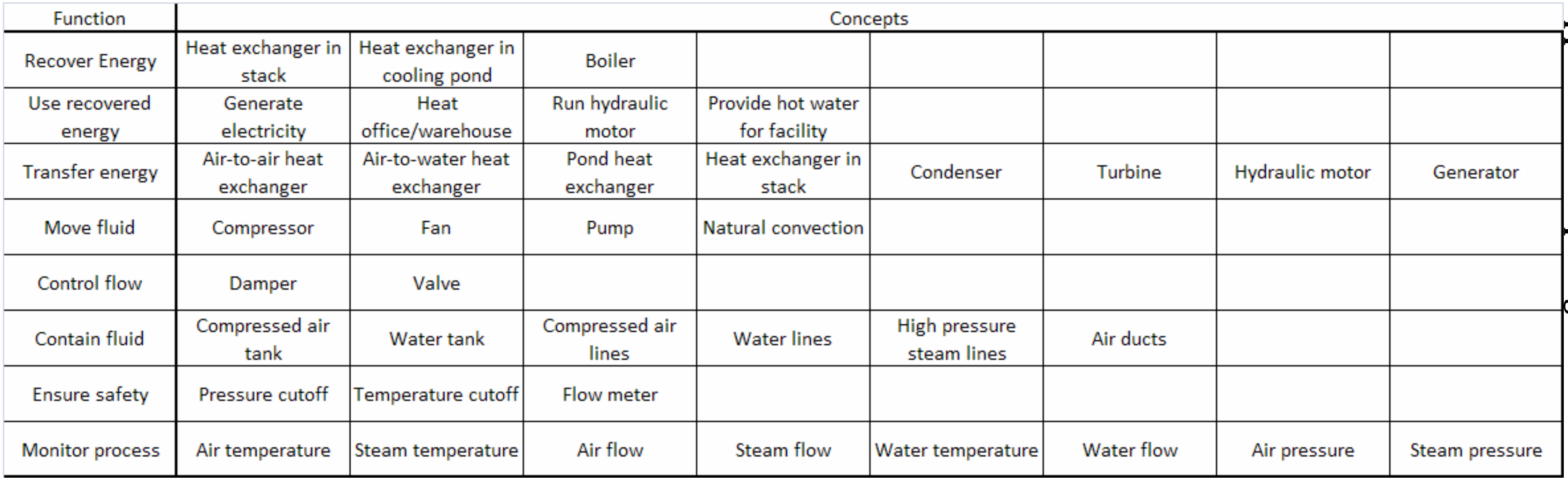
Relationships

++ Strong Positive
+ Medium Positive
- Medium Negative
- - Strong Negative

(+) => more is better
(-) => less is better

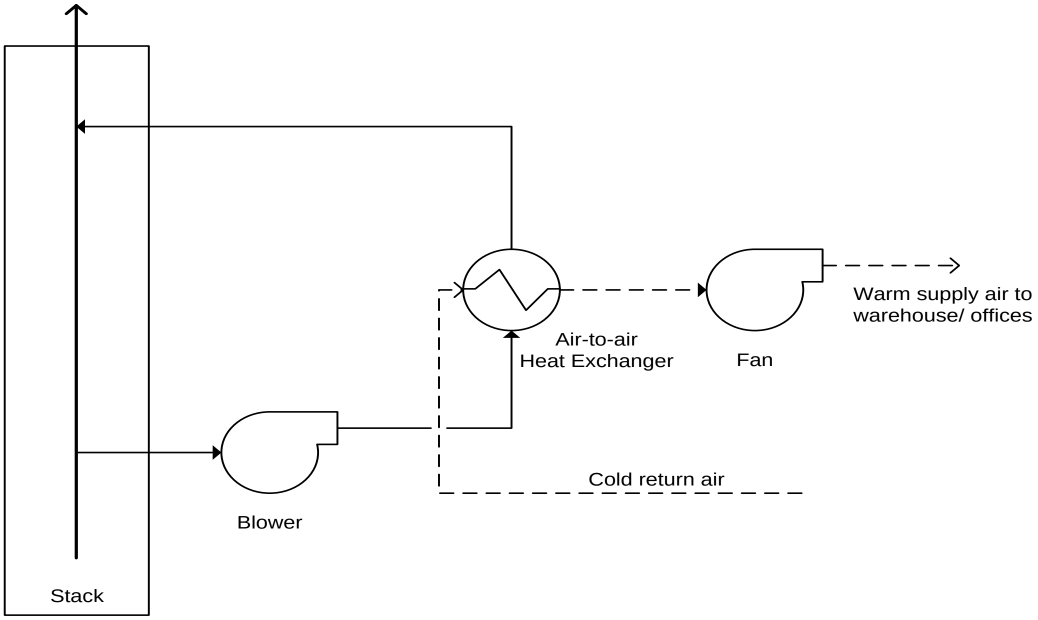
	Weight*	Net Power Gain	Part Selection Cost	Equipment Volume	Component Lifetime	Installation Cost	Maintenance Cost	Emission Quantity	Number of Comp. Req.		Benchmarks		
low installation cost	4		3	1		9			3				
efficient space usage	4			9			1		3				
reduces energy usage	10	9	3	1					1				
low maintenance/ high reliability	7	3	3		9		9		3				
low equipment cost	5		9	3	3		3		3				
meets government regulations	3	3						9					
meets ISO 14000	6	3			1			9					
does not interfere with prod. qual.	10				1								
easy system integration	7		1	3		3			3				
Measurement Unit		MMBTU/ HR	$	ft^3	yrs	$	$/month	tons	#				
Target Value		15	1.1 million	2000	20	600000	1600	0	10				
Importance Rating		**1**	**2**	**5**	**3**	**7**	**6**	**6**	**4**				
Total		138	115	86	94	57	82	81	91				
Normalized		0.19	0.15	0.12	0.13	0.08	0.11	0.11	0.12				

