Evaluation of Heat Recovery Options for Improved Energy Efficiency of a Manufacturing Facility

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EVALUATION OF HEAT RECOVERY OPTIONS FOR IMPROVED ENERGY EFFICIENCY OF A MANUFACTURING FACILITY

by

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ABSTRACT
EVALUATION OF HEAT RECOVERY OPTIONS FOR IMPROVED ENERGY EFFICIENCY OF A MANUFACTURING FACILITY

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Nationwide process heating in the manufacturing sector accounts for 7,815 trillion BTU of energy use annually; this is roughly one-third of the sector's total energy consumption [Energetics Incorporated, 2014]. The U.S. Department of Energy estimates that seventy percent of process heating is fueled by the onsite burning of fossil fuels [Energetics Incorporated, 2014]. These fuel-fired process heating applications are prime opportunities for heat recovery projects capable of saving energy and, consequently, reducing operating costs. This thesis evaluates different methods for heat recovery in the Milwaukee manufacturing facility of STRATTEC Security Corporation. As a basis for this work, the overall energy usage of the facility is evaluated and the largest process heating and cooling loads are identified. Systems that will be evaluated include the zinc melt furnace, the low pressure steam system and the chilled water system. The energy recovered can be used to improve the efficiency of the source piece of equipment, to meet other process heating needs in the facility, or to generate electricity. These systems also can benefit from receiving energy recovered from a power generating process. Models of the energy and exergy balances in these systems are developed to predict the potential reduction in operating costs when heat recovery is implemented in the STRATTEC facility. In addition, the models and energy use information are used to identify inefficiencies in the systems that should be addressed before heat recovery is applied. Finally, a thermo-economic analysis is used to compare the various heat recovery options and select the most cost effective plan for implementing heat recovery. This analysis found that, for the existing equipment, heat recovery could not be implemented economically. However, opportunities for cost savings exist in the selection of new equipment to replace aging systems. Specifically, it was found that heat recovery could be implemented economically by replacing the existing chiller with an absorption chiller system that used waste heat from a power generation system.

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CHAPTER 1

INTRODUCTION

Nationwide process heating in the manufacturing sector accounts for 7,815 trillion BTU of energy use annually; this is roughly one-third of the sector's total energy consumption [Energetics Incorporated, 2014]. The U.S. Department of Energy estimates that seventy percent of process heating is fueled by the onsite burning of fossil fuels [Energetics Incorporated, 2014]. These fuel-fired process heating applications are prime opportunities for heat recovery projects capable of saving energy and, consequently, reducing operating costs. The majority of process heating applications use either direct-fired natural gas or steam generated in natural gas-fired boilers. Natural gas-fired processes typically reject exhaust to the environment at an elevated temperature. With careful planning and a detailed knowledge of the systems in a facility, the rejected heat can be recovered to improve the efficiency of the original process, for other process heating applications or for power generation.

Heat recovery technology can be especially beneficial when a manufacturing facility utilizes more than one process heating application. Typically, the process heating application that requires the highest grade heat must receive energy from a direct source. The other process heating applications can recover the heat rejected from the high temperature process. This creates a system where energy is cascaded around the facility until its work potential or exergy is destroyed or it is no longer economically feasible to transfer the energy to another process. A wealth of knowledge on heat recovery is available from the U.S. Department of Energy, the U.S. Environmental Protection Agency and other government and utility agencies in the form of case studies and handbooks. These include technical publications outlining ways to improve various energy

intensive processes from the Departments of Energy's Advanced Manufacturing Office and reviews of current combined heat and power technology from the Environmental Protection Agency
[U.S. Department of Energy, 2014b][Darrow et al., 2014][BCS Incorporated, 2008]. These resources can be helpful in determining which heat recovery methods have proven successful in the past and are most likely to be economically viable in a given application. This information can be used in conjunction with engineering principles and recorded data to produce gray box models of the various options for heat recovery in a facility, which can be numerous.

This thesis evaluates different methods for heat recovery in the Milwaukee manufacturing facility of STRATTEC Security Corporation. Systems that will be evaluated include the zinc melt furnace, the low pressure steam system and the chilled water system. The energy recovered can be used to improve the efficiency of the source piece of equipment, to meet other process heating needs in the facility, or to generate electricity. These systems also can benefit from receiving energy recovered from a power generating process. Models are developed to predict the potential reduction in operating costs when heat recovery is implemented. The results are used to identify a cost effective plan for implementing heat recovery in the STRATTEC facility.

1.1 Project Objectives

This research aims to evaluate heat recovery options and assess their applicability to STRATTEC's Milwaukee operations. As a basis for this work, the overall energy usage of the facility is evaluated and the largest process heating and cooling loads are identified. Energy and exergy balances are used to develop models of each process that can be used to estimate the energy savings possible through different heat recovery methods. In addition, the models and energy use information are used to identify inefficiencies in the systems that should be addressed before heat recovery is applied. Finally, a thermo-economic analysis is used to compare the various heat recovery options and select the most cost effective options. For those options that are not currently cost effective, the models can be used to predict when they may become financially viable as production capacity and thermal loads change over time.

1.2 Overview of STRATTEC Facility

The facility being evaluated is the Milwaukee manufacturing facility and headquarters of STRATTEC Security Corporation. STRATTEC produces lock, latch and key products, primarily for the automotive industry. The Milwaukee facility contains several different manufacturing processes including hot chamber zinc die casting, stamping, milling, machining and electroplating. STRATTEC currently spends approximately $1.5 million per year on energy for its Milwaukee facility. It was found that 55% of the energy purchased for the facility was in the form of electricity and the remainder in natural gas. The energy used by each of the most energy intensive processes, the zinc melt furnace, the low pressure steam system and the chilled water system, is summarized in the following sub-sections.

1.2.1 Zinc Melt Furnace

The zinc melt furnace is a five burner, induction tube, natural gas fired furnace. It is used to melt the zinc alloy, ZAMAK 5, for use in a portion of the facility’s conventional die cast machines and all of the facility’s multiple-slide die cast machines. The furnace was monitored from April of 2012 through December of 2012 and the operating parameters averaged to obtain the values that will be used for this analysis. The furnace operators were required to record the type and weight of zinc alloy melted and the amount of natural gas used each shift. The form used can be found in Appendix A.

On average, the furnace uses 4.0 Dth/shift of natural gas during production. During production, the furnace currently melts approximately 11,000 pounds of ZAMAK 5 per shift. This is well below the melt rate of 53,000 pounds per shift for which the furnace is rated. On average, this metal is made up of 55% raw material and 45% remelted scrap material. The furnace melts and holds the alloy at a constant 820°F. This is just below the furnace's rated maximum temperature of 825°F. The supply of molten zinc is kept very close to the furnace's capacity of 32,500 pounds by taking the material needed for production and refilling the furnace on an hourly basis.

The furnace is currently equipped with 5 Halick RTG Radiant Tube Gas Burners, Model Number 102. These burners operate by switching between two operating states: high fire and low fire. During high fire, the burners are rated to output 540,800 Btu/hr each [Hauck Manufacturing Company, 2002]. It has been observed during bi-annual preventative maintenance that the exhaust gas exits the five immersion tube burners at 1,100°F during high fire operation. Also during preventative maintenance, the burners are tuned to operate with 4% excess oxygen when running at high fire. During low fire the percent excess O_2 is not controlled. Due to the danger of damaging the immersion tubes if the alloy were allowed to freeze and the high cost of re-heating the alloy, the furnace is not allowed to cool during downtime. All parameters characterizing the operation of the furnace are summarized in Table 1.1.

1.2.2 Low Pressure Steam System

The low pressure steam system is supplied by two shell-and-tube natural gas-fired boilers with a rated capacity of 10,350 pounds of steam per hour per

Table 1.1: Furnace Parameters

Parameter	Value	Unit
Pot Temperature	820	$^\circ F$
Exhaust Temperature	1100	$^\circ F$
Average Natural Gas Usage During Production	4.0	$Dth/shift$
Average Zinc Usage	$11,000$	$lb/shift$
Average Percent Scrap Melted	45	%
Percent Excess Oxygen in Combustion Products	4	%
RTG Radiant Tube Gas Burner High Fire Output	$540,800$	Btu/hr

machine at 15 psig. The boiler system is equipped with an integrated control system and panel display which stores a history of the operating parameters for both boilers. This system was used to obtain the performance data used for the analysis of the steam system. The boilers are set to supply steam at 11 psig. This steam is used for process heating around the facility. Combustion products are exhausted at 235°F. This system is relatively new, as it was installed in 2012.

1.2.3 Chilled Water System

The manufacturing portion of the facility currently uses a chilled water system with a nominal capacity of 300 tons of refrigeration, TR. The system consists of three 100 TR water-cooled scroll chillers and two 150 TR cooling towers. A plate and frame heat exchanger is also used to obtain cooling from the cooling towers when the outdoor temperature drops below 35°F. The system, which was installed in 1996, is reaching the end of its life cycle. Water-cooled scroll chillers can be expected to last around 20 years. Additionally, the demand on the system is expected increase up to 500 TR in the coming years.

1.3 Heat Recovery Technologies

The furnace, steam and chilled water systems are natural targets for heat recovery. The following sections outline the heat recovery technologies that will be analyzed in this paper. Heat recovery systems can be used for either process heating or power generation. Process heating methods can be broken down by the heat recovery medium, which include zinc, air, or water. When water is the heat recovery medium, the resulting hot water or steam can be used either for process heating or for cooling via an absorption chiller. Power generation can be achieved through either a bottoming or topping cycle. Bottoming cycles take energy from the exhaust of a process and use it to produce electricity. For example, the steam produced by recovering heat from the exhaust of a process can be used in a Rankine cycle to generate electricity. Similarly, the heat can be recovered via an organic working fluid and used in an organic Rankine cycle. Topping cycles take the thermal energy produced as a by-product of power generation and use the thermal energy for process heating or cooling.

1.3.1 Process Heating

Zinc Heating

Energy contained in the zinc furnace exhaust stream can be recovered by the zinc being charged to the furnace. The zinc alloy is currently charged to the furnace at room temperature. If the hot furnace exhaust stream were brought into contact with the zinc alloy, heat could be transfered from the exhaust to the zinc alloy. In this situation, less energy would be needed for the furnace to raise the temperature of the alloy to the required temperature.

For non-throughput furnaces, such as the unit at STRATTEC, this modification can be accomplished by loading the charge into an unfired portion of the furnace to be heated by the exhaust before adding it to the molten zinc. Alternatively, the exhaust can be pumped into a structure external to the furnace where the charge can be heated. This is a common method of heat recovery recommended by the U.S. Department of Energy and it has been implemented successfully in many metal processing facilities. For example, this method of heat recovery helped an aluminum die cast facility reduce the energy consumption of its furnace to 47% below the energy consumption of conventional furnaces [U.S. Department of Energy, 2008a].

Air Heating

Heating the air used for combustion is another common form of heat recovery recommended by the U.S. Department of Energy. Many types of fuel-fired processes can benefit from combustion air heating if the burners are designed to accept heated combustion air. In STRATTEC's facility, only the zinc melt furnace has burners that could potentially benefit from this method of heat recovery. Air heating is often achieved through the use of recuperators or regenerators. Recuperators are gas to gas heat exchangers that are compact and can be customized for most applications. Traditionally, concentric tube heat exchangers were used as recuperators. Today, heat pipes are becoming more common due to improved heat transfer properties and better resistance to fouling and corrosion.

Regenerators consist of pairs of heat storage structures with high specific heat capacity. One structure receives heat from the hot exhaust while the other releases heat to the cold incoming combustion air and then the air flows or structure positions are reversed in order to continually supply heat to the cold air stream. In order to store the thermal energy needed to preheat the incoming air for a reasonable amount of time, regenerators are large structures, but they can be effective, particularly for large installations [U.S. Department of Energy, 2007]. Just one recuperator was found to save US Steel 0.221 million Dth per year out of the 4.9 million Dth of natural gas consumed annually by the facility

[U.S. Department of Energy, 2008b].

The effectiveness of air heating as a method of heat recovery is limited by the heat exchanger effectiveness and the proximity of the equipment supplying and utilizing the thermal energy. This is because hot air ductwork has inherently large heat transfer and frictional losses. In addition to heating combustion air, heat recovery via air is also commonly used to condition air for space heating. However, the pieces of equipment being analyzed in this thesis are located in parts of the facility that do not have space heating loads to displace. Therefore, building heating is not considered a feasible heat recovery method in this study.

Water Heating

Compared to air, water is a much better medium for heat recovery because of its higher specific heat capacity and density. It has advantageous thermal properties for effective heat transfer in heat exchangers and can be used to transport thermal energy over a large distance with relatively little heat loss. Heat recovery via water heating can be utilized to produce hot water, low pressure steam or high pressure steam. In the current project, the biggest challenge in utilizing hot water heat recovery is finding a use for the hot water. At STRATTEC, the uses for hot water are limited compared to other industries where large amounts of water are used for process heating. However, a few options do exist. One option is for the water entering the boiler system to be pre-heated, reducing the load on the boiler. Alternately heat could be recovered in the form of steam. Low pressure steam could be used to offset some of the load on the existing low pressure steam system. High pressure steam could be used to generate electricity in a Rankine cycle. Alternately, process cooling could be achieved utilizing hot water, low pressure steam or high pressure steam to run an absorption chiller.

1.3.2 Power Generation

Bottoming Cycles

For heat recovery utilizing a bottoming cycle, the heat must be used to produce a high temperature and pressure fluid. This fluid can be water, as utilized in a Rankine cycle, or an organic working fluid, as utilized in an organic Rankine cycle (ORC). The power that can be generated by these types of heat recovery systems is limited by the Carnot, or maximum, efficiency of the cycle. This efficiency, $\eta_{th,rev}$, is a function of the source and sink temperatures, T_H and T_L respectively, for the cycle:

$$\eta_{th,rev} = 1 - \frac{T_L}{T_H}. \tag{1.1}$$

Since the sink temperature is typically fixed by the environment, the efficiency increases as the source temperature increases. Therefore, Rankine cycles work best with high temperature heat sources. However, ORC systems cannot work with a high temperature source above 800°F due to decomposition of the working fluid [Naik-Dhungel, 2012]. Nonetheless, ORCs do have some advantages, as they can be less costly to maintain and operate than Rankine cycles [Naik-Dhungel, 2012]. It was found that Kennecott Utah Copper was able to recover exhaust heat from their smelter and generate an average of 20-25 MW of electricity using a Rankine cycle for the facility [Brinker, 2010].

Topping Cycles

Topping systems, more commonly referred to as combined heating and power or CHP systems, utilize the heat rejected by power generating equipment for process heating applications. The benefit of these systems comes from an increase in the efficiency of the overall system. It is estimated that producing power in a typical power plant and producing steam separately in an industrial boiler system has an overall efficiency of 49%, whereas producing the same outputs in a CHP system results in an overall efficiency of 75% [BCS Incorporated, 2008]. The economic success of a CHP system largely depends on the local electricity and natural gas rates and grid buyback arrangements for excess electrical output. The power generating equipment most commonly utilized in CHP systems are gas turbines, reciprocating engines, steam turbines, microturbines and fuel cells [BCS Incorporated, 2008]. A well-applied system would supply STRATTEC's thermal load while also producing electricity not in excess of STRATTEC's base electrical load of 2.1 MW.

CHAPTER 2

ENERGY AND EXERGY ANALYSIS

In order to evaluate the viability of the energy recovery techniques introduced in the previous chapter, as they would be applied at STRATTEC, mass, energy and exergy balances are applied. This information is used to calculate the current and potential efficiencies of the systems.

2.1 Zinc Melt Furnace

2.1.1 Existing System

The energy entering and leaving the furnace can be understood and analyzed using a series of mass, energy and exergy balances. These calculations were performed in EES and can be found in Appendix B. For the purposes of this analysis, natural gas is modeled as CH_4, air is modeled as $O_2 + 3.76N_2$, and the combustion products are modeled as a combination of CO_2, H_2O, O_2 and N_2. All products and reactants are modeled as ideal gases. During stoichiometric combustion of CH_4 in O_2 and N_2, the following balanced combustion equation describes the process:

$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 7.52N_2. \tag{2.1}$$

Letting x_i represent the mole fraction of component "i", the stoichiometric equation could be written as:

$$CH_4 + x_{air}(O_2 + x_{N_2}N_2) \rightarrow x_{CO_2}CO_2 + x_{H_2O}H_2O + x_{air}x_{N_2}N_2. \tag{2.2}$$

During preventative maintenance, the burners are tuned to use excess air such that the exhaust contains 4% O_2 by volume in dry air. Adding O_2 as a product results in a modified combustion equation:

$$CH_4 + (x_{air} + x_{O_2})(O_2 + x_{N_2}N_2) \rightarrow x_{CO_2}CO_2 + x_{H_2O}H_2O + x_{O_2}O_2 + (x_{air} + x_{O_2})x_{N_2}N_2. \tag{2.3}$$

In the modified combustion equation, x_{air}, x_{CO_2} and x_{H_2O} represent the stoichiometric mole fractions, while x_{O_2} represents the mole fraction of O_2 in the exhaust stream as a result of excess air.

The volume fraction of O_2 in the exhaust stream is represented by ϕ_{O_2}. The mass fraction can be related to the known volume fraction of O_2 in the combustion products using the mole fractions, molar masses and specific volumes of the other products and reactants represented by x_i, M_i and ν_i respectively using the following equation:

$$\phi_{O_2} = \frac{x_{O_2}M_{O_2}\nu_{O_2}}{x_{CO_2}M_{CO_2}\nu_{CO_2} + x_{H_2O}M_{H_2O}\nu_{H_2O} + x_{O_2}M_{O_2}\nu_{O_2} + (x_{air} + x_{O_2})x_{N_2}M_{N_2}\nu_{N_2}}. \tag{2.4}$$

From this information, the following balanced combustion equation can be derived for combustion with 4% excess O_2 in the exhaust by volume:

$$CH_4 + 2.5198(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 0.5198O_2 + 9.4744N_2. \tag{2.5}$$

Using the mole fractions from the balanced combustion reaction equation and the molar masses, the more useful mass ratios, represented by w_i, can be obtained using:

$$w_i = x_i \cdot M_i / M_{CH_4}. \tag{2.6}$$

The resulting mass fractions are summarized in Table 2.1.

For the purpose of analysis, the furnace is modeled as operating at steady-state. It is assumed that all mass enters the furnace at a constant temperature of $77^\circ F$. This is designated as the dead-state temperature and represented by T_0. The furnace is controlled to keep the molten zinc alloy at 820°F,

Table 2.1: Combustion Mass Fractions

Components	Mass to Fuel Ratio, $lb_{m,i}/lb_{m,CH_4}$
Reactants	
CH_4	1
O_2	5.026
N_2	16.54
Products	
CO_2	2.743
H_2O	2.246
O_2	1.037
N_2	16.54

represented by T_{zinc}, and it is assumed that this temperature is constant and that molten zinc alloy leaves the furnace at this temperature. It is observed that the exhaust gas exits the burners at 1100°F. It is assumed that this temperature, $T_{exhaust}$, is constant. From observation of a gage on the furnace, it is known that natural gas is received by the burners at 17.02 psia. Using all of this information, the density of methane can be determined using a thermodynamic equation of state. For the current analysis, EES is used to determine the density. The mass flow rate of fuel can be calculated using the density and the known volumetric flow rate recorded by the furnace operators using the form in Appendix A:

$$\dot{m}_{CH_4} = \dot{V}_{CH_4} \rho_{CH_4}. \tag{2.7}$$

Knowing the mass flow rate of fuel, $\dot{m}_{CH_4}$, Equation 2.8 can be used to calculate the mass flow rate of the remaining components:

$$\dot{m}_i = w_i \cdot \dot{m}_{CH_4}. \tag{2.8}$$

The mass, energy and exergy balances can be applied to the furnace at steady-state on a rate basis using the combustion analysis. First, looking at the conserved quantities of mass and energy, the following equations are applied:

$$\dot{m}_{system} = \dot{m}_{in} - \dot{m}_{out} \tag{2.9}$$

$$\dot{E}_{system} = \dot{E}_{in} - \dot{E}_{out}. \tag{2.10}$$

At steady state, the rate of change in the total mass of the system, $\dot{m}_{system}$, and the total energy of the system, $\dot{E}_{system}$, are both zero.