Appendix D: Morphological Chart

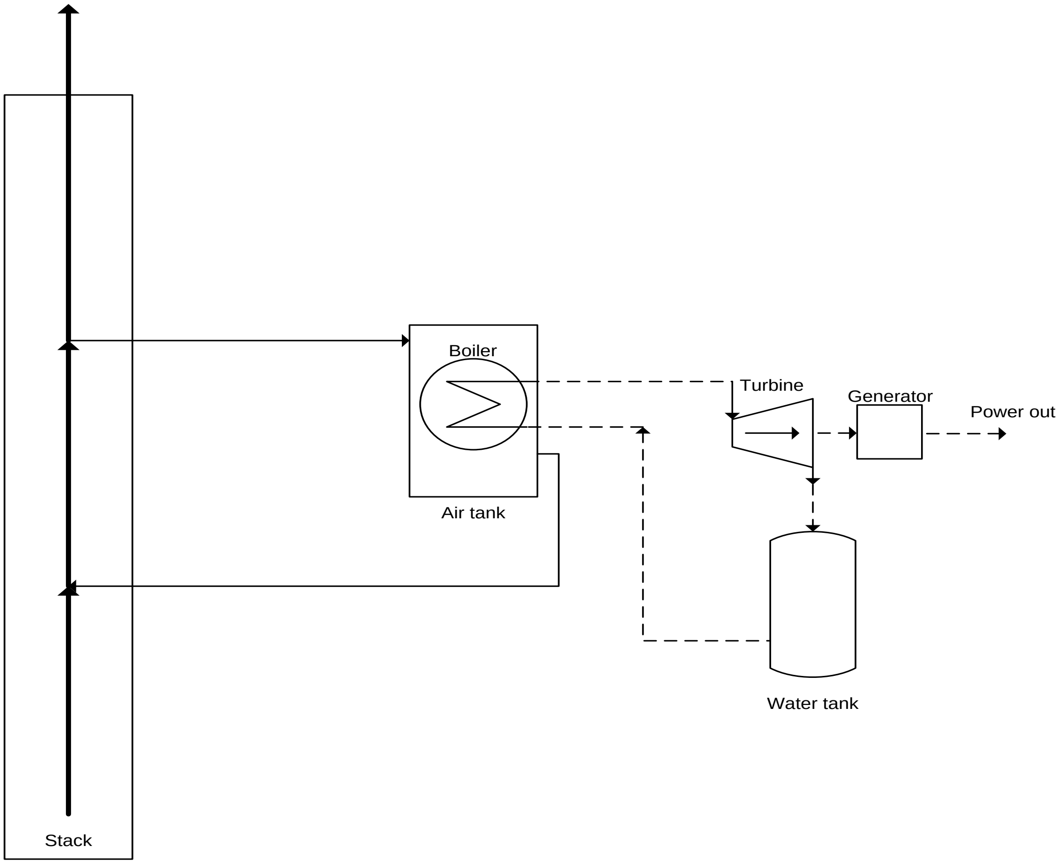


Function	Concepts							
Recover Energy	Heat exchanger in stack	Heat exchanger in cooling pond	Boiler					
Use recovered energy	Generate electricity	Heat office/warehouse	Run hydraulic motor	Provide hot water for facility				
Transfer energy	Air-to-air heat exchanger	Air-to-water heat exchanger	Pond heat exchanger	Heat exchanger in stack	Condenser	Turbine	Hydraulic motor	Generator
Move fluid	Compressor	Fan	Pump	Natural convection				
Control flow	Damper	Valve						
Contain fluid	Compressed air tank	Water tank	Compressed air lines	Water lines	High pressure steam lines	Air ducts		
Ensure safety	Pressure cutoff	Temperature cutoff	Flow meter					
Monitor process	Air temperature	Steam temperature	Air flow	Steam flow	Water temperature	Water flow	Air pressure	Steam pressure

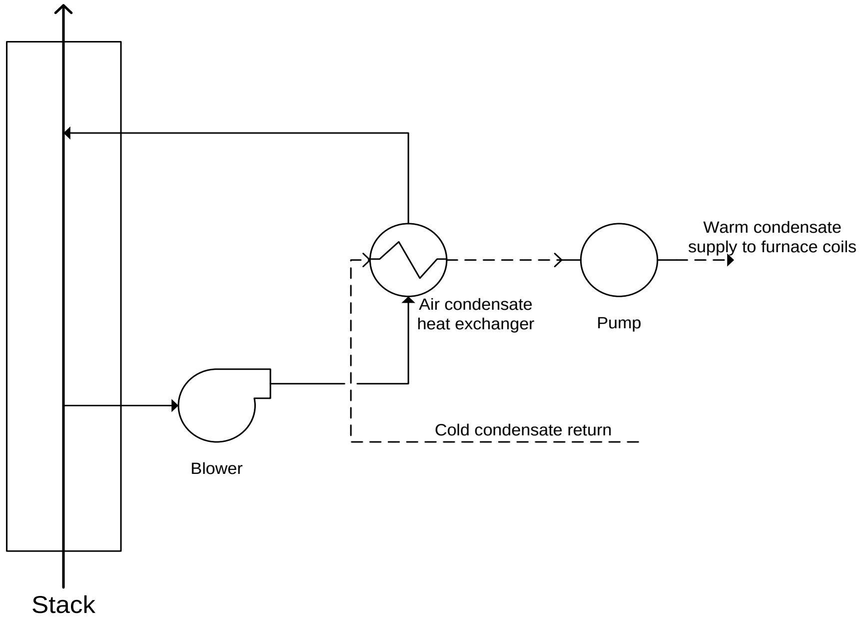
Appendix E.1: Concept 1: Air to Air Heat Exchanger



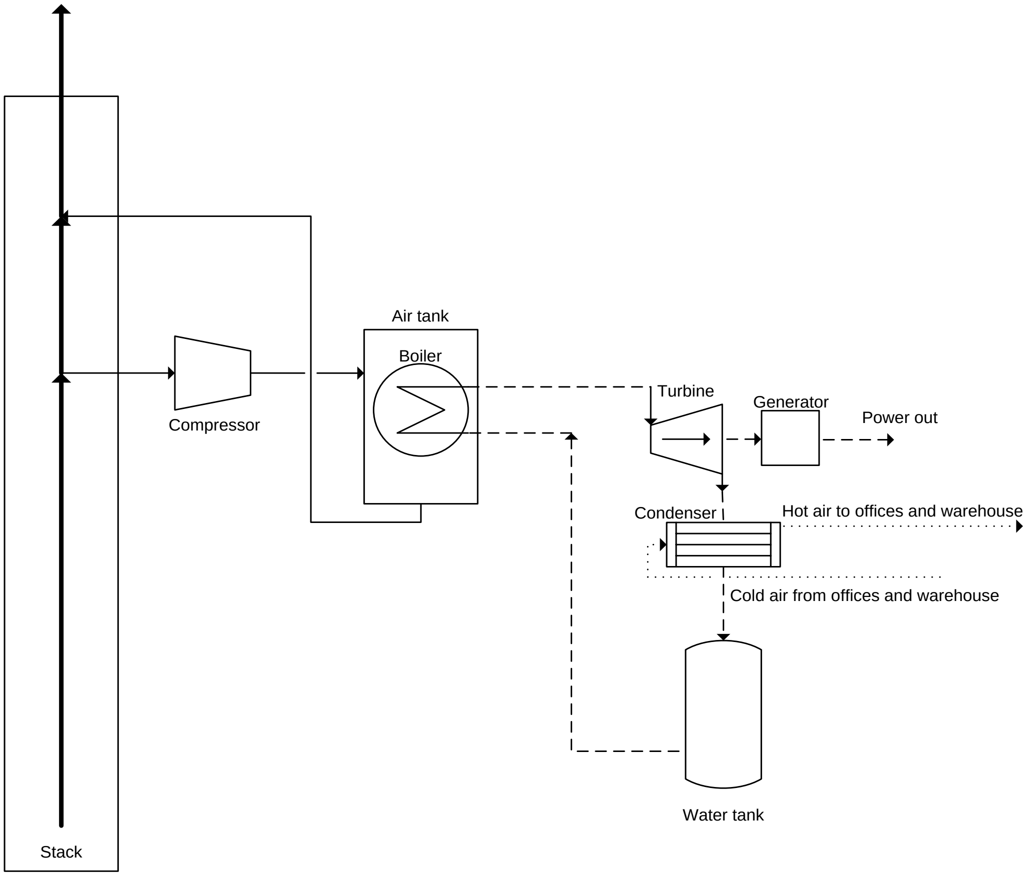
Appendix E.2: Concept 2: Air Convection - Steam Generation



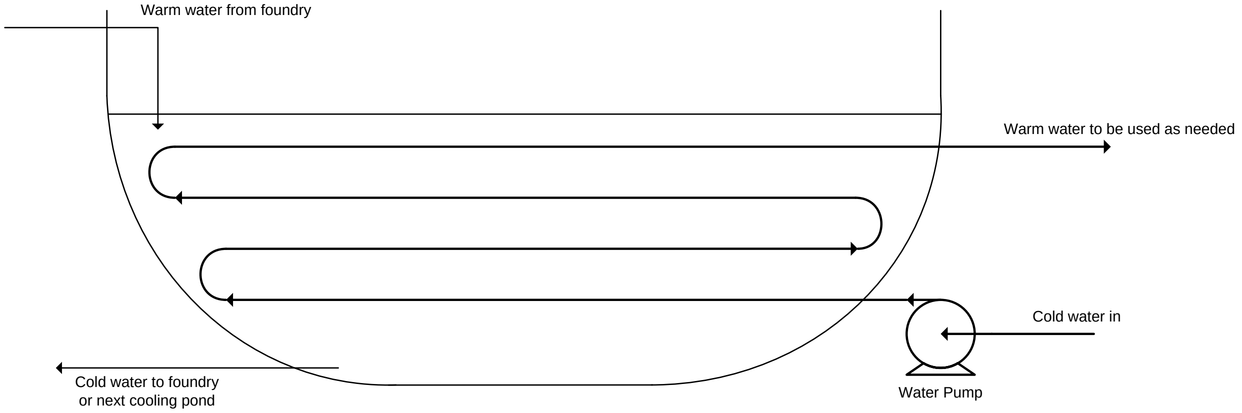
Appendix E.3: Concept 3: Air to Condensate HX