In order to understand how the system will react to changes in production volume, it is useful to think of the zinc melt furnace as two control volumes, illustrated in Figure 2.1. This can be represented in a simpler form by the block diagram shown in Figure 2.2. The burners, outlined in red, are described by the

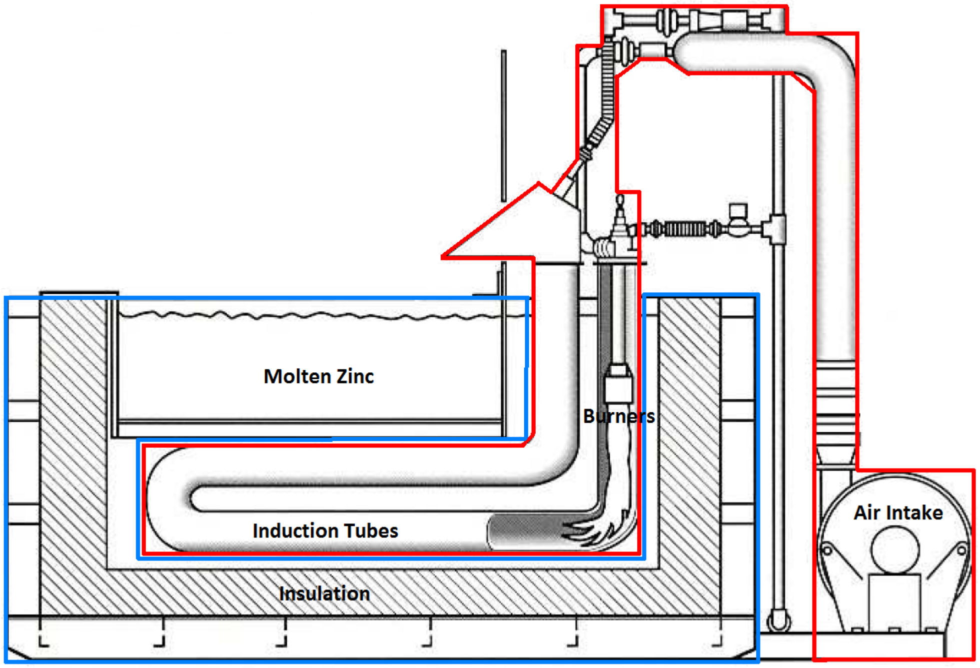

Figure 2.1: Zinc Melt Furnace With Control Volumes
[Thermal Product Solutions, nd]

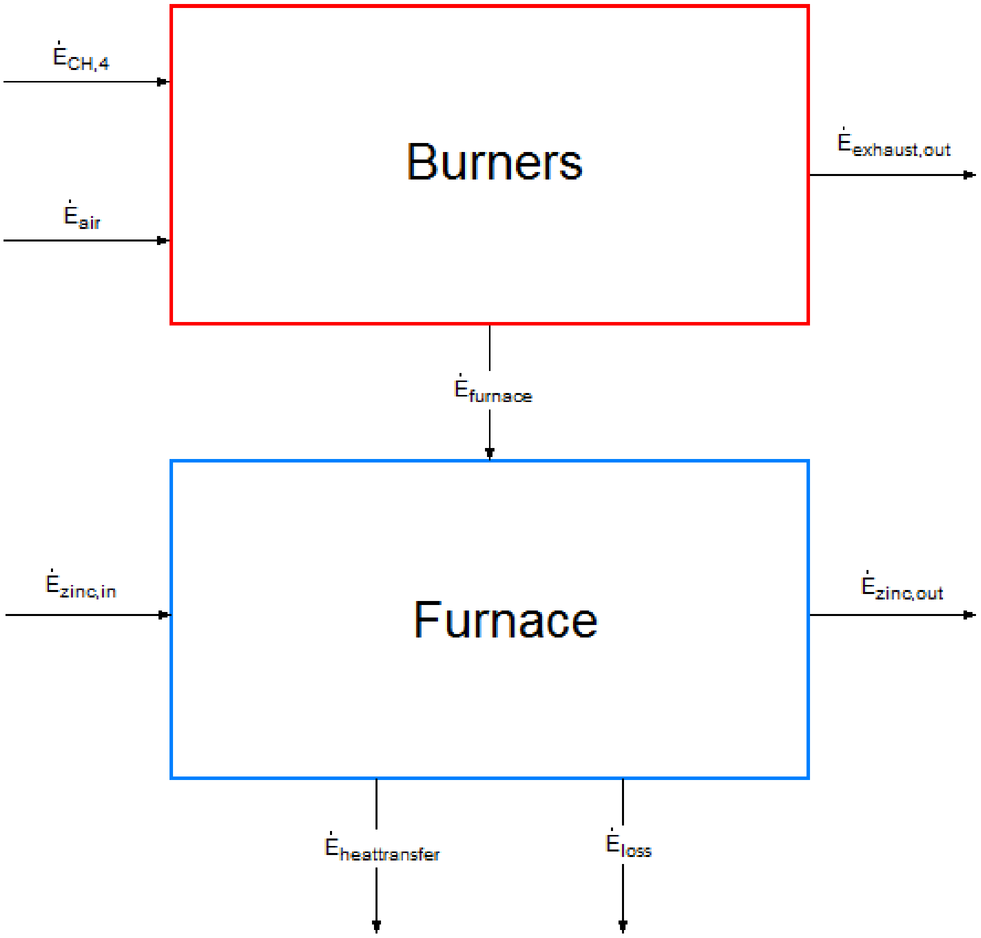

Figure 2.2: Zinc Melt Furnace Energy Balance Diagram

following mass and energy balances:

$$0 = \dot{m}_{CH_4} + \dot{m}_{air} - \dot{m}_{exhaust} \tag{2.11}$$

$$0 = \dot{E}_{CH_4} + \dot{E}_{air} - \dot{E}_{exhaust} - \dot{E}_{furnace}. \tag{2.12}$$

In these equations, $\dot{m}_{air}$ is the mass flow rate of air used for combustion and $\dot{m}_{exhaust}$ is the mass flow rate of exhaust, both calculated using Equation 2.8. $\dot{E}_{CH_4}$ is the energy of the fuel entering the burners, $\dot{E}_{air}$ is the energy of the air entering the burners and $\dot{E}_{exhaust}$ is the energy of the combustion products. Neglecting kinetic and potential energy, the energy of element "i" is modeled by:

$$\dot{E}_i = \dot{m}_i h_i. \tag{2.13}$$

Here h_i is the mass specific enthalpy of the element as an ideal gas evaluated by EES at the specified temperature using the JANAF table references. The final term in the burner energy balance outlined in Equation 2.12, $\dot{E}_{furnace}$, is the energy transfered by heat from the burners to the furnace.

The furnace, outlined in blue in Figures 2.1 and 2.2, is described by the following mass and energy balances:

$$0 = \dot{m}_{zinc,in} - \dot{m}_{zinc,out} \tag{2.14}$$

$$0 = \dot{E}_{zinc,in} + \dot{E}_{furnace} - \dot{E}_{zinc,out} - \dot{E}_{heattransfer} - \dot{E}_{loss}. \tag{2.15}$$

In these equations, $\dot{m}_{zinc,in}$ is the mass flow rate of zinc entering the furnace while $\dot{m}_{zinc,out}$ is the mass flow rate of zinc exiting the furnace. $\dot{E}_{heattransfer}$ is the energy lost to the environment via convective and radiative heat transfer, which is estimated using standard heat transfer relations. However, because the calculated heat transfer may not match the actual heat transfer exactly, a residual term, $\dot{E}_{loss}$, is defined to account for any differences between these values. In addition, $\dot{E}_{loss}$ accounts for the energy lost due to deviation from perfect combustion with 4% excess O_2 and deviation from steady-state operation.

In order to determine the energy transferred to the zinc alloy, it is modeled as an incompressible substance with a constant specific heat, c_p, of 0.10 $Btu/lb_m - F$, and an enthalpy of fusion, h_{fusion}, of 48.6 Btu/lb_m as provided by the material supplier [Eastern Alloys, 2012][R. Winter, personal communication, November 13, 2014]. Again neglecting kinetic and potential energy effects, the energy in the zinc entering the furnace can be determined based on its temperature:

$$\dot{E}_{zinc,in} = \dot{m}_{zinc} c_p T. \tag{2.16}$$

The energy of the zinc leaving the furnace can be calculated in a similar manner but must include the heat of fusion of the zinc, h_{fusion}:

$$\dot{E}_{zinc,out} = \dot{m}_{zinc}(c_p T + h_{fusion}). \tag{2.17}$$

Heat transfer principles and relations outlined by Bergman et al. (2011) can be used to calculate $\dot{E}_{heattransfer}$, which accounts for energy lost by radiation and convection from the sides of the furnace and portions of the molten metal surface not covered by the hood, as shown in the following equation:

$$\dot{E}_{heattransfer} = \dot{E}_{convection,metal} + \dot{E}_{radiation,metal} + \dot{E}_{convection,case} + \dot{E}_{radiation,case}. \tag{2.18}$$

The heat loss from the uncovered portions of the metal surface is via convection and radiation. The rate of energy lost via convection can be calculated by:

$$\dot{E}_{convection,metal} = \bar{h}A(T_{zinc} - T_0), \tag{2.19}$$

where $\bar{h}$ represents the average convective heat transfer coefficient and A is the area available for heat transfer. When uncovered, the surface of the molten metal can be modeled as a hot plate facing upward with natural convection. For such a situation, $\bar{h}$ has the following relation:

$$\bar{h} = \frac{\bar{N}u * k}{A/P}. \tag{2.20}$$

In this equation $\bar{N}u$ is the average Nusselt number. The conductivity of the air, represented by k, is evaluated at the film temperature in EES. P is the perimeter of the area, A, available for heat transfer. The film temperature is the average of the zinc temperature, T_{zinc} and the temperature, T_0, of the surroundings.

To calculate the Nusselt number, first the Grashof number must be calculated. The Grashof number is represented by Gr and is a function of the surface geometry, fluid properties and temperature difference. For a horizontal plate, Gr is calculated using the following equation:

$$Gr = g\beta(T_{zinc} - T_0)\frac{A/P^3}{\nu^2}. \tag{2.21}$$

Here g is the acceleration due to gravity. The fluid properties are evaluated in EES at the film temperature. These include β, which is the coefficient of thermal expansion, μ, which is the dynamic viscosity and ρ, which is the density. The dynamic viscosity and the density are used to find the kinematic viscosity represented by ν using the following equation:

$$\nu = \frac{\mu}{\rho}. \tag{2.22}$$

The Grashof number is used along with the Prandlt number to calculate the Rayleigh number. The Prandlt number is represented by Pr and it is also evaluated in EES at the film temperature. The Rayleigh number is calculated as shown:

$$Ra = GrPr. \tag{2.23}$$

The Rayleigh number indicates whether the flow is laminar or turbulent. For the air flow induced by the hot surface of the uncovered metal, the Rayleigh number is found to be above the laminar to turbulent transition point, which is 10^7 for free convection from a horizontal plate. For this situation of turbulent flow, the average Nusselt number is found by:

$$\bar{Nu} = 0.15Ra^{0.33}. \tag{2.24}$$

In addition to the heat transfer by convection, $\dot{E}_{heattransfer}$ includes the energy lost via radiation from the uncovered metal. Energy lost via radiation from the uncovered metal can be calculated as:

$$\dot{E}_{radiation,metal} = \sigma * A * e * (T_{zinc}^4 - T_0^4). \tag{2.25}$$

In this equation, σ is the Stefan-Boltzman constant and e is the emissivity of the surface. For these calculation, the emissivity of the zinc surface will be estimated as 0.11 as given by Omega for zinc and the emissivity of the case of the furnace will be estimated as 0.8 as given by Omega for oxidized steel [Omega, nd]. The radiation from the sides of the furnace can be calculated using the following equation:

$$\dot{E}_{radiation,case} = \sigma * A * e * (T_{case}^4 - T_0^4). \tag{2.26}$$

In this equation T_{case} is the temperature of the sides of the furnace. To calculate the convection from the sides of the furnace, represented by $\dot{E}_{convection,case}$, Equation 2.18 is used with the case temperature in place of the zinc temperature. The sides of the furnace can be modeled as hot vertical plates. For free convection from a vertical plate, the laminar to turbulent transition occurs at a Rayleigh number of 10^9. Substituting the case temperature of the furnace for the zinc temperature in Equation 2.20 and using Equation 2.22 to solve for the resulting Rayleigh number, the flow is found to be laminar. The relations for free convection from a vertical plate in laminar flow for $\bar{h}$ and $\bar{Nu}$ are as follows:

$$\bar{h} = \frac{\bar{Nu} * k}{L} \tag{2.27}$$

$$\bar{Nu} = 0.68 + \frac{(0.67 * Ra)^{1/4}}{(1 + (\frac{0.492}{Pr})^{9/16})^{4/9}}. \tag{2.28}$$

The final energy flow impacting the furnace is $\dot{E}_{loss}$. This term accounts for deviations from ideal operating conditions such as unsteady operation or operation with a percent excess O_2 different from the value set during maintenance. It also accounts for error in the estimated heat transfer values due to uncertainty in the empirically determined heat transfer coefficients and estimated heat transfer values. Since $\dot{E}_{loss}$ is a combination of so many effects, it may account for a significant portion of the energy used by the furnace. This is not a concern since it is used to match the theoretical model to the observed data. It will be shown in the following section that this term can be reduced by modeling the system with improved burners that operate closer to the desired excess air conditions. Other ways to reduce this term are not likely to exist.

The energy balances were solved using the EES code found in Appendix B to determine the value of $\dot{E}_{loss}$. It will be assumed that $\dot{E}_{loss}$ is constant over a variety of operating conditions because an assumption must be made about the functionality of $\dot{E}_{loss}$ and it is reasonable to assume that the heat transfer and deviations from ideal operating conditions will not change significantly with the addition of heat recovery. This will make it possible to use the model to estimate the fuel used as operating conditions change. The calculated values of the energy flow rates are listed in Table 2.2.

The zinc and fuel mass flow rates are estimated using measurements taken by operators on the floor, which introduces the potential for human error. These measurements have the potential to strongly impact the analysis. To understand this impact, an uncertainty propagation analysis was performed in EES. The recorded values of $\dot{m}_{zinc}$ and $\dot{m}_{CH_4}$ are assumed to have a potential uncertainty of 6.25% or roughly one half an hour of production in an eight hour shift. The value of uncertainty calculated by EES is reported in Table 2.2. Even with the uncertainty in these critical measurements, the uncertainty analysis shows that the model and the values reported are still a good representation of the system.

Just as mass and energy balances are applied to the zinc melt furnace, exergy balances are applied to better understand where losses occur in the furnace. Exergy is defined as the maximum useful work that could be obtained from a system at a given state in a specified environment [Cengel, 2008]. Unlike mass and energy, exergy is not conserved. It can be destroyed. This results in the

Table 2.2: Existing Zinc Melt Furnace Energy Flow Rates

Energy Flow Rate	Model Result (Dth/shift)	Uncertainty (Dth/shift)
$\dot{E}_{CH_4}$	4.0	0.25
$\dot{E}_{air}$	0	0
$\dot{E}_{exhaust}$	1.2	0.074
$\dot{E}_{furnace}$	2.8	0.17
$\dot{E}_{zinc,in}$	0	0
$\dot{E}_{zinc,out}$	1.4	0.084
$\dot{E}_{heattransfer}$	0.11	N/A
$\dot{E}_{loss}$	1.3	0.19

following exergy balance:

$$\dot{X}_{system} = \dot{X}_{in} - \dot{X}_{out} + \dot{X}_{destroyed}. \tag{2.29}$$

The specified environment used for the furnace analysis, also referred to as the dead state, is a temperature, T_0, of 77°F and a pressure of, P_0, 14.7 psia or atmospheric pressure. The system boundaries are applied so that the boundary is at the dead-state and only negligible heat transfer via radiation occurs across the system boundaries. Mass crosses the boundaries in the form of air, fuel and zinc entering the system and the exhaust gases and zinc exiting the system. All of the exergy flows in the equations below are calculated in the EES code found in Appendix B by the following equation from *Advanced Engineering Thermodynamics* by Bejan [Bejan, 1997]:

$$\dot{X}_i = \dot{m}_i(h_i - h_0 - T_0(s_i - s_0)). \tag{2.30}$$

In this equation $\dot{X}_i$ is the exergy flow rate and $\dot{m}_i$ is the mass flow rate of element "i". The mass specific enthalpy and entropy of element "i", represented by h_i and s_i, are evaluated in EES at the specified temperature using the JANAF table reference states for the various ideal gases. Again the zinc is assumed to be an incompressible substance with constant specific heat and an average melting point, T_{melt}, of 722°F [Eastern Alloys, 2012]. Therefore, h_{zinc} and s_{zinc} are evaluated using the following equations:

$$h_{zinc} = c_p T + h_{fusion} \tag{2.31}$$

$$s_{zinc} = c_p ln(T) + \frac{h_{fusion}}{T_{melt}}. \tag{2.32}$$

Evaluating the exergy transfer rate in Equation 2.30 also requires the mass specific enthalpy and entropy of element "i" evaluated at the dead state conditions, represented by h_0 and s_0. These properties are again evaluated in EES using the JANAF reference states for the ideal gases.

The temperatures used to evaluate the exergy transfer terms in Equation 2.30 depend on the extent of the system analyzed. Adjusting the system boundaries to control the temperature of the exhaust exiting the system can show where in the system exergy is destroyed. First, the exergy analysis is applied to a control volume that only includes the portions of the burners where combustion occurs and excludes the immersion tubes that transfer the heat released by the combustion to the zinc alloy. It is assumed that the combustion chamber is small enough that any heat transfer across the boundary is negligible and the exhaust exits the control volume at the flame temperature. The following exery balance describes the system:

$$0 = \dot{X}_{CH_4} + \dot{X}_{air} - \dot{X}_{exhaust} + \dot{X}_{destroyed,combustion}. \tag{2.33}$$

Here $\dot{X}_{destroyed,combustion}$ represents the exergy destroyed during the combustion process. Next, the system boundary is extended so that it includes the whole furnace with the exhaust leaving at 1100°F. Exergy is still destroyed by the combustion process as well as by the losses associated with the system such as the heat transfer. The extended boundary results in the following balance:

$$0 = \dot{X}_{CH_4} + \dot{X}_{air} + \dot{X}_{zinc,in} - \dot{X}_{exhaust} - \dot{X}_{zinc,out} + \dot{X}_{destroyed,combustion} + \dot{X}_{destroyed,losses}. \tag{2.34}$$

Finally, the system boundary is extended to that the exhaust exits the system at the dead-state temperature. Now exergy is destroyed by combustion, the losses and the exhaust being cooled to the dead-state temperature. This results in the following balance:

$$\begin{aligned} 0 =& \dot{X}_{CH_4} + \dot{X}_{air} + \dot{X}_{zinc,in} \\ & - \dot{X}_{exhaust} - \dot{X}_{zinc,out} \\ & + \dot{X}_{destroyed,combustion} + \dot{X}_{destroyed,losses} + \dot{X}_{destroyed,exhaust}. \end{aligned} \tag{2.35}$$

The amount of exergy utilized to heat the zinc can be found by:

$$\dot{X}_{utilized} = \dot{X}_{zinc,out} - \dot{X}_{zinc,in}. \tag{2.36}$$

The amount of exergy destroyed by each mechanism is compared to the amount of exergy entering the system and being utilized for heating the zinc in Table 2.3. Again an uncertainty analysis is applied to understand how the uncertainty in the measured variables affects the system model.

The final exergy balance presented in Equation 2.35 is used to determine the second law efficiency of the zinc melt furnace. The most useful formulation of the second law efficiency, η_{II}, for the applications discussed here, given by Bejan [Bejan, 1997], is:

$$\eta_{II} = \frac{\dot{X}_{utilized}}{\dot{X}_{supplied}}. \tag{2.37}$$

In this equation $\dot{X}_{supplied}$ is the sum of $\dot{X}_{CH_4}$, $\dot{X}_{air}$ and $\dot{X}_{zinc,in}$. This results in a second law efficiency of 7.6% with an uncertainty of ± 0.67%. The second law efficiency is presented for all existing and proposed systems in this thesis.

Table 2.3: Existing Zinc Melt Furnace Exergy Flow Rates

Exergy Flow Rate	Dth/shift	Uncertainty
$\dot{X}_{CH_4}$	4.0	0.25
$\dot{X}_{air}$	0	0
$\dot{X}_{zinc,in}$	0	0
$\dot{X}_{destroyed,combustion}$	1.3	0.082
$\dot{X}_{destroyed,losses}$	1.9	0.14
$\dot{X}_{destroyed,exhaust}$	0.53	0.033
$\dot{X}_{zinc,out}$	0.31	0.019

Although less common in industry than the first law definition of energy efficiency, it more accurately compares how energy is used in a facility relative to the best possible performance. Since exergy is destroyed just as fuel is used up and electricity is expended, it is, as argued by Petit and Gaggioli, ″completely consistent with our intuition and everyday perceptions; it is what the layman calls ′energy′″[Petit and Gaggioli, 1980].

2.1.2 Optimizing Existing Operation

Applying the energy and exergy balances to the furnace reveals opportunities to improve its efficiency as it currently operates without heat recovery. The analysis shows exergy is destroyed in the combustion process and in heat transfer. These losses should be minimized before heat recovery is applied. New burners can minimize the losses in the combustion process. The current burners operate by switching between high-fire and low-fire settings. During low-fire operation, the combustion is not well controlled. The manufacturer has replaced this burner model with one that can operate by switching between high-fire and off or high and low-fire. Additionally, the amount of air used by each burner during both high-fire and low-fire operation can be controlled. This is not possible with the old model. The manufacturer estimates that replacing the burners with the new model will save 30,000 Btu/hr per burner. This change will reduce $\dot{E}_{loss}$ because $\dot{E}_{loss}$ accounts for losses due to inefficiencies in the burners. With five new burners, $\dot{E}_{loss}$ is reduced from 1.3 Dth/shift to 0.49 Dth/shift. More importantly, this results in $\dot{E}_{CH_4}$ being reduced from 4.0 Dth/shift to 2.8 Dth/shift. This will result in a cost savings for the facility, which will be calculated in Chapter 3. This also reduces the energy in the exhaust stream. Although this is not favorable for implementing heat recovery, this is the more cost effective way of improving the energy efficiency of the process. The other energy flow rates in the system and the associated uncertainties will change as shown in Table 2.4. This is the last time the uncertainty with be reported in this analysis.

Table 2.4: Optimized Zinc Melt Furnace Energy Flow Rates

Energy Flow Rate	Dth/shift	Uncertainty
$\dot{E}_{CH_4}$	2.8	0.25
$\dot{E}_{air}$	0	0
$\dot{E}_{exhaust}$	0.83	0.074
$\dot{E}_{furnace}$	1.9	0.17
$\dot{E}_{zinc,in}$	0	0
$\dot{E}_{zinc,out}$	1.4	0.084
$\dot{E}_{heattransfer}$	0.11	N/A
$\dot{E}_{loss}$	0.49	0.19

The same boundaries and exergy balances established in the exergy analysis in Section 2.1.1 apply to the modified system, but the values will change as outlined in the Table 2.5. The table shows that the exergy destroyed by all aspects of the furnace operation is reduced. This is due to the smaller amount of fuel being burned. $\dot{X}_{destroyed,losses}$ is also further reduced because the process more closely resembles the model, now that the amount of air used for combustion is controlled at all times. Applying these improvements to the furnace would result in a second law efficiency of 11% compared to the initial efficiency of 7.6%. Because of the energy and thus cost savings possible with the new burners, all calculations from this point on assume that this improvement will be made before implementing heat recovery.

Table 2.5: Optimized Zinc Melt Furnace Exergy Flow Rates

Exergy Flow Rate	Dth/shift
$\dot{X}_{CH_4}$	2.8
$\dot{X}_{air}$	0
$\dot{X}_{zinc,in}$	0
$\dot{X}_{destroyed,combustion}$	0.92
$\dot{X}_{destroyed,losses}$	1.2
$\dot{X}_{destroyed,exhaust}$	0.37
$\dot{X}_{zinc,out}$	0.31

2.1.3 Zinc Heating

The first method of heat recovery to be analyzed is using the exhaust gas to heat the zinc entering the furnace. Figure 2.3 shows that the energy from the furnace exhaust enters the heat recovery system as $\dot{E}_{exhaust,in}$ and transfers energy to the incoming zinc, represented by $\dot{E}_{zinc,heated,in}$ before exiting as $\dot{E}_{exhaust,out}$, while the heated zinc enters the furnace as $\dot{E}_{zinc,heated,out}$. The mass and energy

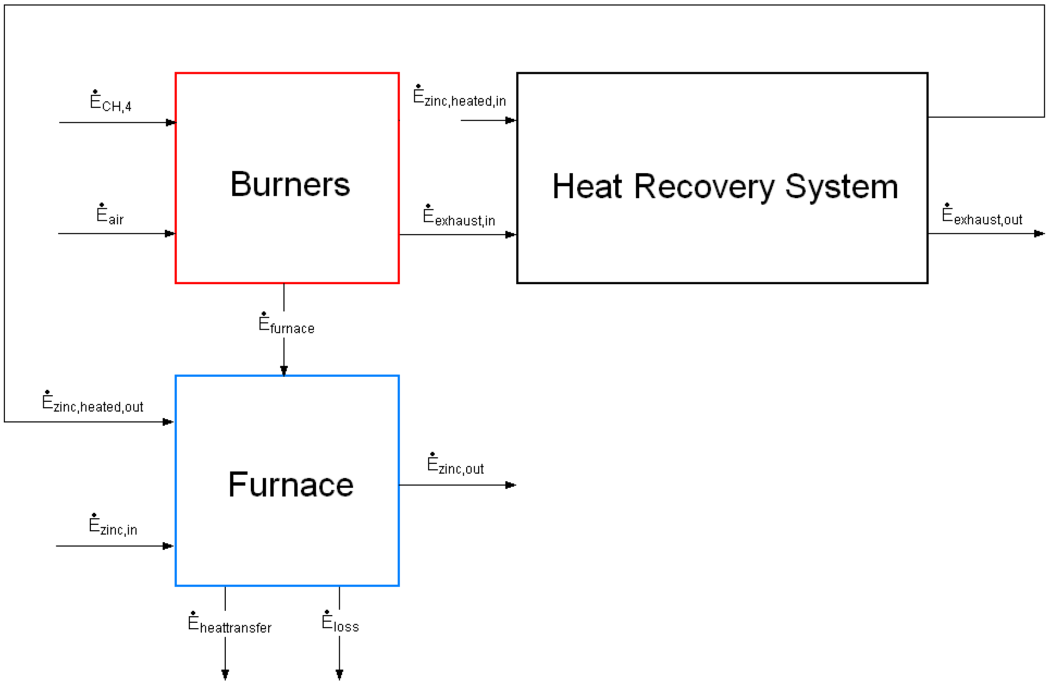

Figure 2.3: Zinc Melt Furnace with Zinc Heating Energy Balance Diagram

balances change as shown to include these terms:

$$0 = \dot{m}_{CH_4} + \dot{m}_{air} - \dot{m}_{exhaust,in} \tag{2.38}$$

$$0 = \dot{m}_{exhaust,in} - \dot{m}_{exhaust,out} \tag{2.39}$$

$$0 = \dot{m}_{zinc,heated,in} - \dot{m}_{zinc,heated,out} \tag{2.40}$$

$$0 = \dot{m}_{zinc,heated,out} + \dot{m}_{zinc,in} - \dot{m}_{zinc,out} \tag{2.41}$$

$$0 = \dot{E}_{CH_4} + \dot{E}_{air} - \dot{E}_{exhaust,in} - \dot{E}_{furnace} \tag{2.42}$$

$$0 = \dot{E}_{exhaust,in} + \dot{E}_{zinc,heated,in} - \dot{E}_{zinc,heated,out} - \dot{E}_{exhaust,out} \tag{2.43}$$

$$0 = \dot{E}_{zinc,heated,out} + \dot{E}_{furnace} + \dot{E}_{zinc,in} - \dot{E}_{zinc,out} - \dot{E}_{heattransfer} - \dot{E}_{loss}. \tag{2.44}$$

In an ideal situation, all of the zinc entering the furnace would be preheated while the exhaust stream would be cooled to the dead state temperature. Unfortunately this is not possible because the scrap portion of the material being melted in the furnace is difficult to handle. Loading it into an area to be preheated would be impractical. Additionally, the zinc cannot be heated for an infinite amount of time. Currently, metal is removed from and added to the furnace on an hourly basis. Realistically the heat recovery system could be made large enough to hold two hours worth of bars. This would work by loading the bars into the heat recovery system in batches. In this design, only the bars being melted would be preheated for two hours at a time while the scrap material would still enter the furnace at room temperature. A simple rack, pictured in Figure 2.4, of square tube stock could allow the bars to be heated on both sides.

Figure 2.4: Zinc Bar Heat Recovery System

In this situation energy would be transfered from the hot exhaust to the bars via convection. The bars can be modeled as a flat plate with lumped capacitance in forced convection with both sides of the plate available for heat transfer. Letting T_{heat} represent is the final temperature of the bars after being heated for a length of time, t, the temperature can be calculated using the following equation:

$$\frac{T_{heat} - T_{exhaust}}{T_0 - T_{exhaust}} = e^{\frac{-\bar{h}A}{\rho V c_{zinc}}t}. \tag{2.45}$$

Here V is the volume of the batch of bars and ρ is the density of the alloy. The average heat transfer coefficient has the following relation for this situation:

$$\bar{h} = \frac{\bar{Nu} * k}{L}. \tag{2.46}$$

For the heat transfer calculation, all of the thermodynamic properties of the exhaust are calculated by EES at the average film temperature using the JANAF reference states. The Nusselt number has the following relation:

$$\bar{Nu} = 0.664 * Re^{1/2} * Pr^{1/3}. \tag{2.47}$$

The Reynolds number follows this relation:

$$Re = \frac{u * L}{\nu}. \tag{2.48}$$

In this equation, u is the air speed of the exhaust as it passes over the zinc bars. It is estimated by using the mass flow rate of the exhaust and the density of the exhaust to find the volume flow rate. Dividing the volume flow rate of exhaust by the cross-sectional area under the hood gives an average velocity of the exhaust, as shown:

$$u = \frac{\dot{m}_{exhaust}}{\rho A_{hood}}. \tag{2.49}$$

This analysis requires EES to iteratively solve both the energy balances and the heat transfer equations since the average film temperature depends on the final temperature of the bars and the exhaust air speed depends on the heat required by the furnace. To ensure that the lumped capacitance assumption is valid, the Biot number, represented by Bi, should be calculated to be less than 0.1:

$$Bi = \frac{\bar{h} * L_c}{k}. \tag{2.50}$$

In this equation, L_c is the critical length of the mass being heated:

$$L_c = V/A. \tag{2.51}$$

Here V is the volume of zinc being heated and A is the surface area available for heat transfer. These calculations result in the energy flow rates outlined in Table 2.6. This method of heat recovery reduces $\dot{E}_{CH_4}$ from 2.8 Dth/shift to 2.6 Dth/shift. It this is because the energy required to heat the zinc to temperature is decreased as seen in the reduction of $\dot{E}_{furnace}$ from 1.9 Dth/shift to 1.8 Dth/shift.

Table 2.6: Zinc Melt Furnace with Zinc Heating Energy Flow Rates

Energy Flow Rate	Dth/shift
$\dot{E}_{CH_4}$	2.6
$\dot{E}_{air}$	0
$\dot{E}_{exhaust,in}$	0.77
$\dot{E}_{exhaust,out}$	0.63
$\dot{E}_{furnace}$	1.8
$\dot{E}_{zinc,heated,in}$	0
$\dot{E}_{zinc,in}$	0
$\dot{E}_{zinc,heated,out}$	0.14
$\dot{E}_{zinc,out}$	1.4
$\dot{E}_{heattransfer}$	0.11
$\dot{E}_{loss}$	0.49

Again, since none of the changes made to the system cross the system boundaries established for the exergy analysis, the exergy balances will not change, just the associated values as shown in Table 2.6. The second law efficiency of this system would be 12% compared to the initial efficiency of 7.6% and the efficiency of 11% after the burner upgrades. This improvement in the second law efficiency is due to a very slight reduction in the exergy destroyed. The exergy destroyed in combustion is less due to less fuel being burned. The

Table 2.7: Zinc Melt Furnace with Zinc Heating Exergy Flow Rates

Exergy Flow Rate	Dth/shift
$\dot{X}_{CH_4}$	2.6
$\dot{X}_{air}$	0
$\dot{X}_{zinc,in}$	0
$\dot{X}_{destroyed,combustion}$	0.85
$\dot{X}_{destroyed,losses}$	1.1
$\dot{X}_{destroyed,exhaust}$	0.34
$\dot{X}_{zinc,out}$	0.31

exergy destroyed in the exhaust is less since exergy is transfered to the incoming zinc instead of being destroyed as the exhaust is allowed to cool.

2.1.4 Air Heating

The hot exhaust from the zinc melt furnace can also be used to preheat the air used for combustion. Theoretically the exergy of the exhaust stream should go to zero, indicating that all of the useful work has been extracted and the exhaust exits at the dead state. This is not practically feasible. An industry standard heat pipe heat exchanger quoted for this application by MANTRA can preheat the incoming air to 586°F when the furnace is operating at high-fire [P. Cranny, personal communication, May 29, 2014]. Figure 2.5 shows the energy flow rates for this heat recovery system. $\dot{E}_{exhaust,in}$ is the rate of energy leaving the furnace in the exhaust and entering the heat exchanger, where it transfers energy to the incoming air stream, which has an energy flow rate represented by $\dot{E}_{air}$. The air is heated in the heat recovery system and exits to the burners with an energy flow rate of $\dot{E}_{air,heated}$. The exhaust exits the heat recovery system with an energy flow rate of $\dot{E}_{exhaust,out}$. The following mass and energy balances describe the system:

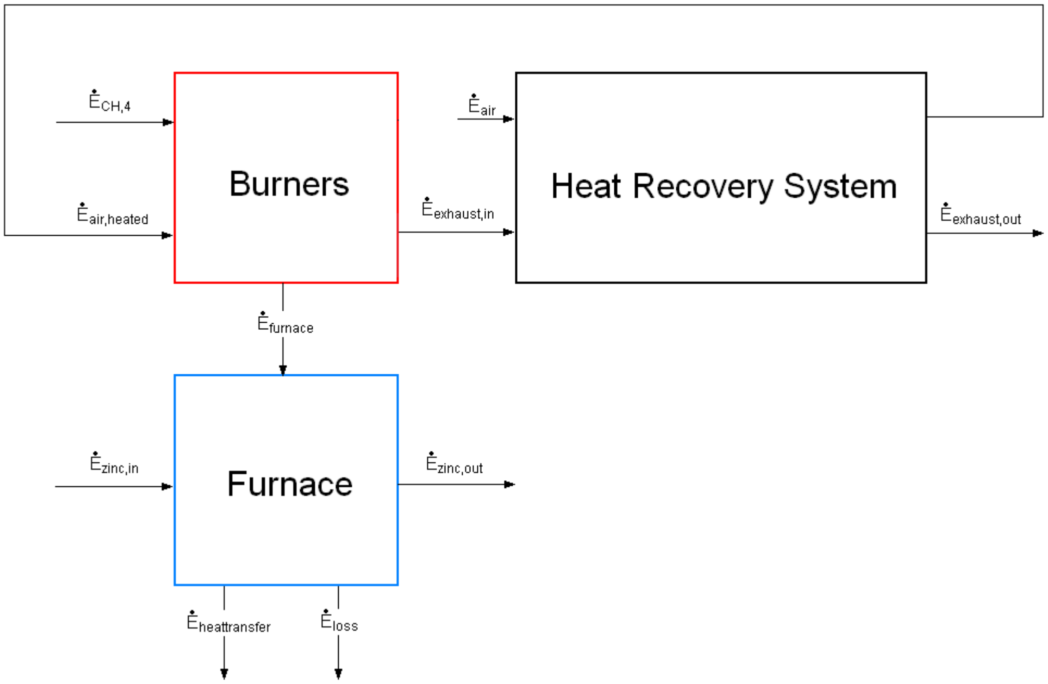

Figure 2.5: Zinc Melt Furnace with Air Heating Energy Balance Diagram

$$0 = \dot{m}_{CH_4} + \dot{m}_{air,heated} - \dot{m}_{exhaust,in} \tag{2.52}$$

$$0 = \dot{m}_{exhaust,in} - \dot{m}_{exhaust,out} \tag{2.53}$$

$$0 = \dot{m}_{air} - \dot{m}_{air,heated} \tag{2.54}$$

$$0 = \dot{m}_{zinc,in} - \dot{m}_{zinc,out} \tag{2.55}$$

$$0 = \dot{E}_{CH_4} + \dot{E}_{air,heated} - \dot{E}_{exhaust,in} - \dot{E}_{furnace} \tag{2.56}$$

$$0 = \dot{E}_{exhaust,in} + \dot{E}_{air} - \dot{E}_{air,heated} - \dot{E}_{exhaust,out} \tag{2.57}$$

$$0 = \dot{E}_{zinc,in} + \dot{E}_{furnace} - \dot{E}_{zinc,out} - \dot{E}_{heattransfer} - \dot{E}_{loss}. \tag{2.58}$$

Solving these balances in EES results in the energy flow rates outlined in Table 2.8. This method of heat recovery reduces $\dot{E}_{CH_4}$ from 2.8 Dth/shift to 2.4 Dth/shift. This is a greater reduction than that achieved by heat recovery via zinc heating. Less fuel is used since energy is brought into the combustion process via the heated air. $\dot{E}_{exhaust}$ is reduced because less fuel is used; therefore less mass exits as exhaust and it is cooler since energy is transfered to the incoming air. The other terms remain constant and are not affected by this method of heat recovery. Again, since none of the changes made to the system cross the system boundary lines established for the exergy analysis in Equations 2.29 through 2.37, the balances will not change, just the associated values as shown in Table 2.9. This heat recovery system would result in a second law efficiency of 12% compared to the initial efficiency of 7.6% and the efficiency of 11% with the new burners. This method of heat recovery reduces the exergy required by the process. Less exergy is destroyed in the combustion process because less fuel is used and the air enters the combustion process heated so less exergy goes into raising the temperature of the air to the flame temperature. Additionally, less exergy is destroyed in the exhaust because less fuel is used and the exhaust exits at a cooler temperature; exergy is transfered to the incoming air instead of being destroyed as the exhaust is allowed to cool.

Table 2.8: Zinc Melt Furnace with Air Heating Energy Flow Rates

Energy Flow Rate	Dth/shift
$\dot{E}_{CH_4}$	2.4
$\dot{E}_{air,in}$	0
$\dot{E}_{exhaust,in}$	0.72
$\dot{E}_{exhaust,out}$	0.47
$\dot{E}_{furnace}$	1.9
$\dot{E}_{zinc,in}$	0
$\dot{E}_{air,heated}$	0.25
$\dot{E}_{zinc,out}$	1.4
$\dot{E}_{heattransfer}$	0.11
$\dot{E}_{loss}$	0.49

Table 2.9: Zinc Melt Furnace with Air Heating Exergy Flow Rates

Exergy Flow Rate	Dth/shift
$\dot{X}_{CH_4}$	2.5
$\dot{X}_{air}$	0
$\dot{X}_{zinc,in}$	0
$\dot{X}_{destroyed,combustion}$	0.8
$\dot{X}_{destroyed,losses}$	1.0
$\dot{X}_{destroyed,exhaust}$	0.32
$\dot{X}_{zinc,out}$	0.31

2.1.5 Combined Air and Zinc Heating

The two heat recovery methods outlined above can be combined to achieve a greater improvement in efficiency. First the hot exhaust will pass over the zinc bars to preheat them, then through a gas to air heat pipe heat exchanger in counterflow with the intake air. The heat exchanger used is the same one described in the last section. It will be assumed that it has the capability to heat the incoming air to the same temperature quoted in the last section. This is a reasonable assumption because the system quoted would bleed in different amounts of cold air to supply the exhaust to the heat exchanger at the same temperature in both situations. It is assumed that the change in air mass flow rate would be minimal because the heat transfered to the zinc would be minimal. Figure 2.6 shows how the system will be modeled. The following mass and energy balances describe the system:

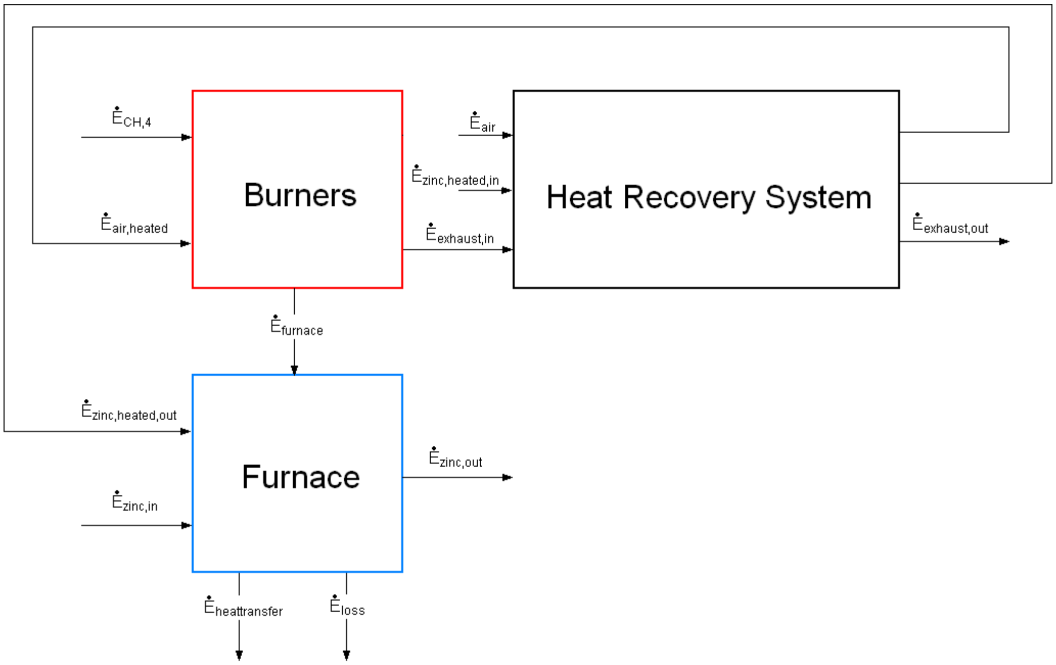

Figure 2.6: Zinc Melt Furnace with Zinc and Air Heating Energy Balance Diagram

$$0 = \dot{m}_{CH_4} + \dot{m}_{air,heated} - \dot{m}_{exhaust,in} \tag{2.59}$$

$$0 = \dot{m}_{exhaust,in} - \dot{m}_{exhaust,out} \tag{2.60}$$

$$0 = \dot{m}_{air} - \dot{m}_{air,heated} \tag{2.61}$$

$$0 = \dot{m}_{zinc,heated,in} - \dot{m}_{zinc,heated,out} \tag{2.62}$$

$$0 = \dot{m}_{zinc,in} + \dot{m}_{zinc,preheated,out} - \dot{m}_{zinc,out} \tag{2.63}$$

$$0 = \dot{E}_{CH_4} + \dot{E}_{air,heated} - \dot{E}_{exhaust,in} - \dot{E}_{furnace} \tag{2.64}$$

$$0 = \dot{E}_{exhaust,in} + \dot{E}_{air} + \dot{E}_{zinc,heated,in} - \dot{E}_{air,heated} - \dot{E}_{zinc,heated,out} - \dot{E}_{exhaust,out} \tag{2.65}$$

$$0 = \dot{E}_{zinc,in} + \dot{E}_{zinc,heated,out} + \dot{E}_{furnace} - \dot{E}_{zinc,out} - \dot{E}_{heattransfer} - \dot{E}_{loss}. \tag{2.66}$$

Solving these equations in EES results in the energy flow rates outlined in Table 2.10. This modification results in $\dot{E}_{CH_4}$ being reduced from 2.8 Dth/shift to 2.2 Dth/shift. This is the greatest reduction in fuel used by the furnace via heat recovery. $\dot{E}_{furnace}$ is reduced because less energy is needed to raise the zinc to the required temperature. $\dot{E}_{exhaust,out}$ is reduced due to less fuel being used and thus less exhaust being produced. Additionally the exhaust exits the system at a cooler temperature after transferring energy to the incoming zinc and air. Again, since none of the changes made to the system cross the system boundary lines established for the exergy analysis in Equations 2.29 through 2.37, the balances will not change, just the associated values as shown in Table 2.11. Less exergy is destroyed in the combustion process because less fuel is being burned and the air enters the process heated. Less exergy is destroyed in the ”losses” term because less energy is transferred from the induction tubes to the furnace. Less exergy is detroyed in the exhaust because it transfers exergy to the incoming zinc and air instead of the exergy being destroyed as the exhaust is allowed to cool. This will

Table 2.10: Zinc Melt Furnace with Zinc and Air Heating Energy Flow Rates

Energy Flow Rate	Dth/shift
$\dot{E}_{CH_4}$	2.2
$\dot{E}_{air,heated}$	0.28
$\dot{E}_{exhaust,in}$	0.66
$\dot{E}_{furnace}$	1.8
$\dot{E}_{air}$	0
$\dot{E}_{zinc,heated,in}$	0
$\dot{E}_{zinc,heated,out}$	0.13
$\dot{E}_{exhaust,out}$	0.53
$\dot{E}_{zinc,in}$	0
$\dot{E}_{zinc,out}$	1.4
$\dot{E}_{heattransfer}$	0.11
$\dot{E}_{loss}$	0.49

Table 2.11: Zinc Melt Furnace with Zinc and Air Heating Exergy Flow Rates

Exergy Flow Rate	Dth/shift
$\dot{X}_{CH_4}$	2.2
$\dot{X}_{air}$	0
$\dot{X}_{zinc,in}$	0
$\dot{X}_{zinc,heated,in}$	0
$\dot{X}_{destroyed,combustion}$	0.72
$\dot{X}_{destroyed,losses}$	0.90
$\dot{X}_{destroyed,exhaust}$	0.29
$\dot{X}_{zinc,out}$	0.31

result in a second law efficiency of 14% compared to the initial efficiency of 7.6% and 11% with the new burners.

2.1.6 Water Heating

There are several types of heated water that may be useful to a manufacturing facility. No matter the temperature of the water delivered by the heat recovery system, any system using the exhaust from the zinc melt furnace to heat water can be modeled as shown in Figure 2.7. Since the energy is not being

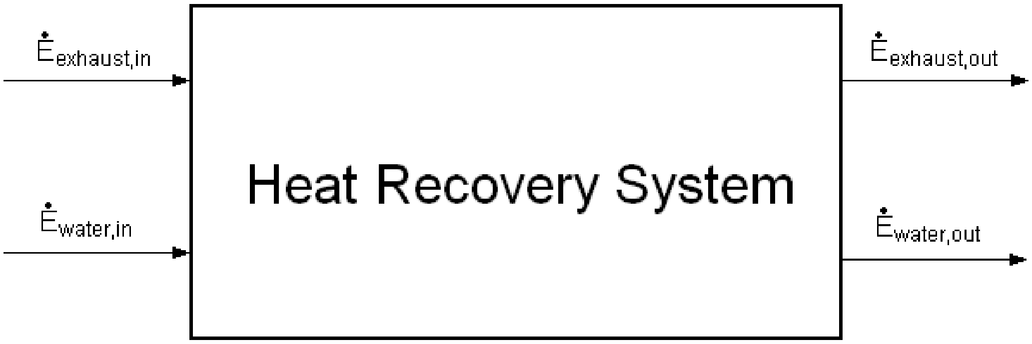

Figure 2.7: Zinc Melt Furnace with Water Heating Energy Balance Diagram

fed back into the furnace as in the previous examples, the furnace itself is not included in the system model. This method will be analyzed for the best case scenario with the exhaust exiting at the dead-state temperature. The following mass and energy balances describe the system:

$$0 = \dot{m}_{exhaust,in} - \dot{m}_{exhaust,out} \tag{2.67}$$

$$0 = \dot{m}_{water,in} - \dot{m}_{water,out} \tag{2.68}$$

$$0 = \dot{E}_{exhaust,in} + \dot{E}_{water,in} - \dot{E}_{exhaust,out} - \dot{E}_{water,out}. \tag{2.69}$$

Solving the mass and energy balances, the maximum change in the energy flow rate of heated water is found to be 0.83 Dth/shift. Since the hot water generated by heat recovery could reduce the load on the low pressure steam system currently used for water heating, the exergy analysis will not be calculated here but in Section 2.2, which discusses the steam system.

2.1.7 Power Generation

The zinc melt furnace can operate in conjunction with either a bottoming or a topping power generation system. In a bottoming system the furnace would accept air heated by a power generating device, such as a gas turbine or microturbine [Darrow et al., 2014]. However, gas turbines have poor part load performance and a start-up time of up to one hour, and the furnace is often cycling or operating at a partial load. Therefore, this technology will not be considered further. Instead, a system with a microturbine as the power generating system will be analyzed. While the previous analyses have used the average furnace operating conditions, the microturbine will be sized to meet the maximum requirement for hot air when the burners are on high fire. The new burners can accept air heated up to 800°F and each has a rated capacity of 500,000 Btu/hr [Hauck Manufacturing Company, 2002]. This information can be used to determine the mass flow rate of fuel and air through the furnace during high fire. Once the maximum mass flow rate of air is known, the energy required to heat the air can be determined based on the enthalpy of the air at room temperature, h_0, and the enthalpy at the maximum inlet temperature, h_{max}:

$$\dot{Q}_{max} = \dot{m}_{max}(h_{max} - h_0). \tag{2.70}$$

Using this equation, the required rate of heat rejection from the microturbine is found to be 3.6 Dth/shift. Therefore, using a microturbine with an assumed average efficiency, η, of 80%, and a heat to power ratio, X, of 0.93, it is calculated that the required thermal output could be produced while generating 0.2 MW of power using the following equations [Darrow et al., 2014]:

$$\eta = \frac{\dot{E}_{power} + \dot{E}_{heat}}{\dot{E}_{CH_4}} \tag{2.71}$$

$$X = \frac{\dot{E}_{power}}{\dot{E}_{heat}}. \tag{2.72}$$

The second law efficiency of the combined zinc melt furnace/microturbine system is found to be 17% using Equation 2.37 where $\dot{X}_{utilized}$ is the exergy of the electricity generated plus the exergy used to heat the zinc alloy and $\dot{X}_{supplied}$ is the exergy of the fuel entering the microturbine and the zinc melt furnace during high fire operation.