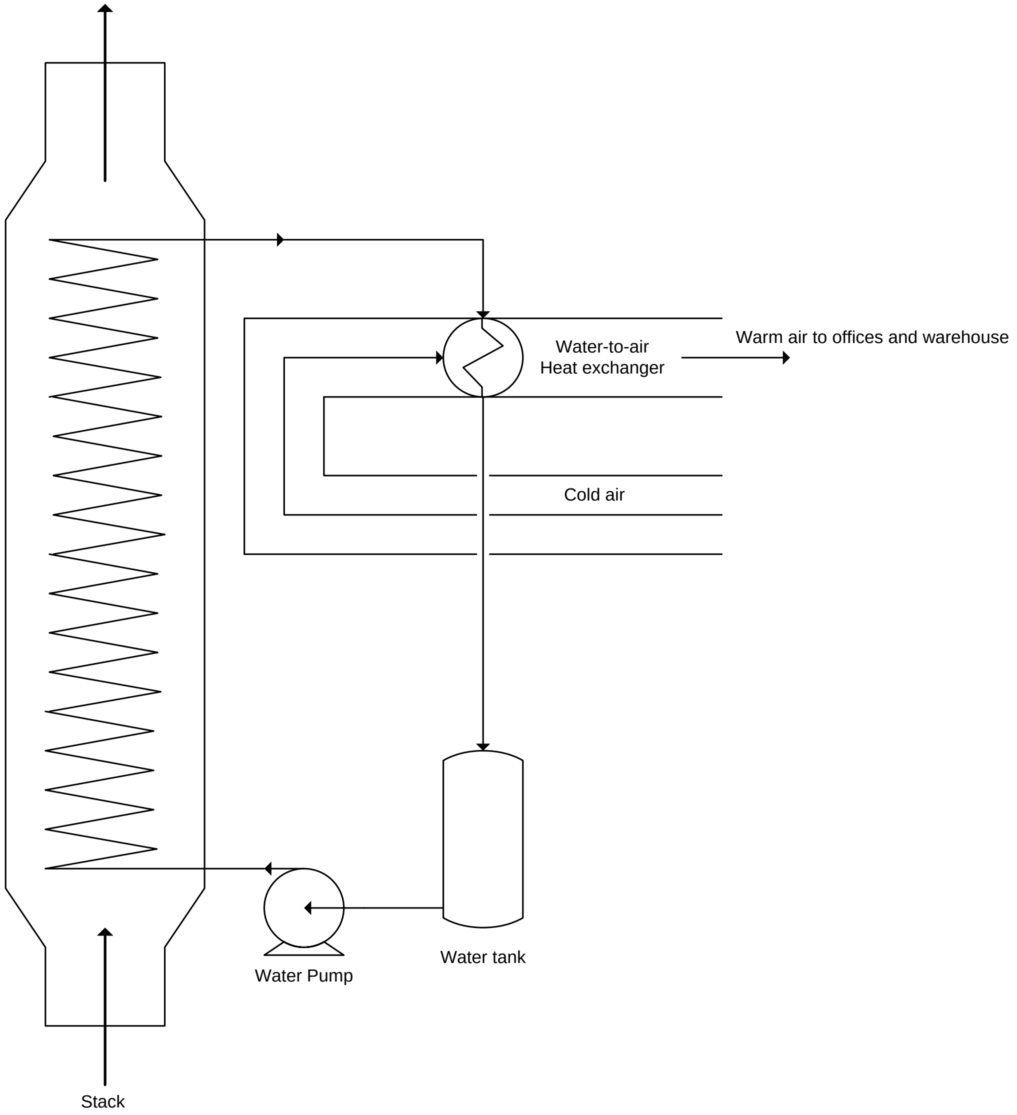
Appendix E.4: Concept 4 - Condenser Loop off Steam Line



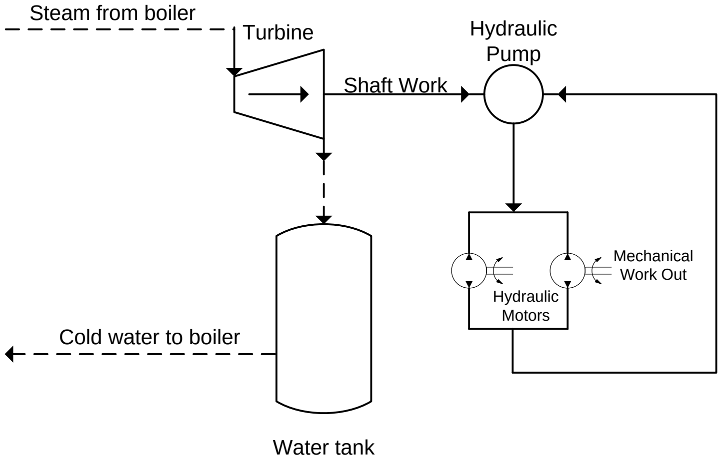
Appendix E.5: Concept 5: Cooling Pond HX