In a topping cycle the furnace would provide heat to a working fluid in a power cycle. The exergy analysis in Section 2.1.2 estimated the work potential of the exhaust stream to be 0.37 Dth/shift or 14 kW. This is much smaller than any commercially available system. As such, this technology will not be analyzed further because it is not considered feasible.

2.2 Low Pressure Steam System

2.2.1 Existing System

All the calculations for the low pressure steam system where performed in EES and can be found in Appendix C. The low pressure steam system uses boilers which are tuned to use 4% excess O_2 by volume in the exhaust. Since this is the same as the zinc melt furnace, the combustion analysis, presented earlier in Equations 2.1 through 2.8, applies to the boilers as well. Similarly the boilers can also be thought of as a two part system as illustrated in Figure 2.8. The same simplifying assumptions applied to the zinc melt furnace apply to this system as well. Applying mass and energy balances to the burners results in the following equations:

$$0 = \dot{m}_{CH4} + \dot{m}_{air} - \dot{m}_{exhaust} \tag{2.73}$$

$$0 = \dot{E}_{CH_4} + \dot{E}_{air} - \dot{E}_{exhaust} - \dot{E}_{boiler}. \tag{2.74}$$

Applying mass and energy balances to the boilers results in the following equations:

$$0 = \dot{m}_{water,in} - \dot{m}_{steam,out} \tag{2.75}$$

$$0 = \dot{E}_{water,in} + \dot{E}_{boiler} - \dot{E}_{steam,out} - \dot{E}_{loss}. \tag{2.76}$$

Because the fuel consumption of the boilers and the percent excess O_2 are known, Equation 2.70 can be used along with the combustion analysis to solve for the air and exhaust mass flow rates. Then the measured inlet and exit conditions described in Section 1.2.2 are used to solve Equation 2.71 for the energy transfer rate to the boiler, $\dot{E}_{boiler}$. Since the boiler surfaces are reasonably insulated, the losses due to heat transfer are lumped into the $\dot{E}_{loss}$ term. The average operating

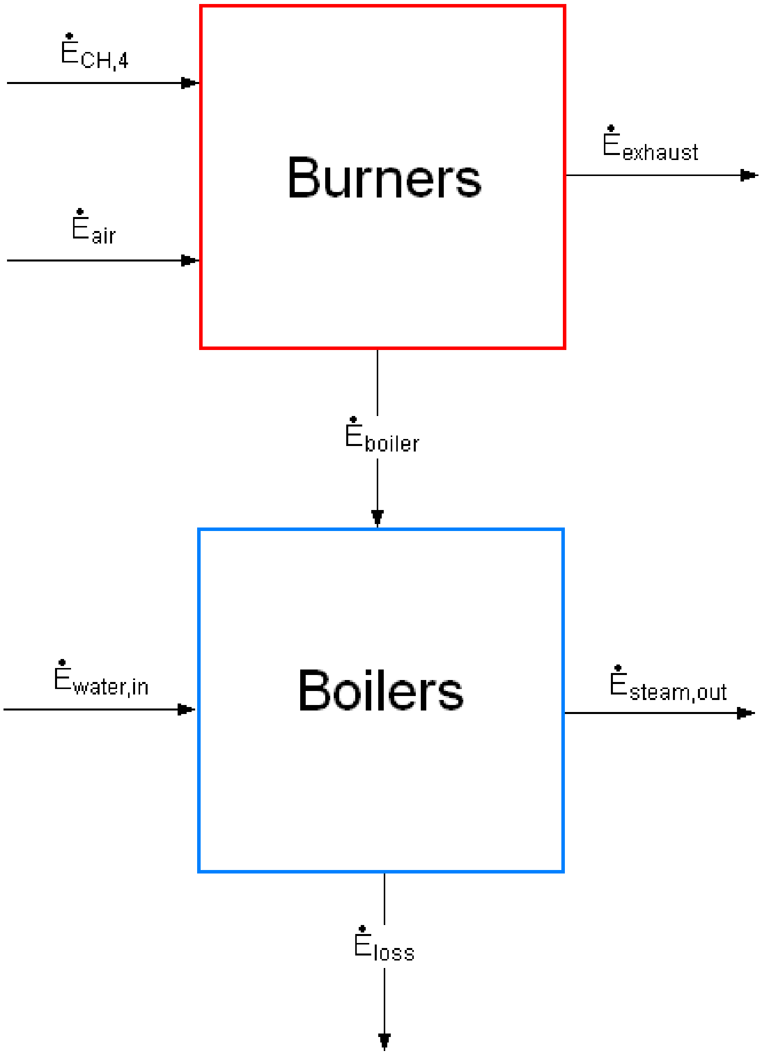

Figure 2.8: Low Pressure Steam System Energy Balance Diagram

conditions are used to solve for $\dot{E}_{loss}$. This term involves the heat transfer losses as stated earlier, along with blow down losses and deviation from ideal operating conditions. Solving the energy balances in EES results in the energy flow rates outlined in Table 2.12. It should be noted that very little energy in contained in the exhaust stream. There is energy contained in the water entering the furnace. This is because the water is first processed in a de-aerator before entering the boilers.

The process for applying the exergy balance to the boiler system is very similar to the analysis for the zinc melt furnace. First, applying the balance to

Table 2.12: Existing Low Pressure Steam System Energy Flow Rates

Energy Flow Rate	Dth/shift
$\dot{E}_{CH_4}$	27
$\dot{E}_{air}$	0
$\dot{E}_{exhaust}$	1.2
$\dot{E}_{boiler}$	26
$\dot{E}_{water,in}$	2.4
$\dot{E}_{steam,out}$	19
$\dot{E}_{loss}$	9.2

portion of the burners where the combustion process occurs and excluding the portion in which heat transfer occurs to the water results in:

$$0 = \dot{X}_{CH_4} + \dot{X}_{air} - \dot{X}_{exhaust} - \dot{X}_{destroyed,combustion}. \tag{2.77}$$

Extending the system and applying the exergy balance so that it includes the whole of each boiler with the exhaust leaving the system at the measured exhaust temperature of 235°F results in the following balance:

$$0 = \dot{X}_{CH_4} + \dot{X}_{air} + \dot{X}_{water,in} - \dot{X}_{exhaust} - \dot{X}_{steam,out} - \dot{X}_{destroyed,combustion} - \dot{X}_{destroyed,losses}. \tag{2.78}$$

Finally, applying the exergy balance so that the exhaust exits the system at the dead state temperature results in the following equation:

$$\begin{aligned} 0 =& \dot{X}_{CH_4} + \dot{X}_{air} + \dot{X}_{water,in} \\ & - \dot{X}_{exhaust} - \dot{X}_{steam,out} \\ & + \dot{X}_{destroyed,combustion} + \dot{X}_{destroyed,losses} + \dot{X}_{destroyed,exhaust}. \end{aligned} \tag{2.79}$$

The amount of exergy utilized to produce steam can be found by:

$$\dot{X}_{utilized} = \dot{X}_{steam,out} - \dot{X}_{water,in}. \tag{2.80}$$

The amount of exergy destroyed by each mechanism and the amount of exergy utilized for the production of steam is presented in Table 2.13. The table shows that this exergy destroyed by losses is two orders of magnitude larger than the exergy destroyed by allowing the exhaust to cool. This is why is it not surprising that heat recovery is found to not be viable. $\dot{X}_{destroyed,loss}$ cannot be reasonably reduced. This includes the exergy destroyed as heat is transfered from the hot combustion products to the water and steam and through the cases to the environment. This cannot be avoided. All of the exergy flows in the equations above are calculated in EES and the second law efficiency of the low pressure steam system is found to be 15%.

Table 2.13: Existing Low Pressure Steam System Exergy Flow Rates

Exergy Flow Rate	Dth/shift
$\dot{X}_{CH_4}$	27
$\dot{X}_{air}$	0
$\dot{X}_{water,in}$	0.27
$\dot{X}_{destroyed,combustion}$	7.8
$\dot{X}_{destroyed,losses}$	15
$\dot{X}_{destroyed,exhaust}$	0.15
$\dot{X}_{destroyed,total}$	23
$\dot{X}_{steam,out}$	4.1
$\dot{X}_{utilized}$	3.8

2.2.2 Process Heating

Unlike the zinc melt furnace, the burners on the boilers cannot accept preheated air. Therefore, this method of heat recovery will not be analyzed for this situation. Instead, the hot exhaust from the boilers can be used to heat the water coming into the boiler. The water currently enters the boilers at 220°F after being processed by the de-aerator. Since the exhaust air exits the boilers at $235°F$, the small difference between the water and the exhaust temperatures would make heat transfer ineffective. It would be more effective to heat the water going into the de-aerator to reduce the steam load from the de-aerator. Currently, no effort is being made to heat the returned condensation and make-up water going into the de-aerator. The temperature of the water entering the de-aerator is observed to be approximately 100°F. The de-aerator can accept water up to 180°F in its current configuration. Assuming all energy in the exhaust could be transfered to the water going into the de-aerator, then the reduction in the load can be calculated based on the enthalpy of the air at room temperature, h_0, and its enthalpy at the current exhaust temperature, h_{max}:

$$\dot{Q}_{max} = \dot{m}_{air}(h - h_0). \tag{2.81}$$

Using the exhaust from the boiler this recoverable heat is found to be 1.2 Dth/shift, which would only heat the water to 170°F. Earlier it was considered that the exhaust from the furnace also could be used to heat water. As indicated earlier, the zinc melt furnace can only provide 0.83 Dth/shift. Therefore, it would be better to use the boiler exhaust for water heating. Since the de-aerator is outside of the low pressure steam system analyzed the exergy going into and out of the system will change but the second law efficiency presented in Section 2.2.1 will not change.

2.2.3 Power Generation

As seen with the furnace, the exergy contained in the boiler exhaust is too small to generate power using any commercially available systems. However, the boiler could use energy recovered from a power generating process to pre-heat water entering the de-aerator. The systems available for on-site power generation that commonly recover exhaust energy in the form of hot water include reciprocating engines, gas turbines, microturbines and fuel cells [Darrow et al., 2014]. The waste heat resulting from the power generation, $\dot{E}_{heat}$, and the electrical power generated, represented by $\dot{E}_{power}$, can be calculated by the following series of equations:

$$\eta = \frac{\dot{E}_{power} + \dot{E}_{heat}}{\dot{E}_{CH_4}} \tag{2.82}$$

$$\eta_e = \frac{\dot{E}_{power}}{\dot{E}_{CH_4}} \tag{2.83}$$

$$X = \frac{\dot{E}_{power}}{\dot{E}_{heat}}. \tag{2.84}$$

In these equations, η is the overall efficiency of the power producing process, $\dot{E}_{CH_4}$ is the energy flow rate of fuel, η_e is the electrical efficiency of the power producing process, and X is the power to heat ratio of the power producing process. Average values for the power producing processes evaluated are reported by the EPA [Darrow et al., 2014]. Gas turbines have poor performance at partial load; since the boiler often operates at a partial load, this technology will not be considered further. Reciprocating engines have an average efficiency of 75% and an average power to heat ratio of 0.75 [Darrow et al., 2014]. If this is used to heat the average flow rate of water going into the de-aerator from 50°F to 180°F, then the rate at which heat must be supplied is:

$$\dot{E}_{heat} = \dot{m}_{water}(h_{max} - h_{water}). \tag{2.85}$$

In this equation h_{max} is the enthalpy of the water when heated and h_{water} is the enthalpy as it enters the de-aerator. Based on the equation, 0.15 Dth/shift of heat must be supplied by the reciprocating engine, and thus it would need to generation 0.061 MW of power. The second law efficiency is calculated using Equation 2.36, where $\dot{X}_{utilized}$ is the exergy added to the water entering the de-aerator plus the exergy delivered by the engine as electrical power, and $\dot{X}_{supplied}$ is the exergy supplied by the fuel burned in the power producing process. Applying this definition to the boiler and reciprocating engine system results in an efficiency of 3.7%.

Microturbines have an efficiency of 80% and a power to heat ratio of 0.93 [Darrow et al., 2014]. Following the same process used for the reciprocating engine, it can be calculated that heating the water entering the de-aerator would require the generation of 20 kW of power. As this is smaller than available commercial systems, this method of heat recovery will not be evaluated further.

Fuel cells have an average efficiency of 67.5% and an average power to heat ratio of 1.5 [Darrow et al., 2014]. Heating the water entering the de-aerator would require the generation of 1.9 MW of power. Applying the same process used for the reciprocating engine and microturbine to the boiler and fuel cell system results in an efficiency of 6.6%.

2.3 Chilled Water System

2.3.1 Theoretical System

STRATTEC does not currently own a chilled water system that has the potential for heat recovery. However, since STRATTEC's current system is reaching the end of its projected life, a new system will need to be installed in the coming years. Heat recovery is possible when a chiller systems utilizes absorption cooling technology. A formal evaluation of the chiller load should be conducted before any system is quoted. It is reasonable to assume that the system will be sized somewhere between the current load of 300 TR and an increased load up to 500 TR. The evaluation here will be presented so that the analysis can be applied to a system in this range.

Using the load on the chilled water system, represented by $\dot{E}_{load}$, and the COP, the maximum rate of heat needed to power the system at full load, $\dot{E}_{heat}$, can be calculated:

$$\dot{E}_{heat} = \frac{\dot{E}_{load}}{COP}. \tag{2.86}$$

For this analysis, the nominal loads of 300 TR and 500 TR will be used. Once the chiller load is evaluated, a loading factor can be applied to this analysis to determine how the real system will perform. The heat required to run an absorption cooling system can be accepted from another process heating system, as shown in Section 2.3.2, or from a power producing process, as shown in Section 2.3.3. This heat can be recovered in the form of hot air or exhaust gas, hot water, low pressure steam or high pressure steam. Absorption chillers can be either single-stage or two-stage. Single-stage chillers have a typical COP of 0.7 while two-stage chillers have a typical COP of 0.98 but require higher grade heat [U.S. Department of Energy, 2012]. Certain absorption cooling units are designed to accept heat in different forms. This analysis will utilize several different models of absorption chillers to address a majority of the reasonable options for STRATTEC.

2.3.2 Process Heating

The two major sources of heat in an exhaust stream at STRATTEC are the zinc melt furnace and low pressure steam system as analyzed in Sections 2.1 and 2.2. As previously calculated and summarized in Table 2.4, the exhaust stream from the zinc melt furnace has an energy flow rate of 0.83 Dth/shift on average. Because the energy is measured relative to the energy at the dead state, this represents the average amount of energy that could be recovered if the exhaust were cooled to room temperature. However, even more energy could be recovered when the furnace operates at high fire. Based on the approach described in Section 2.1.7, a maximum of 6.0 Dth/shift could be recovered while operating at high fire. Similarly, Table 2.12 shows that the exhaust stream from the low pressure steam system could provide 1.2 Dth/shift of heat on average, and it has been determined that it could provide a maximum of 8.3 Dth/shift at max capacity. Based on these numbers, the best case scenario would be to power a two-stage absorption chiller using the boiler when it operates at high fire, providing the maximum amount of heat. Applying Equation 2.86, 84 TR could be generated by the absorption chiller in this situation. This is not sufficient to meet the cooling load of STRATTEC's facility.

2.3.3 Power Generation

Absorption cooling systems can recover heat from a variety of power producing process. These include steam turbines, reciprocating engines, gas turbines, microturbines and fuels cells [Darrow et al., 2014]. The waste heat resulting from the power generation,$\dot{E}_{heat}$, and the electrical power generated, represented by $\dot{E}_{power}$, can be calculated by the following series of equations:

$$\eta = \frac{\dot{E}_{power} + \dot{E}_{heat}}{\dot{E}_{CH_4}} \tag{2.87}$$

$$\eta_e = \frac{\dot{E}_{power}}{\dot{E}_{CH_4}} \tag{2.88}$$

$$X = \frac{\dot{E}_{power}}{\dot{E}_{heat}}. \tag{2.89}$$

In these equations, η is the overall efficiency of the power producing process, $\dot{E}_{CH_4}$ is the energy flow rate of fuel, η_e is the electrical efficiency of the power producing process, and X is the power to heat ratio of the power producing process. Average values for the power producing processes evaluated are reported by the EPA [Darrow et al., 2014]. For those processes that appeared viable, actual values have been obtained from potential suppliers.

As explained earlier, gas turbines have poor performance at partial load. This makes gas turbines a poor fit for this application as the chillers may often run at a partial load. Steam turbines have an average overall efficiency of 80% and an average power to heat ratio of 0.2 [Darrow et al., 2014]. Heat can be recovered from steam turbines in the form of either low or high pressure steam. Low pressure steam can be utilized by a single-stage absorption chiller with an average COP of 0.793 [Johnson Controls, 2010]. With this COP, a 500 TR chiller would require 2,218 kW of heat input. Based on the steam turbine's power to heat ratio, it would need to generate 0.44 MW of power to meet this demand for heat. High pressure steam can be utilized by a two stage absorption chiller with an average COP of 1.38 [Johnson Controls, 2010]. In this case the steam turbine would only need to produce 0.25 MW of power to meet the chiller load. Typical commercial steam turbines are designed to produce between 0.5 and 250 MW of power. As such, this is not a good fit for this application [Darrow et al., 2014].

Reciprocating engines have an average overall efficiency of 75% and an average power to heat ratio of 0.75 [Darrow et al., 2014]. Heat can be recovered from reciprocating engines in the form of either hot water or low pressure steam [Darrow et al., 2014]. Both of these options can be utilized by a single-stage absorption chiller system [Johnson Controls, 2010]. If the chiller has a COP of 0.793, this would require the reciprocating engine to produce 2.19 MW of electricity and would result in a system second law efficiency of 43%. The second law efficiency is calculated using Equation 2.37, where $\dot{X}_{utilized}$ is the exergy removed from the water cooled by the chiller plus the exergy delivered by the engine as electrical power, and $\dot{X}_{supplied}$ is the exergy supplied by the fuel burned in the power producing process.

Microturbines have a quoted overall efficiency of 80% and a power to heat ratio of 0.93 [Darrow et al., 2014]. Heat can be recovered from microturbines in the form of either heat, hot water or low pressure steam [Darrow et al., 2014]. Both hot water and low pressure steam can be utilized by a single-stage absorption chiller system [Johnson Controls, 2010]. Assuming the chiller has a COP of 0.793, this would require the microturbine to produce 2.06 MW with a system second law efficiency of 40%. If the heat is used to drive a two-stage absorption chiller instead, the miroturbine would only need to generate 1.45 MW of electricity with a system second law efficiency of 40%.

Fuel cells have an average overall efficiency of 67.5% and an average power to heat ratio of 1.5 [Darrow et al., 2014]. Heat can be recovered from fuel cells in the form of either hot water, low or high pressure steam. Hot water and low pressure steam can be utilized by a single-stage absorption chiller system. Assuming a chiller COP of 0.793, this would require the fuel cell to produce 2.84 MW of electrical power, with a system second law efficiency of 27%. High pressure steam can be utilized by a two-stage absorption chiller system with a higher COP of 1.38. Therefore, the fuel cell would only need to produce 1.63 MW of electricity to meet the chiller heat load with a system second law efficiency of 27%.

The analysis assumes that the power generation systems are sized to meet the heat load of the absorption chiller. The resulting systems were estimated to produce between 0.25 and 2.84 MW of power. The STRATTEC facility has a base electrical load of 2.1 MW. Therefore, it is possible for the electricity generated to exceed this base load, but only with the fuel cell running at full power with a single-stage chiller. This could be avoided by using a two-stage chiller with a higher COP.

CHAPTER 3

THERMO-ECONOMIC ANALYSIS

The analysis performed in Chapter 2 can be used to determine the economic viability of each heat recovery method. For the economic analysis it will be assumed that natural gas costs \$7.60/Dth while electricity costs \$0.093459/kWh during peak hours, 10 am to 10 pm, and \$0.05104 during non-peak hours. The natural gas price used is the average price per Dth for the 2014 fiscal year, from July 2013 through June 1014, while the electrical rates used are the rates fixed by We Energies for 2014. Projects will be evaluated based on the simple payback period for the project. The simple payback period can be evaluated by the following equations:

$$Payback\ Period = \frac{Project\ Cost}{Cost\ Savings} \tag{3.1}$$

$$Cost\ Savings = \Delta E_{ng} Cost_{ng} + \Delta E_{elec} Cost_{elec}. \tag{3.2}$$

In this equation, the project cost is made up of the cost of equipment, labor and downtime associated with implementing the improvement minus any applicable utility or government incentives. The utility and government incentive that will be used for this analysis are the Focus on Energy custom incentive program and the Federal Business Energy Investment Tax Credit. The Focus on Energy custom incentive provides \$0.04 per kWH saved, \$125 per peak kW reduced and \$0.4 per therm of natural gas saved [Focus on Energy, 2014]. The program requires that the project has a payback period between 1.5 and 10 years [Focus on Energy, 2014]. Additionally the program will only cover up to 50% of a project's cost at a maximum of \$200,000 per project and \$400,000 per year [Focus on Energy, 2014]. The Federal Business Energy Investment Tax Credit provides a tax credit of 10% of expenditures on CHP projects up to 50 MW with an energy efficiency greater than 60% [U.S. Department of Energy, 2014a]. ΔE_{ng} is the change in annual natural gas use and ΔE_{elec} is the change in annual electricity use, while $Cost_{ng}$ is the cost of natural gas and $Cost_{elec}$ is the cost of electricity. The change in natural gas use is calculated by comparing the energy flow rate into a process before and after modifications, $\dot{E}_{CH_4,old}$ and $\dot{E}_{CH_4,new}$, respectively:

$$\Delta E_{ng} = \Delta t(\dot{E}_{CH_4,old} - \dot{E}_{CH_4,new}). \tag{3.3}$$

To calculate the energy saved each year, the time period, Δt, is set equal to 1095 shifts. This assumes 3 shifts a day, 7 days a week. It is currently STRATTEC's intention to move toward this type of work schedule, but the calculations could easily be modified to any number of production shifts per year.

3.1 Zinc Melt Furnace

The new burners to optimize the existing melt furnace without heat recovery have already been implemented. The new burners recommended in section 2.1.2 were quoted to cost \$15,844 to purchase and install. The cost savings is expected to be \$9,513 per year. This will result in a simple payback period of 1.67 years using Equation 3.1. For this situation, ΔE_{ng} is based on the difference between $\dot{E}_{CH_4}$ shown in Table 2.2 and $\dot{E}_{CH_4}$ shown in Table 2.4.