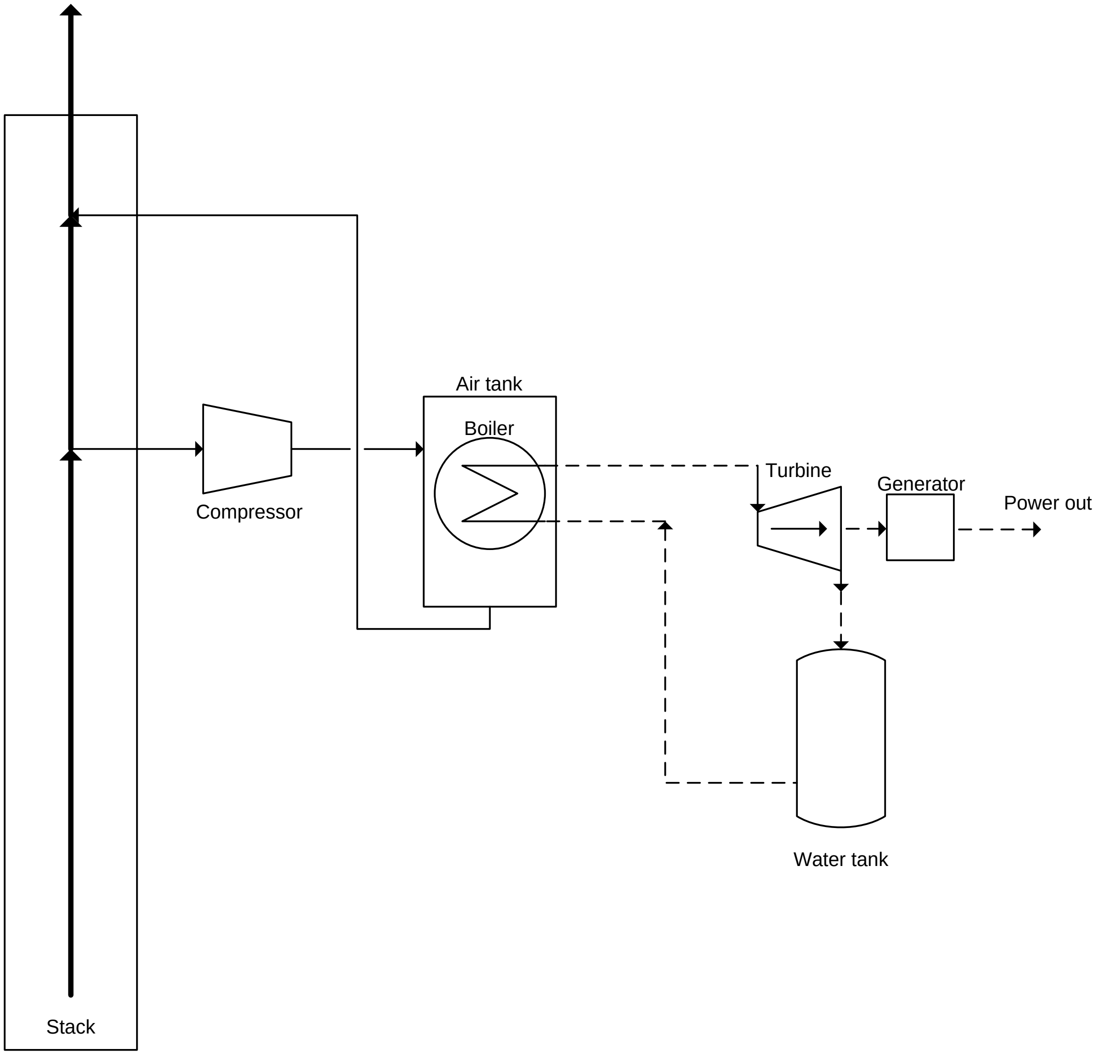
Appendix E.6: Concept 6: Heat Exchanger in Stack