Utilizing the exhaust from the zinc melt furnace to heat zinc bars before melting, as shown in Section 2.1.3, would result in a cost savings of \$1,535 per year using Equation 3.2. In this situation ΔE_{ng} is based on the difference between $\dot{E}_{CH_4}$ shown in Table 2.4 and $\dot{E}_{CH_4}$ shown in Table 2.6. This method of heat recovery would require installing a rack in the furnace to hold the zinc bars while they are heated before being introduced into the bath. The space for this rack inside the furnace hood is limited; as such, even if production volume increases, the amount of zinc being heated would remain constant. However, the amount of time spent at high-fire would increase if production volume increases, providing more heat to the zinc in the exhaust stream, and the cost savings would increase. After the onset of this project, modifications were made to the hood on the furnace that have eliminated what room there was for zinc heating. If changes are made so all scrap is processed at the machine where it is produced or the set-up is changed to allow room under the hood for bars, then zinc heating could again be viable.

Utilizing the exhaust to heat air for combustion would result in a cost savings of $2,916 per year at current production volume using Equation 3.2. In this situation, ΔE_{ng} is based on the difference between $\dot{E}_{CH_4}$ shown in Table 2.4 and $\dot{E}_{CH_4}$ shown in Table 2.8. If production volume were to increase, the cost savings would increase proportionally since the heat exchanger is sized to the furnace during high fire operation and the furnace would spend more time at high fire. The heat pipe heat exchanger supplied by MANTRA is quoted to cost $25,244 [P. Cranney, personal communication, May 29, 2014]. This results in a simple payback period of 8.5 years calculated using Equation 3.1, which is significantly longer than that required by STRATTEC. Applying heat recovery via both zinc and air would result in a cost savings of $4,640 per year using Equation 3.2. In this situation, ΔE_{ng} is based on the difference between $\dot{E}_{CH_4}$ shown in Table 2.4 and $\dot{E}_{CH_4}$ shown in Table 2.10. If production volume were to increase, the cost savings would follow suit. While these cost savings are greater than with air or zinc heating alone, the issues of space for zinc heating and the cost of air heating apply here as well.

Analyzing the operating costs of a topping cycle that uses a microturbine to produce electricity while supplying the zinc melt furnace with hot air for combustion reveals that this system would reduce operating costs but have a long payback period. Using Equation 3.2, the cost savings is found to be minimal becuase the decrease in electricity use barely makes up for the increase in gas use. ΔE_{ng} is based on the difference between $\dot{E}_{CH_4}$ shown in Table 2.4 and $\dot{E}_{CH_4}$ shown in Table 2.8 plus the fuel used by the microturbine calculated using Equations 2.87 through 2.89. The electricity produced by the microturbine is also found using Equations 2.87 through 2.89. Although the microturbine will save \$8,700 per year in electricity use and \$4,700 per year in natural gas use by the zinc melt furnace, it is estimated that maintenance on such a system would be \$2,200 per year and the natural gas use by the microturbine would be \$8,000 per year. The maintenance cost is estimated using data from the EPA indicating that microturbine systems typically cost \$0.0185 per kWh to maintain [Darrow et al., 2014].

3.2 Low Pressure Steam System

Heating the water entering the de-aerator tank would result in a cost savings of \$2,920 per year using Equation 3.2. ΔE_{ng} is based on the reduction in load calculated in Section 2.2. This is not sufficient to justify the needed expenses based on an understanding of the cost associated with taking the boiler system down for a period of time needed for such improvements. Generating power while heating water entering the de-aerator via a reciprocating engine or a fuel cell would result in a negative cost savings.

3.3 Chilled Water System

Several systems were quoted to determine the economic feasibility of implementing an absorption chiller. The systems quoted are a microturbine/absorption chiller system and a reciprocating/absorption chiller system. Both systems were quoted for a 300 TR chiller system and a 500 TR chiller system. Upon quoting the systems, it was realized that the reciprocating/absorption chiller system is only capable of generating enough heat for a 300 TR system with a simple payback of 7.2 years using Equation 3.1. For these calculations ΔE_{ng} is based on $\dot{E}_{CH_4}$, the energy flow rate of gas used by the reciprocating engine, calculated in Section 2.3.2. The term ΔE_{elec} is equal to $\dot{E}_{power}$, the power output of the engine calculated in Section 2.3.2, minus the power use by the current chiller, reported by the supplier as 0.897 kW/Ton. The microturbine/absorption chiller system resulted in a much more promising simple payback of 5.4 years for a 300 TR system. For the 300 TR chiller systems, the systems are designed to meet the current cooling load. If the new chiller is sized to have extra capacity that would accommodate future growth in production, it is estimated that a 500 TR system would be adequate. For a 500 TR system, the simple payback would be 5.3 years when the microturbines are controlled to run at full load during peak hours regardless of chiller load. In order to used standard sized equipment, the 500 TR system would utilize microturbines that could serve a 600 TR system. This gives the system the ability to over-produce electricity in excess of that generated while producing heat for the absorption cooling process. This is only economically beneficial during peak hours.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 Zinc Melt Furnace

At this time, no additional changes should be made to the zinc melt furnace. If the process changes so that all zinc scrap is melted at the machine generating the scrap and only bars are added to the the zinc melt furnace, then zinc heating should be implemented. This would increase the savings possible through zinc heating from $1,535 per year to $3,300 per year. The implementation of this method of heat recovery is relatively simple, including only the installation of a shelf in the furnace hood. The main problem with applying heat recovery in the form of air heating to the zinc melt furnace is the small amount of time the furnace operates at high fire. If the furnace ever approached full load, then a four year payback or better could be possible for air heating. However, acheiving a four year payback for air heating would require an increase in load of over 400%.

4.2 Low Pressure Steam System

At this time, no changes should be made to the boiler system. However, if the amount of steam generated or the cost of natural gas increases significantly, then this analysis should be revisited.

4.3 Chilled Water System

When the chiller system is replaced, the actual chiller load should be determined and a microturbine/absorption cooling system of the appropriate size implemented.

4.4 Overall

Heat recovery is just one way to decrease energy costs. This analysis, while focusing on heat recovery, also illuminated sources of inefficiencies in the processes, such as the burners on the zinc melt furnace. Now that models have been developed for each major process, the tracking of the energy used by major processes should continue. This information is necessary to continue making improvements in energy efficiency. As equipment ages and technology improves, there will always be new opportunities for energy savings.

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APPENDIX A

FURNACE OPERATOR FORM

Table A.1: Form Used to Collect Data From Furnace Operators

Shift	
ID #	
Bars Melted	
Pounds of Scrap Melted	
Gas Meter Reading at the Beginning of Shift	
Gas Meter Reading at the End of Shift	

APPENDIX B

ZINC MELT FURNACE EES CODE

Zinc Melt Furnace Section 1.png

```
 "Dead State Conditions"
 T_0=converttemp('C','F',25)                    {Dead State Temperature in F}
 P_0=1*convert('atm','psia')                    {Dead State Pressure in psia}
 "Furnace Operating Parameters"
 T_exhaust=1100                                 {Temperature of the exhaust in F as it leaves the
--                                              induction tubes}
 T_zinc=820                                     {Temperture of the molten zinc in F}
 T_case=180                                     {Temperature of the case of the furnace in F}
 phi_O2P=0.04                                   {Volume fraction of O2 in the combustion products}
 P_CH4=(16+101.325)*convert('kPa','psia')       {The pressure of the natural gas in psia as
--                                              received by the Furnace}
 "Furnace Current Operating Conditions"
 ng=3900[ft^3/shift]                            {average flow rate of natural gas in ft^3/shift during
--                                              production as recorded by furnace operators}
 m_ng=ng*density(CH4, T=T_0, P=P_CH4)           {average mass flow rate of natural gas, modeled
--                                              as CH4, during production in lb_m/s}
 m_zinc=11000[lbm/shift]                        {average mass flow rate of zinc in lb_m/shift during
--                                              production as recorded by furnace operators}
 "Energy Costs"
 cost_ng=0.0000076[$/Btu]                       {average natural gas price for FY14}
 cost_elec=(cost_nonpeak+(cost_demand/(30.5*24[h]))+cost_peak+(cost_demand/(30.5*24[h]))+(
--cost_demand_peak/(30.5*12[h])))/2             {average of average peak and average non-
--                                              peak rates}
 cost_elec_p=cost_peak+(cost_demand/(30.5*24[h])+(cost_demand_peak/(30.5*12[h]))){average peak
--                                              rate including demand charge}
 cost_elec_np=cost_nonpeak+(cost_demand/(30.5*24[h])){average non-peak rate including demand
--                                              charge}
 cost_nonpeak=0.05104[$/kWh]                    {non-peak electrical rate}
 cost_demand=1.306[$/kW]                        {monthly non-peak demand charge}
 cost_peak=0.07118[$/kWh]                       {peak electrical rate}
 cost_demand_peak=7.501[$/kW]                   {monthly peak demand charge}
 "Zinc Properties"
 c_zinc=0.1                                     {heat capacity of ZAMAK 5 in Btu/lb_m-F taken
--                                              from supplier website, http://www.eazall.com/zinc-
```

Zinc Melt Furnace Section 2.png

```
                                                    die-casting-alloys}
rho_zinc=0.24                                       {density of ZAMAK 5 in lb_m/in^3 taken from
--                                                  supplier website, http://www.eazall.com/zinc-die-
--                                                  casting-alloys}
k_zinc=62.9*convert('Btu/ft-hr-F','Btu/in-shift-F') {thermal conductivity of ZAMAK 5 in Btu/in-s-F
--                                                  taken from supplier website, http://www.eazall.com/
--                                                  zinc-die-casting-alloys}
h_fg_zinc = 48.6[Btu/lbm]                           {heat of fusion of ZAMAK 5 in Btu/lb_m from Ryan
--                                                  Winter}
T_melt=722                                          {melting point of ZAMAK 5}
"Stoichiometry"
n_O2R=(2[mol]+x)/((2[mol]+x)+(2[mol]+x)*3.76)       {mole fraction of O2 in the combustion reactants}
n_N2R=((2[mol]+x)*3.76)/((2[mol]+x)+(2[mol]+x)*3.76) {mole fraction of N2 in the combustion reactants}
n_CO2P=1[mol]/(1[mol]+2[mol]+x+(2[mol]+x)*3.76)     {mole fraction of CO2 in the combustion products}
n_H2OP=2[mol]/(1[mol]+2[mol]+x+(2[mol]+x)*3.76)     {mole fraction of H2O in the combustion products}
n_O2P=x/(1[mol]+2[mol]+x+(2[mol]+x)*3.76)           {mole fraction of O2 in the combustion products}
n_N2P=((2[mol]+x)*3.76)/(1[mol]+2[mol]+x+(2[mol]+x)*3.76){mole fraction of N2 in the combustion products}
w_O2R=((2[mol]+x)*molarmass(O2))/(1[mol]*molarmass(CH4)){mass fraction of O2 in the combustion
--                                                  reactants}
w_N2R=((2[mol]+x)*3.76*molarmass(N2))/(1[mol]*molarmass(CH4)){mass fraction of N2 in the combustion
--                                                  reactants}
w_CO2P=(1[mol]*molarmass(CO2))/(1[mol]*molarmass(CH4)){mass fraction of CO2 in the combustion
--                                                  products}
w_H2OP=(2[mol]*molarmass(H2O))/(1[mol]*molarmass(CH4)){mass fraction of H2O in the combustion
--                                                  products}
w_O2P=(x*molarmass(O2))/(1[mol]*molarmass(CH4))     {mass fraction of O2 in the combustion products}
w_N2P=((2[mol]+x)*3.76*molarmass(N2))/(1[mol]*molarmass(CH4)){mass fraction of N2 in the combustion
--                                                  products}
p_O2R=n_O2R*P_0                                     {partial pressure of O2 in the combustion
--                                                  reactants}
p_N2R=n_N2R*P_0                                     {partial pressure of N2 in the combustion
--                                                  reactants}
p_CO2P=n_CO2P*P_0                                   {partial pressure of CO2 in the combustion
--                                                  products}
```

Zinc Melt Furnace Section 3.png

```
p_H2OP=n_H2OP*P_0                                {partial pressure of H2O in the combustion
..                                               products}
p_O2P=n_O2P*P_0                                  {partial pressure of O2 in the combustion products}
p_N2P=n_N2P*P_0                                  {partial pressure of N2 in the combustions
..                                               producs}
phi_O2P=(x*MWO2*volume(O2, T=T_exhaust, P=P_0))/(1[mol]*MWCO2*volume(CO2, T=T_exhaust, P=P_0)
..+2[mol]*MWH2O*volume(H2O, T=T_exhaust, P=P_0)+x*MWO2*volume(O2, T=T_exhaust, P=P_0)+(2[mol]+
..x)*3.76*MWN2*volume(N2, T=T_exhaust, P=P_0))   {volume fraction of O2 in the combustion products}
MWO2=molarmass(O2)*convert(lb_m/lbmol,lb_m/mol)  {molar mass of O2 in lb_m/mol}
MWCO2=molarmass(CO2)*convert(lb_m/lbmol,lb_m/mol){molar mass of CO2 in lb_m/mol}
MWH2O=molarmass(H2O)*convert(lb_m/lbmol,lb_m/mol){molar mass of H2O in lb_m/mol}
MWN2=molarmass(N2)*convert(lb_m/lbmol,lb_m/mol)  {molar mass of N2 in lb_m/mol}
"Zinc Melt Furnace Energy and Exergy Balance w/o Heat Recovery"
"Energy In"
E_CH4=m_ng*(enthalpy(CH4, T=T_0)-w_CO2P*enthalpy(CO2, T=T_0)-w_H2OP*enthalpy(H2O, T=T_0)-
..w_O2P*enthalpy(O2, T=T_0)-w_N2P*enthalpy(N2, T=T_0)){Energy entering the burners in the form of
..                                               natural gas estimated as CH4}
E_air=m_ng*(w_O2R*enthalpy(O2, T=T_0)+w_N2R*enthalpy(N2, T=T_0)){Energy entering the burners in the
..                                               form of air estimated as O2 and N2}
E_zinc_in=m_zinc*(T_0-T_0)*c_zinc                {Energy entering the furnace in the form of ZAMAK
..                                               5 bars and scrap}
"Energy Out"
E_exhaust=m_ng*(w_CO2P*enthalpy(CO2, T=T_exhaust)+w_H2OP*enthalpy(H2O, T=T_exhaust)+w_O2P*
..enthalpy(O2, T=T_exhaust)+w_N2P*enthalpy(N2, T=T_exhaust)-w_CO2P*enthalpy(CO2, T=T_0)-w_H2OP*
..enthalpy(H2O, T=T_0)-w_O2P*enthalpy(O2, T=T_0)-w_N2P*enthalpy(N2, T=T_0)){Energy leaving the
..                                               burners in the form of exhaust estimated as CO2,
..                                               H2O, O2, and N2}
E_combustion_products=m_ng*(w_CO2P*enthalpy(CO2, T=T_flame)+w_H2OP*enthalpy(H2O, T=T_flame)+
..w_O2P*enthalpy(O2, T=T_flame)+w_N2P*enthalpy(N2, T=T_flame)-w_CO2P*enthalpy(CO2, T=T_0)-
..w_H2OP*enthalpy(H2O, T=T_0)-w_O2P*enthalpy(O2, T=T_0)+w_N2P*enthalpy(N2, T=T_0))
E_zinc_out=m_zinc*((T_zinc-T_0)*c_zinc + h_fg_zinc)   {Energy leaving the furnace in the form of molten
..                                               ZAMAK 5}
"Energy Balance"
E_CH4+E_air=E_exhaust+E_furnace                  {E_furnace is the energy transfered from the
```

Zinc Melt Furnace Section 4.png

```
                                                   burners to the furnace}
  E_zinc_in+E_furnace=E_zinc_out+E_heattransfer+E_loss
  E_combustion_products=E_exhaust+E_furnace
  "Exergy In"
  X_CH4=m_ng*(enthalpy(CH4, T=T_0)+w_O2R*enthalpy(O2, T=T_0)+w_N2R*enthalpy(N2, T=T_0)-w_CO2P*
..enthalpy(CO2, T=T_0)-w_H2OP*enthalpy(H2O, T=T_0)-w_O2P*enthalpy(O2, T=T_0)-w_N2P*enthalpy(N2,
..T=T_0)-converttemp(F,R,T_0)*(entropy(CH4, T=T_0, P=P_CH4)+w_O2R*entropy(O2, T=T_0, P=P_O2R)+
..w_N2R*entropy(N2, T=T_0, P=P_N2R)-w_CO2P*entropy(CO2, T=T_0, P=P_CO2P)-w_H2OP*entropy(H2O,
..T=T_0, P=P_H2OP)-w_O2P*entropy(O2, T=T_0, P=P_O2P)-w_N2P*entropy(N2, T=T_0, P=P_N2P)))
  "Exergy Out"
  X_combustion_products=m_ng*(w_CO2P*(enthalpy(CO2, T=T_flame)-enthalpy(CO2, T=T_0)-converttemp(F,
..R,T_0)*(entropy(CO2, T=T_flame, P=P_CO2P)-entropy(CO2, T=T_0, P=P_CO2P)))+w_H2OP*(enthalpy(H2O,
.. T=T_flame)-enthalpy(H2O, T=T_0)-converttemp(F,R,T_0)*(entropy(H2O, T=T_flame, P=P_H2OP)-entropy(
..H2O, T=T_0, P=P_H2OP)))+w_O2P*(enthalpy(O2, T=T_flame)-enthalpy(O2, T=T_0)-converttemp(F,R,T_0)*(
..entropy(O2, T=T_flame, P=P_O2P)-entropy(O2, T=T_0, P=P_O2P)))+w_N2P*(enthalpy(N2, T=T_flame)-
..enthalpy(N2, T=T_0)-converttemp(F,R,T_0)*(entropy(N2, T=T_flame, P=P_N2P)-entropy(N2, T=T_0, P=
..P_N2P))))
  X_exhaust_interior=m_ng*(w_CO2P*(enthalpy(CO2, T=T_exhaust)-enthalpy(CO2, T=T_0)-converttemp(F,R,
..T_0)*(entropy(CO2, T=T_exhaust, P=P_CO2P)-entropy(CO2, T=T_0, P=P_CO2P)))+w_H2OP*(enthalpy(H2O,
.. T=T_exhaust)-enthalpy(H2O, T=T_0)-converttemp(F,R,T_0)*(entropy(H2O, T=T_exhaust, P=P_H2OP)-
..entropy(H2O, T=T_0, P=P_H2OP)))+w_O2P*(enthalpy(O2, T=T_exhaust)-enthalpy(O2, T=T_0)-converttemp(
..F,R,T_0)*(entropy(O2, T=T_exhaust, P=P_O2P)-entropy(O2, T=T_0, P=P_O2P)))+w_N2P*(enthalpy(N2, T=
..T_exhaust)-enthalpy(N2, T=T_0)-converttemp(F,R,T_0)*(entropy(N2, T=T_exhaust, P=P_N2P)-entropy(N2,
..T=T_0, P=P_N2P))))
  X_zinc_out=m_zinc*((T_zinc)*c_zinc-converttemp(F,R,T_0)*c_zinc*ln(converttemp(F,R,T_zinc)))-m_zinc*(
..T_0*c_zinc-converttemp(F,R,T_0)*c_zinc*ln(converttemp(F,R,T_0)))+m_zinc*(h_fg_zinc/T_melt)
  "Exergy"
  X_destroyed_combustion=X_CH4-X_combustion_products
  X_destroyed_losses=X_combustion_products-X_exhaust_interior-X_zinc_out
  X_destroyed_exhaust=X_exhaust_interior
  X_destroyed_total=X_destroyed_combustion+X_destroyed_losses+X_destroyed_exhaust
  X_supplied=X_CH4
  X_utilized=X_zinc_out
  "Second Law Efficiency"
```

Zinc Melt Furnace Section 5.png

```
eta_II=X_utilized/X_supplied
"Zinc Melt Furnace Zinc w/o Heat Recovery Operating Cost"
Cost=E_CH4*cost_ng
"Funace Heat Transfer Claculations"
E_heattransfer=E_case+E_pumpwell+E_burnerarea        {The energy lost from the furnace at all times via
--                                                   heat transfer}
E_case=q_case_conv+q_case_rad                        {The energy lost from the furnace via the sides}
q_case_conv=h_out_case*AS*(T_case-T_0)               {The energy transfered from the furnace to the
--                                                   surroundings via convection from the sides}
h_out_case=Nussalt_out_case*k_out_case/Hight         {The average heat transfer coefficient}
AS=A1*2+A2*2                                         {The total surface area of the furnace}
Nussalt_out_case=(.68+(0.670*Re_out_case^(1/4)))/((1+(0.492/Pr_out_case)^(9/16))^(4/9)){Nussalt number
--                                                   for free convection from a flat vertical plate with
--                                                   laminar air flow}
k_out_case=conductivity(air, T=(T_case+T_0)/2)*convert('Btu/hr-ft-R','Btu/shift-in-F'){Conductivity}
Hight=52.5                                           {The height of the sides of the furnace in in}
A1=5092.5                                            {Surface area of the short sides of the furnace}
A2=5775                                              {Surface area of the long sides of the furnace}
Re_out_case=Gr_out_case*Pr_out_case                  {The Reynolds number}
Pr_out_case=nu_out_case/alpha_out_case               {Prandlts number}
Gr_out_case=g#*convert('ft/s^2','in/shift^2')*beta_out_case*(T_case-T_0)*(Hight^3/nu_out_case^2)
                                                     {Grashof Number}
nu_out_case=mu_out_case/rho_out_case                 {Kinematic viscosity}
alpha_out_case=k_out_case/(rho_out_case*cp_out_case){Thermal Diffusivity}
beta_out_case=volexpcoef(air, T=(T_case+T_0)/2)*convert('1/R','1/F'){Coefficienty of Thermal Expansion}
mu_out_case=viscosity(air, T=(T_case+T_0)/2)*convert('lb_m/ft-hr','lb_m/in-shift'){Viscosity}
rho_out_case=density(air, T=(T_case+T_0)/2, P=P_0)*convert('lb_m/ft^3','lb_m/in^3'){Density}
cp_out_case=CP(air, T=(T_case+T_0)/2)*convert('Btu/lb_m-R','Btu/lb_m-F'){Specific Heat}
q_case_rad=sigma*AS*e*(T_case^4-T_0^4)               {The energy lost from the furnace to the
--                                                   environment via radiation when the hood is open}
sigma=sigma#*convert('Btu/hr-ft^2-R^4','Btu/shift-in^2-F^4'){Stefan-Boltzman constant}
e=.11
E_pumpwell=q_pumpwell_conv+q_pumpwell_rad            {The energy lost from the surface of the molten
--                                                   zinc in the pumpwell}
```

Zinc Melt Furnace Section 6.png

```
q_pumpwell_conv=h_pumpwell*A_pumpwell*(T_zinc-T_0){The energy lost from the furnace to the
..                                                  environment via convection}
h_pumpwell=Nussalt_pumpwell*k_pumpwell/(A_pumpwell/P_pumpwell)  {average heat transfer coefficient}
A_pumpwell=324                                      {Surface area of the bath in in^2}
Nussalt_pumpwell=0.15*Ra_pumpwell^0.33              {Nussalt number for turbulent natural convection
..                                                  from a horizontal flat plate facing upward}
k_pumpwell=conductivity(air, T=(T_zinc+T_0)/2)*convert('Btu/hr-ft-R','Btu/shift-in-F'){Conductivity}
P_pumpwell=72                                       {Perimeter of the bath in in}
Ra_pumpwell=Gr_pumpwell*Pr_pumpwell                 {Rayleigh number}
Gr_pumpwell=g#*convert('ft/s^2','in/shift^2')*beta_pumpwell*(T_zinc-T_0)*(A_pumpwell/P_pumpwell)^3/
..nu_pumpwell^2                                     {Grashof number}
Pr_pumpwell=nu_pumpwell/alpha_pumpwell              {Prandlts number}
beta_pumpwell=volexpcoef(air, T=(T_zinc+T_0)/2)*convert('1/R','1/F'){Coefficient of thermal expansion}
nu_pumpwell=mu_pumpwell/rho_pumpwell                {Kinematic viscosity}
alpha_pumpwell=k_pumpwell/(rho_pumpwell*cp_pumpwell){Thermal Diffusivity}
mu_pumpwell=viscosity(air, T=(T_zinc+T_0)/2)*convert('lb_m/ft-hr','lb_m/in-shift'){Viscosity}
rho_pumpwell=density(air, T=(T_zinc+T_0)/2, P=P_0)*convert('lb_m/ft^3','lb_m/in^3'){Density}
cp_pumpwell=CP(air, T=(T_zinc+T_0)/2)*convert('Btu/lb_m-R','Btu/lb_m-F'){Specific Heat}
q_pumpwell_rad=sigma*A_pumpwell*e*(T_zinc^4-T_0^4){The energy lost from the furnace to the
..                                                  environment via radiation when the hood is open}
E_burnerarea=q_burnerarea_conv+q_burnerarea_rad     {The energy lost from the surface of the molten
..                                                  zinc in the burner area}
q_burnerarea_conv=h_burnerarea*A_burnerarea*(T_zinc-T_0){The energy lost from the furnace to the
..                                                  environment via convection}
h_burnerarea=Nussalt_burnerarea*k_burnerarea/(A_burnerarea/P_burnerarea)
                                                    {average heat transfer coefficient}
A_burnerarea=180                                    {Surface area of the bath in in^2}
Nussalt_burnerarea=0.15*Ra_burnerarea^0.33          {Nussalt number for turbulent natural convection
..                                                  from a horizontal flat plate facing upward}
k_burnerarea=conductivity(air, T=(T_zinc+T_0)/2)*convert('Btu/hr-ft-R','Btu/shift-in-F'){Conductivity}
P_burnerarea=172                                    {Perimeter of the bath in in}
Ra_burnerarea=Gr_burnerarea*Pr_burnerarea           {Rayleigh number}
Gr_burnerarea=g#*convert('ft/s^2','in/shift^2')*beta_burnerarea*(T_zinc-T_0)*(A_burnerarea/P_burnerarea)^
..3/nu_burnerarea^2                                 {Grashof number}
```

Zinc Melt Furnace Section 7.png

```
Pr_burnerarea=nu_burnerarea/alpha_burnerarea          {Prandlts number}
beta_burnerarea=volexpcoef(air, T=(T_zinc+T_0)/2)*convert('1/R','1/F'){Coefficient of thermal expansion}
nu_burnerarea=mu_burnerarea/rho_burnerarea            {Kinematic viscosity}
alpha_burnerarea=k_burnerarea/(rho_burnerarea*cp_burnerarea){Thermal Diffusivity}
mu_burnerarea=viscosity(air, T=(T_zinc+T_0)/2)*convert('lb_m/ft-hr','lb_m/in-shift'){Viscosity}
rho_burnerarea=density(air, T=(T_zinc+T_0)/2, P=P_0)*convert('lb_m/ft^3','lb_m/in^3'){Density}
cp_burnerarea=CP(air, T=(T_zinc+T_0)/2)*convert('Btu/lb_m-R','Btu/lb_m-F'){Specific Heat}
q_burnerarea_rad=sigma*A_burnerarea*e*(T_zinc^4-T_0^4){The energy lost from the exposed metla near
                                                      the burners}
"Zinc Melt Furnace Energy Balance w/o Heat Recovery"
"Energy In"
E_CH4_calculated=m_ng_calculated*(enthalpy(CH4, T=T_0)-w_CO2P*enthalpy(CO2, T=T_0)-w_H2OP*
enthalpy(H2O, T=T_0)-w_O2P*enthalpy(O2, T=T_0)-w_N2P*enthalpy(N2, T=T_0))
E_air_calculated=m_ng_calculated*(w_O2R*enthalpy(O2, T=T_0)+w_N2R*enthalpy(N2, T=T_0))
E_zinc_in_calculated=m_zinc*(T_0-T_0)*c_zinc
"Energy Out"
E_exhaust_calculated=m_ng_calculated*(w_CO2P*enthalpy(CO2, T=T_exhaust)+w_H2OP*enthalpy(H2O,
T=T_exhaust)+w_O2P*enthalpy(O2, T=T_exhaust)+w_N2P*enthalpy(N2, T=T_exhaust)-w_CO2P*enthalpy(
CO2, T=T_0)-w_H2OP*enthalpy(H2O, T=T_0)-w_O2P*enthalpy(O2, T=T_0)-w_N2P*enthalpy(N2, T=T_0))
E_zinc_out_calculated=m_zinc*((T_zinc-T_0)*c_zinc + h_fg_zinc)
E_loss_calculated=1.330E+06 [Btu/shift]               {E_loss calculated from Energy Balance}
"Energy Balance Calculated"
E_CH4_calculated+E_air_calculated=E_exhaust_calculated+E_furnace_calculated
E_zinc_in_calculated+E_furnace_calculated=E_zinc_out_calculated+E_heattransfer+E_loss_calculated
"Optimized Zinc Melt Furnace Energy Balances w/o Heat Recovery"
"Estimated Energy Saved By New Burners as Quoted by Manufacturer"
E_newburners=30000*5*convert(btu/hr,btu/shift)
E_CH4_optimized=E_CH4-E_newburners
"Energy In"
E_CH4_optimized=m_ng_optimized*(enthalpy(CH4, T=T_0)-w_CO2P*enthalpy(CO2, T=T_0)-w_H2OP*
enthalpy(H2O, T=T_0)-w_O2P*enthalpy(O2, T=T_0)-w_N2P*enthalpy(N2, T=T_0))
E_air_optimized=m_ng_optimized*(w_O2R*enthalpy(O2, T=T_0)+w_N2R*enthalpy(N2, T=T_0))
E_zinc_in_optimized=m_zinc*(T_0-T_0)*c_zinc
"Energy Out"
```

Zinc Melt Furnace Section 8.png

```
E_exhaust_optimized=m_ng_optimized*(w_CO2P*enthalpy(CO2, T=T_exhaust)+w_H2OP*enthalpy(H2O, T=
..T_exhaust)+w_O2P*enthalpy(O2, T=T_exhaust)+w_N2P*enthalpy(N2, T=T_exhaust)-w_CO2P*enthalpy(
..CO2, T=T_0)-w_H2OP*enthalpy(H2O, T=T_0)-w_O2P*enthalpy(O2, T=T_0)-w_N2P*enthalpy(N2, T=T_0))
E_zinc_out_optimized=m_zinc*((T_zinc-T_0)*c_zinc + h_fg_zinc)
"Energy Balance"
E_CH4_optimized+E_air_optimized=E_exhaust_optimized+E_furnace_optimized
E_zinc_in_optimized+E_furnace_optimized=E_zinc_out_optimized+E_heattransfer+E_loss_optimized
"Exergy In"
X_CH4_optimized=m_ng_optimized*(enthalpy(CH4, T=T_0)+w_O2R*enthalpy(O2, T=T_0)+w_N2R*
..enthalpy(N2, T=T_0)-w_CO2P*enthalpy(CO2, T=T_0)-w_H2OP*enthalpy(H2O, T=T_0)-w_O2P*enthalpy(O2,
..T=T_0)-w_N2P*enthalpy(N2, T=T_0)-converttemp(F,R,T_0)*(entropy(CH4, T=T_0, P=P_CH4)+w_O2R*
..entropy(O2, T=T_0, P=P_O2R)+w_N2R*entropy(N2, T=T_0, P=P_N2R)-w_CO2P*entropy(CO2, T=T_0, P=
..P_CO2P)-w_H2OP*entropy(H2O, T=T_0, P=P_H2OP)-w_O2P*entropy(O2, T=T_0, P=P_O2P)-w_N2P*
..entropy(N2, T=T_0, P=P_N2P)))
"Exergy Out"
X_comb_products_optimized=m_ng_optimized*(w_CO2P*(enthalpy(CO2, T=T_flame)-enthalpy(CO2, T=
..T_0)-converttemp(F,R,T_0)*(entropy(CO2, T=T_flame, P=P_CO2P)-entropy(CO2, T=T_0, P=P_CO2P)))+
..w_H2OP*(enthalpy(H2O, T=T_flame)-enthalpy(H2O, T=T_0)-converttemp(F,R,T_0)*(entropy(H2O, T=
..T_flame, P=P_H2OP)-entropy(H2O, T=T_0, P=P_H2OP)))+w_O2P*(enthalpy(O2, T=T_flame)-enthalpy(O2,
..T=T_0)-converttemp(F,R,T_0)*(entropy(O2, T=T_flame, P=P_O2P)-entropy(O2, T=T_0, P=P_O2P)))+w_N2P*
..(enthalpy(N2, T=T_flame)-enthalpy(N2, T=T_0)-converttemp(F,R,T_0)*(entropy(N2, T=T_flame, P=P_N2P)-
..entropy(N2, T=T_0, P=P_N2P))))
X_exhaust_interior_optimized=m_ng_optimized*(w_CO2P*(enthalpy(CO2, T=T_exhaust)-enthalpy(CO2, T=
..T_0)-converttemp(F,R,T_0)*(entropy(CO2, T=T_exhaust, P=P_CO2P)-entropy(CO2, T=T_0, P=P_CO2P)))+
..w_H2OP*(enthalpy(H2O, T=T_exhaust)-enthalpy(H2O, T=T_0)-converttemp(F,R,T_0)*(entropy(H2O, T=
..T_exhaust, P=P_H2OP)-entropy(H2O, T=T_0, P=P_H2OP)))+w_O2P*(enthalpy(O2, T=T_exhaust)-enthalpy(
..O2, T=T_0)-converttemp(F,R,T_0)*(entropy(O2, T=T_exhaust, P=P_O2P)-entropy(O2, T=T_0, P=P_O2P)))+
..w_N2P*(enthalpy(N2, T=T_exhaust)-enthalpy(N2, T=T_0)-converttemp(F,R,T_0)*(entropy(N2, T=T_exhaust,
..P=P_N2P)-entropy(N2, T=T_0, P=P_N2P))))
X_zinc_out_optimized=m_zinc*((T_zinc)*c_zinc-converttemp(F,R,T_0)*c_zinc*ln(converttemp(F,R,T_zinc)))-
..m_zinc*(T_0*c_zinc-converttemp(F,R,T_0)*c_zinc*ln(converttemp(F,R,T_0)))+m_zinc*(h_fg_zinc/T_melt)
"Exergy"
X_destroyed_comb_optimized=X_CH4_optimized-X_comb_products_optimized
X_destroyed_losses_optimized=X_comb_products_optimized-X_exhaust_interior_optimized-
```

Zinc Melt Furnace Section 9.png

```
 X_zinc_out_optimized
 X_destroyed_exhaust_optimized=X_exhaust_interior_optimized
 X_destroyed_total_optimized=X_destroyed_comb_optimized+X_destroyed_losses_optimized+
..X_destroyed_exhaust_optimized
 X_supplied_optimized=X_CH4_optimized
 X_utilized_optimized=X_zinc_out_optimized
 "Second Law Efficiency"
 eta_II_optimized=X_utilized_optimized/X_supplied_optimized
 "Zinc Melt Furnace Zinc w/o Heat Recovery Operating Cost"
 Cost_optimized=E_CH4_optimized*cost_ng
 CostSavings_optimized=Cost-Cost_optimized
 "Zinc Melt Furnace Energy Balance w/ Zinc Heating"
 m_zinc_heat=m_zinc*0.55                                  {only bars melted are heated by exhaust}
 "Energy In"
 E_CH4_zinc=m_ng_zinc*(enthalpy(CH4, T=T_0)-w_CO2P*enthalpy(CO2, T=T_0)-w_H2OP*enthalpy(H2O,
..T=T_0)-w_O2P*enthalpy(O2, T=T_0)-w_N2P*enthalpy(N2, T=T_0))
 E_air_zinc=m_ng_zinc*(w_O2R*enthalpy(O2, T=T_0)+w_N2R*enthalpy(N2, T=T_0))
 E_exhaust_in_zinc=m_ng_zinc*(w_CO2P*enthalpy(CO2, T=T_exhaust)+w_H2OP*enthalpy(H2O, T=
..T_exhaust)+w_O2P*enthalpy(O2, T=T_exhaust)+w_N2P*enthalpy(N2, T=T_exhaust)-w_CO2P*enthalpy(
..CO2, T=T_0)-w_H2OP*enthalpy(H2O, T=T_0)-w_O2P*enthalpy(O2, T=T_0)-w_N2P*enthalpy(N2, T=T_0))
 E_zinc_in_zinc=(m_zinc-m_zinc_heat)*c_zinc*(T_0-T_0)
 E_zinc_heat_in_zinc=m_zinc_heat*c_zinc*(T_0-T_0)
 E_zinc_heat_out_zinc=m_zinc_heat*(c_zinc*(T_zinc_preheat-T_0))
 "Energy Out"
 E_exhaust_out_zinc=m_ng_zinc*(w_CO2P*enthalpy(CO2, T=T_exhaust_zinc)+w_H2OP*enthalpy(H2O, T=
..T_exhaust_zinc)+w_O2P*enthalpy(O2, T=T_exhaust_zinc)+w_N2P*enthalpy(N2, T=T_exhaust_zinc)-
..w_CO2P*enthalpy(CO2, T=T_0)-w_H2OP*enthalpy(H2O, T=T_0)-w_O2P*enthalpy(O2, T=T_0)-w_N2P*
..enthalpy(N2, T=T_0))
 E_zinc_out_zinc=m_zinc*(c_zinc*(T_zinc-T_0)+ h_fg_zinc)
 E_loss_optimized_calc=488607 [Btu/shift]
 "Energy Balance"
 E_CH4_zinc+E_air_zinc=E_exhaust_in_zinc+E_furnace_zinc
 E_exhaust_in_zinc+E_zinc_heat_in_zinc=E_exhaust_out_zinc+E_zinc_heat_out_zinc
 E_zinc_in_zinc+E_zinc_heat_out_zinc+E_furnace_zinc=E_heattransfer+E_zinc_out_zinc+E_l
```

Zinc Melt Furnace Section 10.png

```
oss_optimized_calc
"Exergy In"
X_CH4_zinc=m_ng_zinc*(enthalpy(CH4, T=T_0)+w_O2R*enthalpy(O2, T=T_0)+w_N2R*enthalpy(N2, T=T_0)
..-w_CO2P*enthalpy(CO2, T=T_0)-w_H2OP*enthalpy(H2O, T=T_0)-w_O2P*enthalpy(O2, T=T_0)-w_N2P*
..enthalpy(N2, T=T_0)-converttemp(F,R,T_0)*(entropy(CH4, T=T_0, P=P_CH4)+w_O2R*entropy(O2, T=T_0,
..P=P_O2R)+w_N2R*entropy(N2, T=T_0, P=P_N2R)-w_CO2P*entropy(CO2, T=T_0, P=P_CO2P)-w_H2OP*
..entropy(H2O, T=T_0, P=P_H2OP)-w_O2P*entropy(O2, T=T_0, P=P_O2P)-w_N2P*entropy(N2, T=T_0, P=
..P_N2P)))
"Exergy Out"
X_comb_products_zinc=m_ng_zinc*(w_CO2P*(enthalpy(CO2, T=T_flame)-enthalpy(CO2, T=T_0)-
..converttemp(F,R,T_0)*(entropy(CO2, T=T_flame, P=P_CO2P)-entropy(CO2, T=T_0, P=P_CO2P)))+w_H2OP*
..(enthalpy(H2O, T=T_flame)-enthalpy(H2O, T=T_0)-converttemp(F,R,T_0)*(entropy(H2O, T=T_flame, P=
..P_H2OP)-entropy(H2O, T=T_0, P=P_H2OP)))+w_O2P*(enthalpy(O2, T=T_flame)-enthalpy(O2, T=T_0)-
..converttemp(F,R,T_0)*(entropy(O2, T=T_flame, P=P_O2P)-entropy(O2, T=T_0, P=P_O2P)))+w_N2P*(
..enthalpy(N2, T=T_flame)-enthalpy(N2, T=T_0)-converttemp(F,R,T_0)*(entropy(N2, T=T_flame, P=P_N2P)-
..entropy(N2, T=T_0, P=P_N2P))))
X_exhaust_interior_zinc=m_ng_zinc*(w_CO2P*(enthalpy(CO2, T=T_exhaust)-enthalpy(CO2, T=T_0)-
..converttemp(F,R,T_0)*(entropy(CO2, T=T_exhaust, P=P_CO2P)-entropy(CO2, T=T_0, P=P_CO2P)))+
..w_H2OP*(enthalpy(H2O, T=T_exhaust)-enthalpy(H2O, T=T_0)-converttemp(F,R,T_0)*(entropy(H2O, T=
..T_exhaust, P=P_H2OP)-entropy(H2O, T=T_0, P=P_H2OP)))+w_O2P*(enthalpy(O2, T=T_exhaust)-enthalpy(
..O2, T=T_0)-converttemp(F,R,T_0)*(entropy(O2, T=T_exhaust, P=P_O2P)-entropy(O2, T=T_0, P=P_O2P)))+
..w_N2P*(enthalpy(N2, T=T_exhaust)-enthalpy(N2, T=T_0)-converttemp(F,R,T_0)*(entropy(N2, T=T_exhaust,
..P=P_N2P)-entropy(N2, T=T_0, P=P_N2P))))
X_zinc_out_zinc=m_zinc*((T_zinc)*c_zinc-converttemp(F,R,T_0)*c_zinc*ln(converttemp(F,R,T_zinc)))-
..m_zinc*(T_0*c_zinc-converttemp(F,R,T_0)*c_zinc*ln(converttemp(F,R,T_0)))+m_zinc*(h_fg_zinc/T_melt)
"Exergy"
X_destroyed_comb_zinc=X_CH4_zinc-X_comb_products_zinc
X_destroyed_losses_zinc=X_comb_products_zinc-X_exhaust_interior_zinc-X_zinc_out_zinc
X_destroyed_exhaust_zinc=X_exhaust_interior_zinc
X_destroyed_total_zinc=X_destroyed_comb_zinc+X_destroyed_losses_zinc+X_destroyed_exhaust_zinc
X_supplied_zinc=X_CH4_zinc
X_utilized_zinc=X_zinc_out_zinc
"Second Law Efficiency"
eta_II_zinc=X_utilized_zinc/X_supplied_zinc
```

Zinc Melt Furnace Section 11.png

```
"Zinc Melt Furnace Zinc w/o Heat Recovery Operating Cost"
Cost_zinc=E_CH4_zinc*cost_ng
CostSavings_zinc=Cost_optimized-Cost_zinc
"Zinc Heating Heat Transfer Calculations"
h_zinc=Nussalt_zinc*k_air_zinc/(W1_zinc*n_zinc)           {average heat transfer coefficient}
A_zinc=L_zinc*W1_zinc*n_zinc*2                            {Surface area of the batch of bars loaded for
                                                          preheating}
L_zinc=26                                                 {Length of zinc bars being heated}
W1_zinc=3.375                                             {Width of zinc bars being heated}
n_zinc=30                                                 {number of bars being heated each hour}
Nussalt_zinc=0.664*Re_zinc^(1/2)*Pr_zinc^(1/3)            {Nussalt number for laminar convection (Re < 500,
                                                          000) to a horizontal flat plate}
k_air_zinc=conductivity(air, T=T_film_zinc)*convert('Btu/hr-ft-R','Btu/shift-in-F'){Conductivity}
Pr_zinc=nu_zinc/alpha_air_zinc                            {Prandlt number}
Re_zinc=u_zinc*W1_zinc*n_zinc/nu_zinc                     {Reynolds number}
nu_zinc=mu_zinc/rho_air_zinc                              {Kinematic viscosity}
alpha_air_zinc=k_air_zinc/(rho_air_zinc*cp_air_zinc)      {Thermal Diffusivity of air}
A_air=50*12                                               {Area of exhaust inlet in furnace in in^2}
u_zinc=m_ng_zinc*(w_CO2P*volume(CO2, T=T_film_zinc, P=P_CO2P)*convert(ft^3/lb_m,in^3/lb_m)+
w_H2OP*volume(H2O, T=T_film_zinc, P=P_H2OP)*convert(ft^3/lb_m,in^3/lb_m)+w_O2P*volume(O2, T=
T_film_zinc, P=P_O2P)*convert(ft^3/lb_m,in^3/lb_m)+w_N2P*volume(N2, T=T_film_zinc, P=P_N2P)*convert(
ft^3/lb_m,in^3/lb_m))/(A_air)                             {assumed air speed}
mu_zinc=viscosity(air, T=T_film_zinc)*convert('lb_m/ft-hr','lb_m/in-shift'){Viscosity}
rho_air_zinc=density(air, T=T_film_zinc, P=P_0)*convert('lb_m/ft^3','lb_m/in^3'){Density}
cp_air_zinc=CP(air, T=T_film_zinc)*convert('Btu/lb_m-R','Btu/lb_m-F'){Specific Heat}
(T_zinc_preheat-T_exhaust)/(T_0-T_exhaust)=exp(-((h_zinc*A_zinc)/(rho_zinc*V_zinc*c_zinc))*t)
                                                          {Transient heating of bars for 2 hour}
Theta=(T_zinc_preheat-T_exhaust)/(T_0-T_exhaust)
V_zinc=A_zinc*W2_zinc
W2_zinc=1.625/2                                           {Hight of bars being heated}
t=60*60*2*convert(s,shift)                                {Figure out a way to let the zinc preheat this long}
Bi_zinc=(h_zinc*Lc_zinc)/k_zinc                           {Biot number to confirm lumped capacitance}
Lc_zinc=V_zinc/(A_zinc)
T_average_zinc=(T_zinc_preheat+T_0)/2
```