Appendix E.7: Concept 7: Hydraulic Motor



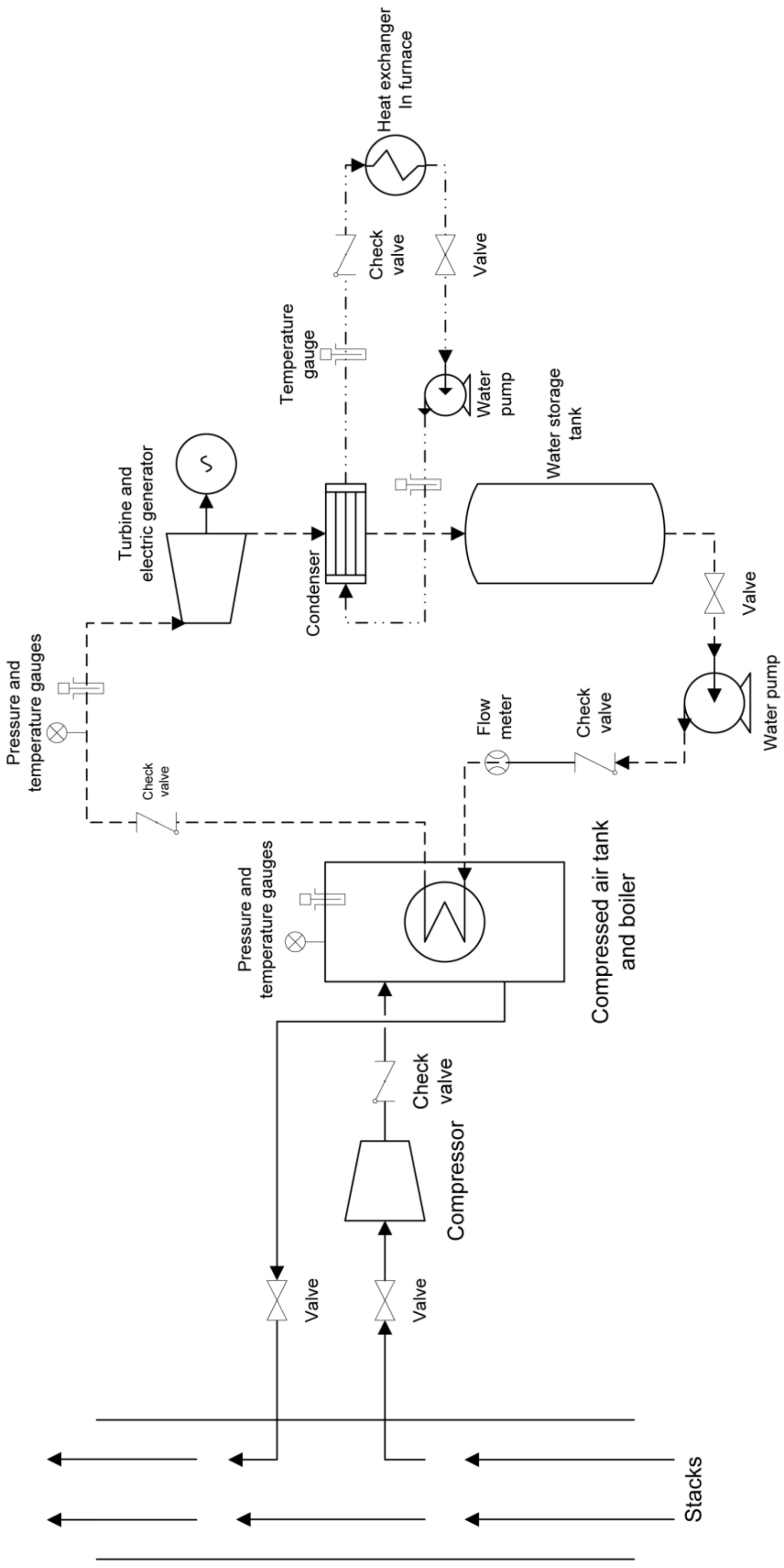
Appendix E.8: Concept 8: Steam Generation - Turbine