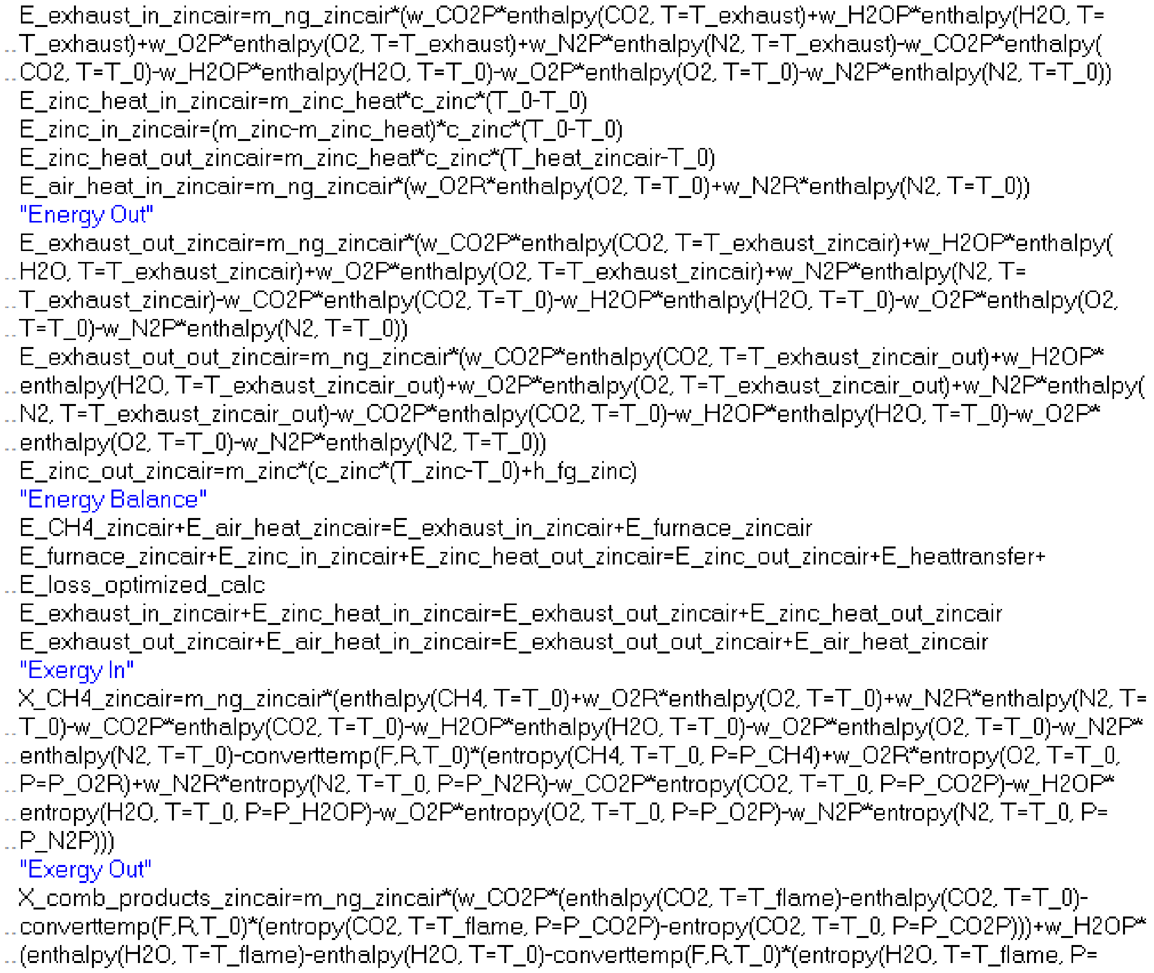
Zinc Melt Furnace Section 12.png

```
T_average_exhaust=(T_exhaust+T_exhaust_zinc)/2
T_film_zinc=(T_average_zinc+T_average_exhaust)/2
"Zinc Melt Furnace Energy Balance w/ Air Heating"
T_air_heat=586{800}                              {The temperature of preheated air using MANTRA
..                                                gas to air heat exchanger}{Max Temperature of
..                                                heated air to burners}
"Energy In"
E_CH4_air=m_ng_air*(enthalpy(CH4, T=T_0)-w_CO2P*enthalpy(CO2, T=T_0)-w_H2OP*enthalpy(H2O, T=
..T_0)-w_O2P*enthalpy(O2, T=T_0)-w_N2P*enthalpy(N2, T=T_0))
E_air_heat_air=m_ng_air*(w_O2P*(enthalpy(O2, T=T_air_heat)-enthalpy(O2, T=T_0))+w_N2P*(enthalpy(N2,
..T=T_air_heat)-enthalpy(N2, T=T_0)))
E_exhaust_in_air=m_ng_air*(w_CO2P*enthalpy(CO2, T=T_exhaust)+w_H2OP*enthalpy(H2O, T=T_exhaust)
..+w_O2P*enthalpy(O2, T=T_exhaust)+w_N2P*enthalpy(N2, T=T_exhaust)-w_CO2P*enthalpy(CO2, T=T_0)-
..w_H2OP*enthalpy(H2O, T=T_0)-w_O2P*enthalpy(O2, T=T_0)-w_N2P*enthalpy(N2, T=T_0))
E_air_air=m_ng_air*(w_O2P*enthalpy(O2, T=T_0)+w_N2P*enthalpy(N2, T=T_0))
E_zinc_in_air=m_zinc*c_zinc*(T_0-T_0)
"Energy Out"
E_zinc_out_air=m_zinc*(c_zinc*(T_zinc-T_0)+ h_fg_zinc)
E_exhaust_out_air=m_ng_air*(w_CO2P*enthalpy(CO2, T=T_exhaust_air)+w_H2OP*enthalpy(H2O, T=
..T_exhaust_air)+w_O2P*enthalpy(O2, T=T_exhaust_air)+w_N2P*enthalpy(N2, T=T_exhaust_air)-w_CO2P*
..enthalpy(CO2, T=T_0)-w_H2OP*enthalpy(H2O, T=T_0)-w_O2P*enthalpy(O2, T=T_0)-w_N2P*enthalpy(N2,
..T=T_0))
"Energy Balance"
E_CH4_air+E_air_heat_air=E_exhaust_in_air+E_furnace_air
E_exhaust_in_air+E_air_air=E_air_heat_air+E_exhaust_out_air
E_zinc_in_air+E_furnace_air=E_zinc_out_air+E_heattransfer+E_loss_optimized_calc
"Exergy In"
X_CH4_air=m_ng_air*(enthalpy(CH4, T=T_0)+w_O2R*enthalpy(O2, T=T_0)+w_N2R*enthalpy(N2, T=T_0)-
..w_CO2P*enthalpy(CO2, T=T_0)-w_H2OP*enthalpy(H2O, T=T_0)-w_O2P*enthalpy(O2, T=T_0)-w_N2P*
..enthalpy(N2, T=T_0)-converttemp(F,R,T_0)*(entropy(CH4, T=T_0, P=P_CH4)+w_O2R*entropy(O2, T=T_0,
..P=P_O2R)+w_N2R*entropy(N2, T=T_0, P=P_N2R)-w_CO2P*entropy(CO2, T=T_0, P=P_CO2P)-w_H2OP*
..entropy(H2O, T=T_0, P=P_H2OP)-w_O2P*entropy(O2, T=T_0, P=P_O2P)-w_N2P*entropy(N2, T=T_0, P=
..P_N2P)))
"Exergy Out"
```

Zinc Melt Furnace Section 13.png

```
 X_comb_products_air=m_ng_air*(w_CO2P*(enthalpy(CO2, T=T_flame)-enthalpy(CO2, T=T_0)-converttemp(
..F,R,T_0)*(entropy(CO2, T=T_flame, P=P_CO2P)-entropy(CO2, T=T_0, P=P_CO2P)))+w_H2OP*(enthalpy(
..H2O, T=T_flame)-enthalpy(H2O, T=T_0)-converttemp(F,R,T_0)*(entropy(H2O, T=T_flame, P=P_H2OP)-
..entropy(H2O, T=T_0, P=P_H2OP)))+w_O2P*(enthalpy(O2, T=T_flame)-enthalpy(O2, T=T_0)-converttemp(F,
..R,T_0)*(entropy(O2, T=T_flame, P=P_O2P)-entropy(O2, T=T_0, P=P_O2P)))+w_N2P*(enthalpy(N2, T=
..T_flame)-enthalpy(N2, T=T_0)-converttemp(F,R,T_0)*(entropy(N2, T=T_flame, P=P_N2P)-entropy(N2, T=
..T_0, P=P_N2P))))
 X_exhaust_interior_air=m_ng_air*(w_CO2P*(enthalpy(CO2, T=T_exhaust)-enthalpy(CO2, T=T_0)-
..converttemp(F,R,T_0)*(entropy(CO2, T=T_exhaust, P=P_CO2P)-entropy(CO2, T=T_0, P=P_CO2P)))+
..w_H2OP*(enthalpy(H2O, T=T_exhaust)-enthalpy(H2O, T=T_0)-converttemp(F,R,T_0)*(entropy(H2O, T=
..T_exhaust, P=P_H2OP)-entropy(H2O, T=T_0, P=P_H2OP)))+w_O2P*(enthalpy(O2, T=T_exhaust)-enthalpy(
..O2, T=T_0)-converttemp(F,R,T_0)*(entropy(O2, T=T_exhaust, P=P_O2P)-entropy(O2, T=T_0, P=P_O2P)))+
..w_N2P*(enthalpy(N2, T=T_exhaust)-enthalpy(N2, T=T_0)-converttemp(F,R,T_0)*(entropy(N2, T=T_exhaust,
..P=P_N2P)-entropy(N2, T=T_0, P=P_N2P))))
 X_zinc_out_air=m_zinc*((T_zinc)*c_zinc-converttemp(F,R,T_0)*c_zinc*ln(converttemp(F,R,T_zinc)))-m_zinc*(
..T_0*c_zinc-converttemp(F,R,T_0)*c_zinc*ln(converttemp(F,R,T_0)))+m_zinc*(h_fg_zinc/T_melt)
 "Exergy"
 X_destroyed_comb_air=X_CH4_air-X_comb_products_air
 X_destroyed_losses_air=X_comb_products_air-X_exhaust_interior_air-X_zinc_out_air
 X_destroyed_exhaust_air=X_exhaust_interior_air
 X_destroyed_total_air=X_destroyed_comb_air+X_destroyed_losses_air+X_destroyed_exhaust_air
 X_supplied_air=X_CH4_air
 X_utilized_air=X_zinc_out_air
 "Second Law Efficiency"
 eta_II_air=X_utilized_air/X_supplied_air
 "Zinc Melt Furnace Zinc w/o Heat Recovery Operating Cost"
 Cost_air=E_CH4_air*cost_ng
 CostSavings_air=Cost_optimized-Cost_air
 "Zinc Melt Furnace Energy Balance w/ Zinc and Air Heating"
 "Energy In"
 E_CH4_zincair=m_ng_zincair*(enthalpy(CH4, T=T_0)-w_CO2P*enthalpy(CO2, T=T_0)-w_H2OP*enthalpy(
..H2O, T=T_0)-w_O2P*enthalpy(O2, T=T_0)-w_N2P*enthalpy(N2, T=T_0))
 E_air_heat_zincair=m_ng_zincair*(w_O2R*(enthalpy(O2, T=T_air_heat)-enthalpy(O2, T=T_0))+w_N2R*(
..enthalpy(N2, T=T_air_heat)-enthalpy(O2, T=T_0)))
```

Zinc Melt Furnace Section 14.png



```
E_exhaust_in_zincair=m_ng_zincair*(w_CO2P*enthalpy(CO2, T=T_exhaust)+w_H2OP*enthalpy(H2O, T=
..T_exhaust)+w_O2P*enthalpy(O2, T=T_exhaust)+w_N2P*enthalpy(N2, T=T_exhaust)-w_CO2P*enthalpy(
..CO2, T=T_0)-w_H2OP*enthalpy(H2O, T=T_0)-w_O2P*enthalpy(O2, T=T_0)-w_N2P*enthalpy(N2, T=T_0))
E_zinc_heat_in_zincair=m_zinc_heat*c_zinc*(T_0-T_0)
E_zinc_in_zincair=(m_zinc-m_zinc_heat)*c_zinc*(T_0-T_0)
E_zinc_heat_out_zincair=m_zinc_heat*c_zinc*(T_heat_zincair-T_0)
E_air_heat_in_zincair=m_ng_zincair*(w_O2R*enthalpy(O2, T=T_0)+w_N2R*enthalpy(N2, T=T_0))
"Energy Out"
E_exhaust_out_zincair=m_ng_zincair*(w_CO2P*enthalpy(CO2, T=T_exhaust_zincair)+w_H2OP*enthalpy(
..H2O, T=T_exhaust_zincair)+w_O2P*enthalpy(O2, T=T_exhaust_zincair)+w_N2P*enthalpy(N2, T=
..T_exhaust_zincair)-w_CO2P*enthalpy(CO2, T=T_0)-w_H2OP*enthalpy(H2O, T=T_0)-w_O2P*enthalpy(O2,
..T=T_0)-w_N2P*enthalpy(N2, T=T_0))
E_exhaust_out_out_zincair=m_ng_zincair*(w_CO2P*enthalpy(CO2, T=T_exhaust_zincair_out)+w_H2OP*
..enthalpy(H2O, T=T_exhaust_zincair_out)+w_O2P*enthalpy(O2, T=T_exhaust_zincair_out)+w_N2P*enthalpy(
..N2, T=T_exhaust_zincair_out)-w_CO2P*enthalpy(CO2, T=T_0)-w_H2OP*enthalpy(H2O, T=T_0)-w_O2P*
..enthalpy(O2, T=T_0)-w_N2P*enthalpy(N2, T=T_0))
E_zinc_out_zincair=m_zinc*(c_zinc*(T_zinc-T_0)+h_fg_zinc)
"Energy Balance"
E_CH4_zincair+E_air_heat_zincair=E_exhaust_in_zincair+E_furnace_zincair
E_furnace_zincair+E_zinc_in_zincair+E_zinc_heat_out_zincair=E_zinc_out_zincair+E_heattransfer+
..E_loss_optimized_calc
E_exhaust_in_zincair+E_zinc_heat_in_zincair=E_exhaust_out_zincair+E_zinc_heat_out_zincair
E_exhaust_out_zincair+E_air_heat_in_zincair=E_exhaust_out_out_zincair+E_air_heat_zincair
"Exergy In"
X_CH4_zincair=m_ng_zincair*(enthalpy(CH4, T=T_0)+w_O2R*enthalpy(O2, T=T_0)+w_N2R*enthalpy(N2, T=
..T_0)-w_CO2P*enthalpy(CO2, T=T_0)-w_H2OP*enthalpy(H2O, T=T_0)-w_O2P*enthalpy(O2, T=T_0)-w_N2P*
..enthalpy(N2, T=T_0)-converttemp(F,R,T_0)*(entropy(CH4, T=T_0, P=P_CH4)+w_O2R*entropy(O2, T=T_0,
..P=P_O2R)+w_N2R*entropy(N2, T=T_0, P=P_N2R)-w_CO2P*entropy(CO2, T=T_0, P=P_CO2P)-w_H2OP*
..entropy(H2O, T=T_0, P=P_H2OP)-w_O2P*entropy(O2, T=T_0, P=P_O2P)-w_N2P*entropy(N2, T=T_0, P=
..P_N2P)))
"Exergy Out"
X_comb_products_zincair=m_ng_zincair*(w_CO2P*(enthalpy(CO2, T=T_flame)-enthalpy(CO2, T=T_0)-
..converttemp(F,R,T_0)*(entropy(CO2, T=T_flame, P=P_CO2P)-entropy(CO2, T=T_0, P=P_CO2P)))+w_H2OP*
..(enthalpy(H2O, T=T_flame)-enthalpy(H2O, T=T_0)-converttemp(F,R,T_0)*(entropy(H2O, T=T_flame, P=
```

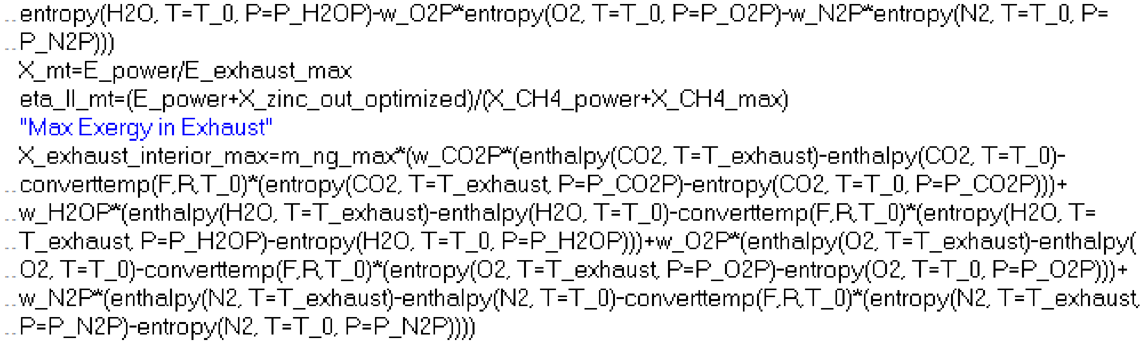
Zinc Melt Furnace Section 15.png

```
 P_H2OP)-entropy(H2O, T=T_0, P=P_H2OP)))+w_O2P*(enthalpy(O2, T=T_flame)-enthalpy(O2, T=T_0)-
..convertemp(F,R,T_0)*(entropy(O2, T=T_flame, P=P_O2P)-entropy(O2, T=T_0, P=P_O2P)))+w_N2P*(
..enthalpy(N2, T=T_flame)-enthalpy(N2, T=T_0)-converttemp(F,R,T_0)*(entropy(N2, T=T_flame, P=P_N2P)-
..entropy(N2, T=T_0, P=P_N2P))))
 X_exhaust_interior_zincair=m_ng_zincair*(w_CO2P*(enthalpy(CO2, T=T_exhaust)-enthalpy(CO2, T=T_0)-
..converttemp(F,R,T_0)*(entropy(CO2, T=T_exhaust, P=P_CO2P)-entropy(CO2, T=T_0, P=P_CO2P)))+
..w_H2OP*(enthalpy(H2O, T=T_exhaust)-enthalpy(H2O, T=T_0)-converttemp(F,R,T_0)*(entropy(H2O, T=
..T_exhaust, P=P_H2OP)-entropy(H2O, T=T_0, P=P_H2OP)))+w_O2P*(enthalpy(O2, T=T_exhaust)-enthalpy(
..O2, T=T_0)-converttemp(F,R,T_0)*(entropy(O2, T=T_exhaust, P=P_O2P)-entropy(O2, T=T_0, P=P_O2P)))+
..w_N2P*(enthalpy(N2, T=T_exhaust)-enthalpy(N2, T=T_0)-converttemp(F,R,T_0)*(entropy(N2, T=T_exhaust,
..P=P_N2P)-entropy(N2, T=T_0, P=P_N2P))))
 X_zinc_out_zincair=m_zinc*((T_zinc)*c_zinc-converttemp(F,R,T_0)*c_zinc*ln(converttemp(F,R,T_zinc)))-
..m_zinc*(T_0*c_zinc-converttemp(F,R,T_0)*c_zinc*ln(converttemp(F,R,T_0)))+m_zinc*(h_fg_zinc/T_melt)
 "Exergy"
 X_destroyed_comb_zincair=X_CH4_zincair-X_comb_products_zincair
 X_destroyed_losses_zincair=X_comb_products_zincair-X_exhaust_interior_zincair-X_zinc_out_zincair
 X_destroyed_exhaust_zincair=X_exhaust_interior_zincair
 X_destroyed_total_zincair=X_destroyed_comb_zincair+X_destroyed_losses_zincair+X_des
..troyed_exhaust_zincair
 X_supplied_zincair=X_CH4_zincair
 X_utilized_zincair=X_zinc_out_zincair
 "Second Law Efficiency"
 eta_II_zincair=X_utilized_zincair/X_supplied_zincair
 "Zinc Melt Furnace Zinc w/o Heat Recovery Operating Cost"
 Cost_zincair=E_CH4_zincair*cost_ng
 CostSavings_zincair=Cost_optimized-Cost_zincair
 "Zinc Heating Heat Transfer Calculations for Zinc and Air Heating"
 h_zincair=Nussalt_zincair*k_air_zincair/(W1_zinc*n_zinc) {average heat transfer coefficient}
 Nussalt_zincair=0.664*Re_zincair^(1/2)*Pr_zincair^(1/3)  {Nussalt number for laminar convection to a
..                                                         horizontal flat plate}
 k_air_zincair=conductivity(air, T=T_film_zincair)*convert('Btu/hr-ft-R','Btu/shift-in-F'){Conductivity}
 Pr_zincair=nu_zincair/alpha_air_zincair                  {Prandlt number}
 Re_zincair=u_zincair*W1_zinc*n_zinc/nu_zincair           {Reynolds number}
 nu_zincair=mu_zincair/rho_air_zincair                    {Kinematic viscosity}
```

Zinc Melt Furnace Section 16.png

```
  alpha_air_zincair=k_air_zincair/(rho_air_zincair*cp_air_zincair){Thermal Diffusivity of air}
  u_zincair=m_ng_zincair*(w_CO2P*volume(CO2, T=T_film_zincair, P=P_CO2P)*convert(ft^3/lb_m,in^3/lb_m)+
..w_H2OP*volume(H2O, T=T_film_zincair, P=P_H2OP)*convert(ft^3/lb_m,in^3/lb_m)+w_O2P*volume(O2, T=
..T_film_zincair, P=P_O2P)*convert(ft^3/lb_m,in^3/lb_m)+w_N2P*volume(N2, T=T_film_zincair, P=P_N2P)*
..convert(ft^3/lb_m,in^3/lb_m))/(A_air)                    {assumed air speed}
  mu_zincair=viscosity(air, T=T_film_zincair)*convert('lb_m/ft-hr','lb_m/in-shift'){Viscosity}
  rho_air_zincair=density(air, T=T_film_zincair, P=P_0)*convert('lb_m/ft^3','lb_m/in^3'){Density}
  cp_air_zincair=CP(air, T=T_film_zincair)*convert('Btu/lb_m-R','Btu/lb_m-F'){Specific Heat}
  (T_heat_zincair-T_exhaust)/(T_0-T_exhaust)=exp(-((h_zincair*A_zinc)/(rho_zinc*V_zinc*c_zinc))*t)
                                                           {Transient heating of bars for 1 hour}
  Bi_zincair=(h_zincair*Lc_zinc)/k_zinc                    {Biot number to confirm lumped capacitance}
  T_average_zincair=(T_heat_zincair+T_0)/2
  T_average_exhaust_zincair=(T_exhaust+T_exhaust_zincair)/2
  T_film_zincair=(T_average_zincair+T_average_exhaust_zincair)/2
  "Energy, Mass and Exergy Flow Rates During High Fire For New Burners"
  "Energy In"
  E_CH4_max=m_ng_max*(enthalpy(CH4, T=T_0)-w_CO2P*enthalpy(CO2, T=T_0)-w_H2OP*enthalpy(H2O,
..T=T_0)-w_O2P*enthalpy(O2, T=T_0)-w_N2P*enthalpy(N2, T=T_0))
  E_CH4_max=500000*5*convert(btu/hr,btu/shift)
  E_exhaust_max=m_ng_max*(w_CO2P*enthalpy(CO2, T=T_exhaust)+w_H2OP*enthalpy(H2O, T=T_exhaust)
..+w_O2P*enthalpy(O2, T=T_exhaust)+w_N2P*enthalpy(N2, T=T_exhaust)-w_CO2P*enthalpy(CO2, T=T_0)-
..w_H2OP*enthalpy(H2O, T=T_0)-w_O2P*enthalpy(O2, T=T_0)-w_N2P*enthalpy(N2, T=T_0))
  E_air_max_heated=m_ng_max*(w_O2R*(enthalpy(O2, T=800[F])-enthalpy(O2, T=T_0))+w_N2R*(enthalpy(
..N2, T=800[F])-enthalpy(O2, T=T_0)))
  "Power Generation"
  eta_mt=0.8
  X_mt=0.93
  eta_mt=(E_power+E_exhaust_max)/E_CH4_power
  E_CH4_power=m_ng_mt*(enthalpy(CH4, T=T_0)-w_CO2P*enthalpy(CO2, T=T_0)-w_H2OP*enthalpy(H2O,
..T=T_0)-w_O2P*enthalpy(O2, T=T_0)-w_N2P*enthalpy(N2, T=T_0))
  X_CH4_power=m_ng_mt*(enthalpy(CH4, T=T_0)+w_O2R*enthalpy(O2, T=T_0)+w_N2R*enthalpy(N2, T=
..T_0)-w_CO2P*enthalpy(CO2, T=T_0)-w_H2OP*enthalpy(H2O, T=T_0)-w_O2P*enthalpy(O2, T=T_0)-w_N2P*
..enthalpy(N2, T=T_0)-converttemp(F,R,T_0)*(entropy(CH4, T=T_0, P=P_CH4)+w_O2R*entropy(O2, T=T_0,
..P=P_O2R)+w_N2R*entropy(N2, T=T_0, P=P_N2R)-w_CO2P*entropy(CO2, T=T_0, P=P_CO2P)-w_H2OP*
```