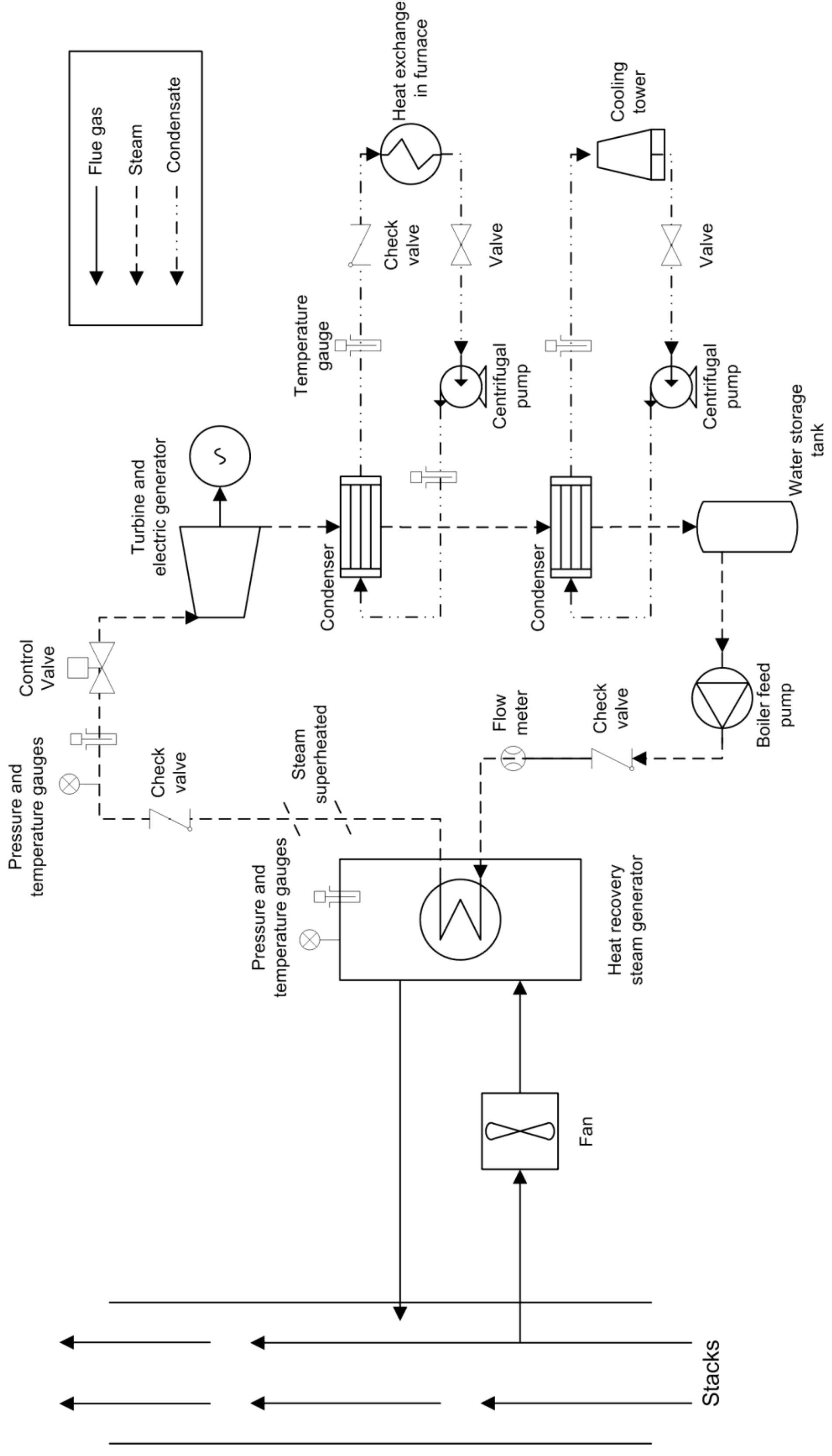
Appendix F: Pugh Chart

	Weight	Concept 1: Air-air HX	Concept 2: Air convection - steam generation	Concept 3: Air to condensate HX	Concept 4 - Condenser loop off steam line	Concept 5: Cooling pond HX	Concept 6: HX in stack	Concept 7: Hydraulic motor	**Concept 8: Steam generation - turbine**
low installation cost	4	+	+	+	+	+	+	+	+
efficient space usage	4	+	+	+	+	+	+	+	+
reduces energy usage	10		-		++	-		+	++
low maintenance/ high reliability	7	+	+	+	+	+	+		+
low equipment cost	5	+	+	+	+	+	+		
meets government regulations	3	-	+	+	+	+	+	+	+
meets ISO 14000	6	+	+	+	+	+	+	+	+
does not interfere with prod. qual.	10	+	+	+	+	+	+	+	+
easy system integration	7	+	+	+	+	+	+	+	+
	Σ+	4.3	4.6	4.6	5.8	4.6	4.6	4.4	6.1
	Σ−	0.3	1	0	0	1	0	0	0
	Σ	4	3.6	4.6	5.8	3.6	4.6	4.4	6.1
	Rank	5	6	3	2	6	3	4	**1**

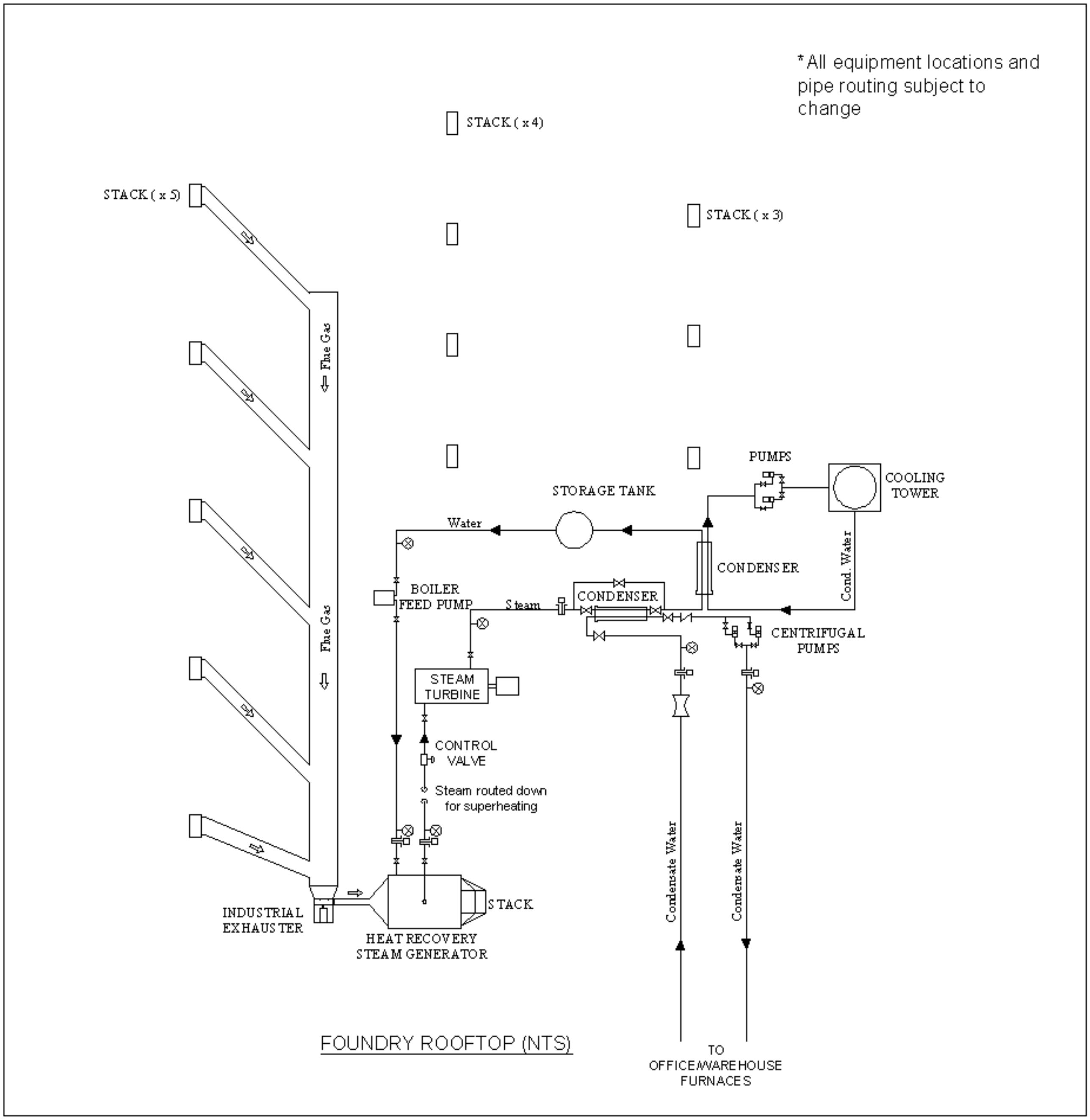
Appendix G: Selected Concept Schematic



Appendix H: Final Design Schematic

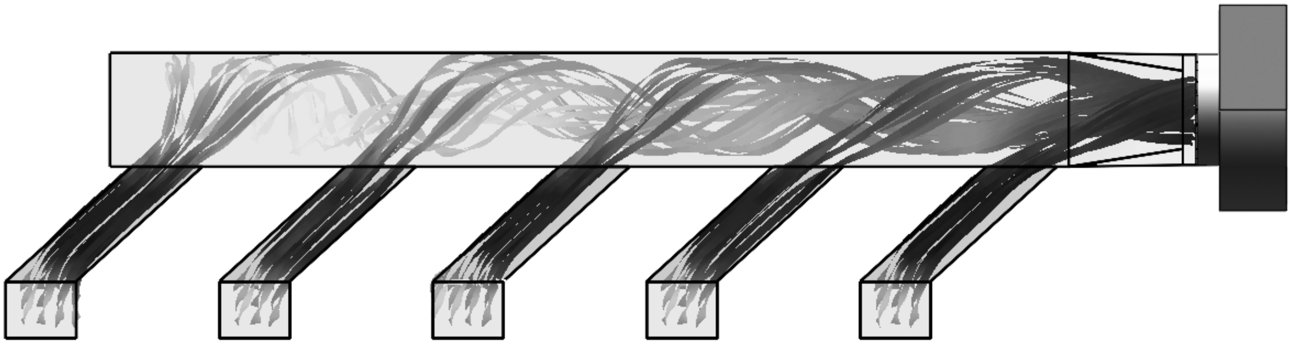


Appendix I: Final Design Layout

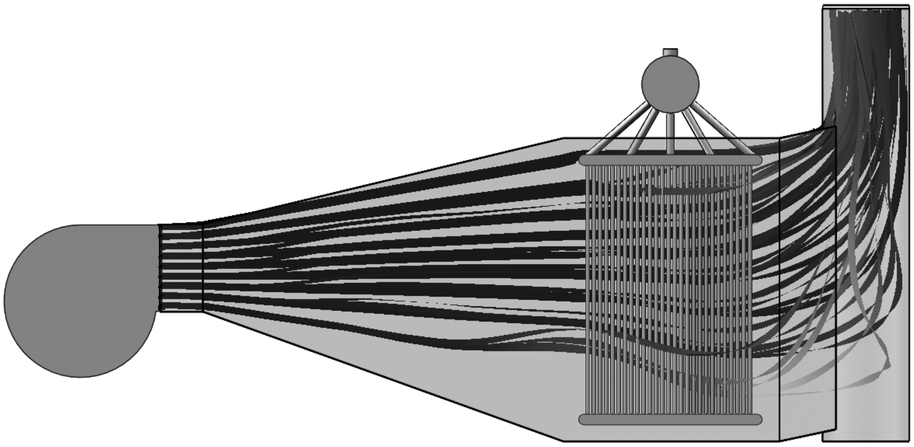


Appendix J: Computer Aided System Analysis

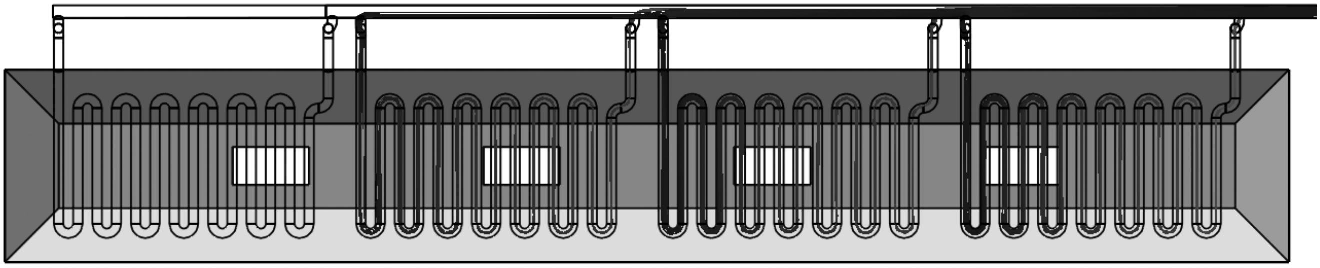
Appendix J.1: Stacks



Appendix J.2: Heat Recovery Steam Generator



Appendix J.3: Superheater



Appendix J.4: Condenser

Appendix K: Project Plan