Zinc Melt Furnace Section 17.png



```
..entropy(H2O, T=T_0, P=P_H2OP)-w_O2P*entropy(O2, T=T_0, P=P_O2P)-w_N2P*entropy(N2, T=T_0, P=
..P_N2P)))
  X_mt=E_power/E_exhaust_max
  eta_II_mt=(E_power+X_zinc_out_optimized)/(X_CH4_power+X_CH4_max)
  "Max Exergy in Exhaust"
  X_exhaust_interior_max=m_ng_max*(w_CO2P*(enthalpy(CO2, T=T_exhaust)-enthalpy(CO2, T=T_0)-
..converttemp(F,R,T_0)*(entropy(CO2, T=T_exhaust, P=P_CO2P)-entropy(CO2, T=T_0, P=P_CO2P)))+
..w_H2OP*(enthalpy(H2O, T=T_exhaust)-enthalpy(H2O, T=T_0)-converttemp(F,R,T_0)*(entropy(H2O, T=
..T_exhaust, P=P_H2OP)-entropy(H2O, T=T_0, P=P_H2OP)))+w_O2P*(enthalpy(O2, T=T_exhaust)-enthalpy(
..O2, T=T_0)-converttemp(F,R,T_0)*(entropy(O2, T=T_exhaust, P=P_O2P)-entropy(O2, T=T_0, P=P_O2P)))+
..w_N2P*(enthalpy(N2, T=T_exhaust)-enthalpy(N2, T=T_0)-converttemp(F,R,T_0)*(entropy(N2, T=T_exhaust,
..P=P_N2P)-entropy(N2, T=T_0, P=P_N2P))))
```

APPENDIX C

LOW PRESSURE STEAM SYSTEM EES CODE

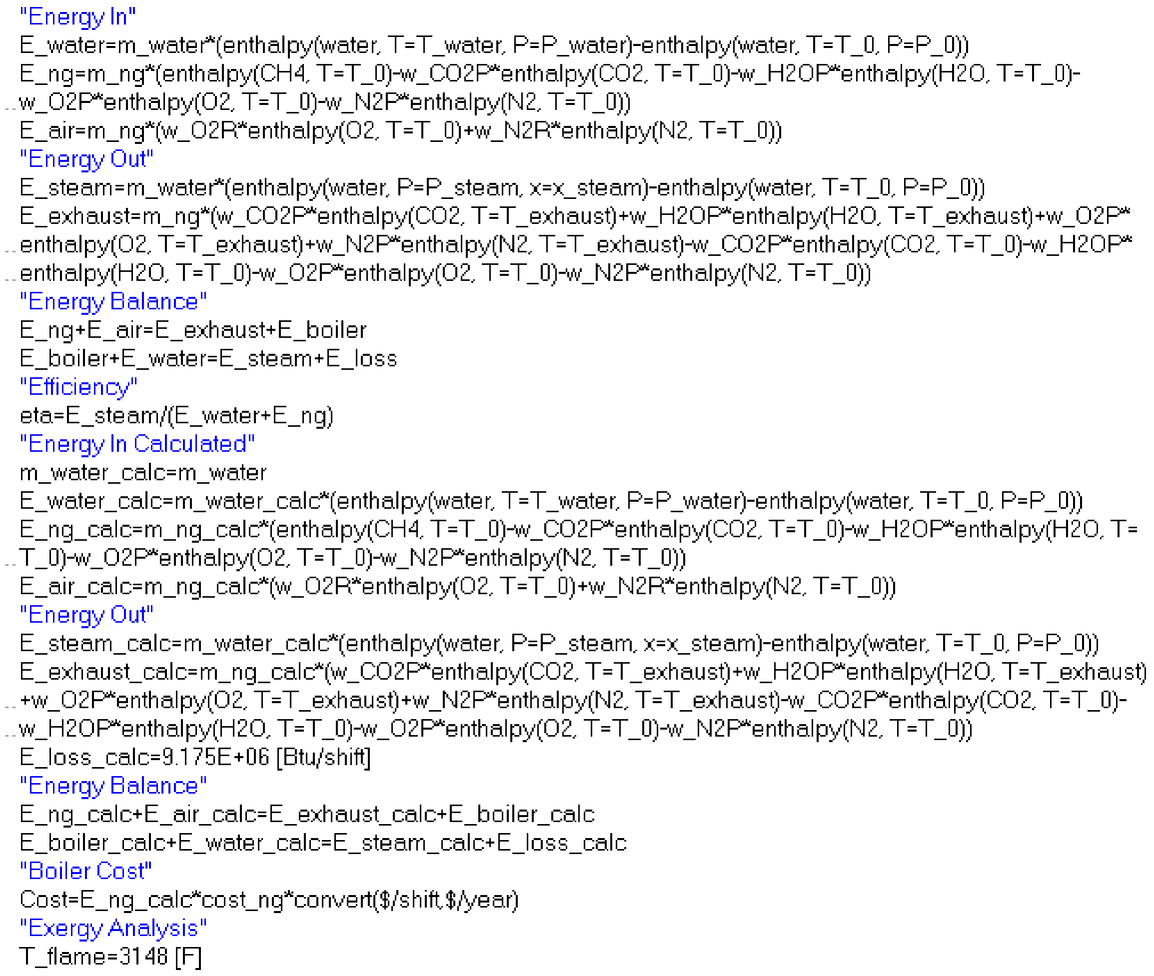
Low Pressure Steam System Section 1.png

```
"Dead State Conditions"
T_0=converttemp('C','F',25)                       {Dead State Temperature in F}
P_0=1*convert('atm','psia')                       {Dead State Pressure in psia}
"Boiler Operating Parameters"
T_exhaust=235                                     {Temperature of the exhaust in F as it leaves the
--                                                boilers}
T_water=220                                       {Temperature of water entering boiler}
P_water=29+14.7                                   {Pressure of water entering boiler}
P_steam=11+14.7                                   {Pressure of steam leaving the boiler}
x_steam=1                                         {Assumed quality of steam leaving the boiler}
phi_O2P=0.05                                      {Volume fraction of O2 in the combustion products}
T_DA=180                                          {Max temperature of water entering dearorator in
--                                                current configuration}
T_condinsate=100                                  {Estimated temperature of water entering the DA}
P_ng=5+14.7                                       {Pressure of natural gas in the facility}
T_sat=Temperature(water, P=P_steam, x=x_steam)    {Steam temperature}
"Combustion Calculations"
n_O2R=(2[mol]+x)/((2[mol]+x)+(2[mol]+x)*3.76)     {mole fraction of O2 in the combustion reactants}
n_N2R=((2[mol]+x)*3.76)/((2[mol]+x)+(2[mol]+x)*3.76)  {mole fraction of N2 in the combustion reactants}
n_CO2P=1[mol]/(1[mol]+2[mol]+x+(2[mol]+x)*3.76)   {mole fraction of CO2 in the combustion products}
n_H2OP=2[mol]/(1[mol]+2[mol]+x+(2[mol]+x)*3.76)   {mole fraction of H2O in the combustion products}
n_O2P=x/(1[mol]+2[mol]+x+(2[mol]+x)*3.76)         {mole fraction of O2 in the combustion products}
n_N2P=((2[mol]+x)*3.76)/(1[mol]+2[mol]+x+(2[mol]+x)*3.76){mole fraction of N2 in the combustion products}
w_O2R=((2[mol]+x)*molarmass(O2))/(1[mol]*molarmass(CH4)){mass fraction of O2 in the combustion
--                                                reactants}
w_N2R=((2[mol]+x)*3.76*molarmass(N2))/(1[mol]*molarmass(CH4)){mass fraction of N2 in the combustion
--                                                reactants}
w_CO2P=(1[mol]*molarmass(CO2))/(1[mol]*molarmass(CH4)){mass fraction of CO2 in the combustion
--                                                products}
w_H2OP=(2[mol]*molarmass(H2O))/(1[mol]*molarmass(CH4)){mass fraction of H2O in the combustion
--                                                products}
w_O2P=(x*molarmass(O2))/(1[mol]*molarmass(CH4))   {mass fraction of O2 in the combustion products}
w_N2P=((2[mol]+x)*3.76*molarmass(N2))/(1[mol]*molarmass(CH4)){mass fraction of N2 in the combustion
--                                                products}
```

Low Pressure Steam System Section 2.png

```
p_O2R=n_O2R*P_0                                       {partial pressure of O2 in the combustion
..                                                    reactants}
p_N2R=n_N2R*P_0                                       {partial pressure of N2 in the combustion
..                                                    reactants}
p_CO2P=n_CO2P*P_0                                     {partial pressure of CO2 in the combustion
..                                                    products}
p_H2OP=n_H2OP*P_0                                     {partial pressure of H2O in the combustion
..                                                    products}
p_O2P=n_O2P*P_0                                       {partial pressure of O2 in the combustion products}
p_N2P=n_N2P*P_0                                       {partial pressure of N2 in the combustions
..                                                    producs}
phi_O2P=(x*MWO2*volume(O2, T=T_exhaust, P=P_0))/(1[mol]*MWCO2*volume(CO2, T=T_exhaust, P=P_0)
..+2[mol]*MWH2O*volume(H2O, T=T_exhaust, P=P_0)+x*MWO2*volume(O2, T=T_exhaust, P=P_0)+(2[mol]+
..x)*3.76*MWN2*volume(N2, T=T_exhaust, P=P_0))         {volume fraction of O2 in the combustion products}
MWO2=molarmass(O2)*convert(lb_m/lbmol,lb_m/mol)       {molar mass of O2 in lb_m/mol}
MWCO2=molarmass(CO2)*convert(lb_m/lbmol,lb_m/mol){molar mass of CO2 in lb_m/mol}
MWH2O=molarmass(H2O)*convert(lb_m/lbmol,lb_m/mol){molar mass of H2O in lb_m/mol}
MWN2=molarmass(N2)*convert(lb_m/lbmol,lb_m/mol)       {molar mass of N2 in lb_m/mol}
"Utility Costs"
cost_ng=0.0000076[$/Btu]                              {average natural gas price for FY14}
cost_elec=(cost_nonpeak+(cost_demand/(30.5*24[h]))+cost_peak+(cost_demand/(30.5*24[h]))+(
..cost_demand_peak/(30.5*12[h])))/2                   {average of peak and non-peak}
cost_elec_p=cost_peak+(cost_demand/(30.5*24[h])+(cost_demand_peak/(30.5*12[h])))
cost_elec_np=cost_nonpeak+(cost_demand/(30.5*24[h]))
cost_nonpeak=0.05104[$/kWh]                           {non-peak electrical rate}
cost_demand=1.306[$/kW]                               {monthly non-peak demand charge}
cost_peak=0.07118[$/kWh]                              {peak electrical rate}
cost_demand_peak=7.501[$/kW]                          {monthly peak demand charge}
"Calculating Heat Loss"{Data sampled 8/12/14 8:15 AM to 8/13/12 8:15 AM, typical production day}
"Average Data"
m_water=2098[lbm/h]*convert(lbm/h,lbm/shift)
v_ng=2832[ft^3/h]
m_ng=v_ng*density(CH4, T=T_0, P=P_ng)*convert(lbm/h,lbm/shift)
w_water2ng=m_ng/m_water
```

Low Pressure Steam System Section 3.png



```
"Energy In"
E_water=m_water*(enthalpy(water, T=T_water, P=P_water)-enthalpy(water, T=T_0, P=P_0))
E_ng=m_ng*(enthalpy(CH4, T=T_0)-w_CO2P*enthalpy(CO2, T=T_0)-w_H2OP*enthalpy(H2O, T=T_0)-
..w_O2P*enthalpy(O2, T=T_0)-w_N2P*enthalpy(N2, T=T_0))
E_air=m_ng*(w_O2R*enthalpy(O2, T=T_0)+w_N2R*enthalpy(N2, T=T_0))
"Energy Out"
E_steam=m_water*(enthalpy(water, P=P_steam, x=x_steam)-enthalpy(water, T=T_0, P=P_0))
E_exhaust=m_ng*(w_CO2P*enthalpy(CO2, T=T_exhaust)+w_H2OP*enthalpy(H2O, T=T_exhaust)+w_O2P*
..enthalpy(O2, T=T_exhaust)+w_N2P*enthalpy(N2, T=T_exhaust)-w_CO2P*enthalpy(CO2, T=T_0)-w_H2OP*
..enthalpy(H2O, T=T_0)-w_O2P*enthalpy(O2, T=T_0)-w_N2P*enthalpy(N2, T=T_0))
"Energy Balance"
E_ng+E_air=E_exhaust+E_boiler
E_boiler+E_water=E_steam+E_loss
"Efficiency"
eta=E_steam/(E_water+E_ng)
"Energy In Calculated"
m_water_calc=m_water
E_water_calc=m_water_calc*(enthalpy(water, T=T_water, P=P_water)-enthalpy(water, T=T_0, P=P_0))
E_ng_calc=m_ng_calc*(enthalpy(CH4, T=T_0)-w_CO2P*enthalpy(CO2, T=T_0)-w_H2OP*enthalpy(H2O, T=
..T_0)-w_O2P*enthalpy(O2, T=T_0)-w_N2P*enthalpy(N2, T=T_0))
E_air_calc=m_ng_calc*(w_O2R*enthalpy(O2, T=T_0)+w_N2R*enthalpy(N2, T=T_0))
"Energy Out"
E_steam_calc=m_water_calc*(enthalpy(water, P=P_steam, x=x_steam)-enthalpy(water, T=T_0, P=P_0))
E_exhaust_calc=m_ng_calc*(w_CO2P*enthalpy(CO2, T=T_exhaust)+w_H2OP*enthalpy(H2O, T=T_exhaust)
..+w_O2P*enthalpy(O2, T=T_exhaust)+w_N2P*enthalpy(N2, T=T_exhaust)-w_CO2P*enthalpy(CO2, T=T_0)-
..w_H2OP*enthalpy(H2O, T=T_0)-w_O2P*enthalpy(O2, T=T_0)-w_N2P*enthalpy(N2, T=T_0))
E_loss_calc=9.175E+06 [Btu/shift]
"Energy Balance"
E_ng_calc+E_air_calc=E_exhaust_calc+E_boiler_calc
E_boiler_calc+E_water_calc=E_steam_calc+E_loss_calc
"Boiler Cost"
Cost=E_ng_calc*cost_ng*convert($/shift,$/year)
"Exergy Analysis"
T_flame=3148 [F]
```

Low Pressure Steam System Section 4.png

```
 P_CH4=17.02 [psia]
 "Exergy In"
 X_CH4=m_ng*(enthalpy(CH4, T=T_0)+w_O2R*enthalpy(O2, T=T_0)+w_N2R*enthalpy(N2, T=T_0)-w_CO2P*
..enthalpy(CO2, T=T_0)-w_H2OP*enthalpy(H2O, T=T_0)-w_O2P*enthalpy(O2, T=T_0)-w_N2P*enthalpy(N2,
..T=T_0)-converttemp(F,R,T_0)*(entropy(CH4, T=T_0, P=P_CH4)+w_O2R*entropy(O2, T=T_0, P=P_O2R)+
..w_N2R*entropy(N2, T=T_0, P=P_N2R)-w_CO2P*entropy(CO2, T=T_0, P=P_CO2P)-w_H2OP*entropy(H2O,
..T=T_0, P=P_H2OP)-w_O2P*entropy(O2, T=T_0, P=P_O2P)-w_N2P*entropy(N2, T=T_0, P=P_N2P)))
 X_water=m_water*(enthalpy(water, T=T_water, P=P_water)-enthalpy(water, T=T_0, P=P_0)-converttemp(F,R,
..T_0)*(entropy(water, T=T_water, P=P_water)-entropy(water, T=T_0, P=P_0)))
 "Exergy Out"
 X_combustion_products=m_ng*(w_CO2P*(enthalpy(CO2, T=T_flame)-enthalpy(CO2, T=T_0)-converttemp(F,
..R,T_0)*(entropy(CO2, T=T_flame, P=P_CO2P)-entropy(CO2, T=T_0, P=P_CO2P)))+w_H2OP*(enthalpy(H2O,
.. T=T_flame)-enthalpy(H2O, T=T_0)-converttemp(F,R,T_0)*(entropy(H2O, T=T_flame, P=P_H2OP)-entropy(
..H2O, T=T_0, P=P_H2OP)))+w_O2P*(enthalpy(O2, T=T_flame)-enthalpy(O2, T=T_0)-converttemp(F,R,T_0)*(
..entropy(O2, T=T_flame, P=P_O2P)-entropy(O2, T=T_0, P=P_O2P)))+w_N2P*(enthalpy(N2, T=T_flame)-
..enthalpy(N2, T=T_0)-converttemp(F,R,T_0)*(entropy(N2, T=T_flame, P=P_N2P)-entropy(N2, T=T_0, P=
..P_N2P))))
 X_exhaust_interior=m_ng*(w_CO2P*(enthalpy(CO2, T=T_exhaust)-enthalpy(CO2, T=T_0)-converttemp(F,R,
..T_0)*(entropy(CO2, T=T_exhaust, P=P_CO2P)-entropy(CO2, T=T_0, P=P_CO2P)))+w_H2OP*(enthalpy(H2O,
.. T=T_exhaust)-enthalpy(H2O, T=T_0)-converttemp(F,R,T_0)*(entropy(H2O, T=T_exhaust, P=P_H2OP)-
..entropy(H2O, T=T_0, P=P_H2OP)))+w_O2P*(enthalpy(O2, T=T_exhaust)-enthalpy(O2, T=T_0)-converttemp(
..F,R,T_0)*(entropy(O2, T=T_exhaust, P=P_O2P)-entropy(O2, T=T_0, P=P_O2P)))+w_N2P*(enthalpy(N2, T=
..T_exhaust)-enthalpy(N2, T=T_0)-converttemp(F,R,T_0)*(entropy(N2, T=T_exhaust, P=P_N2P)-entropy(N2,
..T=T_0, P=P_N2P))))
 X_steam_out=m_water*(enthalpy(water, x=x_steam, P=P_steam)-enthalpy(water, T=T_0, P=P_0)-
..converttemp(F,R,T_0)*(entropy(water, x=x_steam, P=P_steam)-entropy(water, T=T_0, P=P_0)))
 "Exergy"
 X_destroyed_combustion=X_CH4-X_combustion_products
 X_destroyed_losses=X_combustion_products-X_exhaust_interior-(X_steam_out-X_water)
 X_total=X_destroyed_combustion+X_exhaust_interior+X_destroyed_losses+(X_steam_out-X_water)
 X_destroyed=X_destroyed_combustion+X_exhaust_interior+X_destroyed_losses
 X_supplied=X_CH4+X_water
 X_utilized=X_steam_out-X_water
 "Second Law Efficiency"
```

Low Pressure Steam System Section 5.png

```
eta_II=X_utilized/X_supplied
"Energy In Max"
m_water_max=2*10350*convert(lbm/hr,lbm/shift)
E_water_max=m_water_max*(enthalpy(water, T=T_water, P=P_water)-enthalpy(water, T=T_0, P=P_0))
E_ng_max=m_ng_max*(enthalpy(CH4, T=T_0)-w_CO2P*enthalpy(CO2, T=T_0)-w_H2OP*enthalpy(H2O, T=
..T_0)-w_O2P*enthalpy(O2, T=T_0)-w_N2P*enthalpy(N2, T=T_0))
E_air_max=m_ng_max*(w_O2R*enthalpy(O2, T=T_0)+w_N2R*enthalpy(N2, T=T_0))
"Energy Out"
E_steam_max=m_water_max*(enthalpy(water, P=(15+14.7)[psia], x=x_steam)-enthalpy(water, T=T_0, P=
..P_0))
E_exhaust_max=m_ng_max*(w_CO2P*enthalpy(CO2, T=T_exhaust)+w_H2OP*enthalpy(H2O, T=T_exhaust)
..+w_O2P*enthalpy(O2, T=T_exhaust)+w_N2P*enthalpy(N2, T=T_exhaust)-w_CO2P*enthalpy(CO2, T=T_0)-
..w_H2OP*enthalpy(H2O, T=T_0)-w_O2P*enthalpy(O2, T=T_0)-w_N2P*enthalpy(N2, T=T_0))
E_loss_max=9.175E+06 [Btu/shift]
"Energy Balance"
E_ng_max+E_air_max=E_exhaust_max+E_boiler_max
E_boiler_max+E_water_max=E_steam_max+E_loss_max
"Power"
E_chiller=COP*E_exhaust_max
COP=0.98
"Heating Water into DA with exhaust"
E_exhaust_heated=m_water_heated*(enthalpy(water, T=T_DA_new, x=0)-enthalpy(water, T=T_condinsate,
..x=0))
E_exhaust_heated=m_water_reduction*(enthalpy(water, P=P_steam, x=x_steam)-enthalpy(water, T=T_0, P=
..P_0))
"Energy In Calculated"
m_water_heated=m_water_calc-m_water_reduction
E_water_heated=m_water_heated*(enthalpy(water, T=T_water, P=P_water)-enthalpy(water, T=T_0, P=P_0))
E_ng_heated=m_ng_heated*(enthalpy(CH4, T=T_0)-w_CO2P*enthalpy(CO2, T=T_0)-w_H2OP*enthalpy(
..H2O, T=T_0)-w_O2P*enthalpy(O2, T=T_0)-w_N2P*enthalpy(N2, T=T_0))
E_air_heated=m_ng_heated*(w_O2R*enthalpy(O2, T=T_0)+w_N2R*enthalpy(N2, T=T_0))
"Energy Out"
E_steam_heated=m_water_heated*(enthalpy(water, P=P_steam, x=x_steam)-enthalpy(water, T=T_0, P=
..P_0))
```

Low Pressure Steam System Section 6.png

```
E_exhaust_heated=m_ng_heated*(w_CO2P*enthalpy(CO2, T=T_exhaust)+w_H2OP*enthalpy(H2O, T=
..T_exhaust)+w_O2P*enthalpy(O2, T=T_exhaust)+w_N2P*enthalpy(N2, T=T_exhaust)-w_CO2P*enthalpy(
..CO2, T=T_0)-w_H2OP*enthalpy(H2O, T=T_0)-w_O2P*enthalpy(O2, T=T_0)-w_N2P*enthalpy(N2, T=T_0))
"Energy Balance"
E_ng_heated+E_air_heated=E_exhaust_heated+E_boiler_heated
E_boiler_heated+E_water_heated=E_steam_heated+E_loss_calc
Cost_savings_waterheat=(E_ng_calc-E_ng_heated)*cost_ng
"Heating Water into DA with prime mover"
E_water_heat=m_water*(enthalpy(water, T=T_DA, x=0)-enthalpy(water, T=T_condinsate, x=0))
E_exhaust_heated_max=m_water_reduction_max*(enthalpy(water, P=P_steam, x=x_steam)-enthalpy(water,
..T=T_0, P=P_0))
"Energy In Calculated"
m_water_heated_max=m_water_calc-m_water_reduction_max
E_water_heated_max=m_water_heated_max*(enthalpy(water, T=T_water, P=P_water)-enthalpy(water, T=
..T_0, P=P_0))
E_ng_heated_max=m_ng_heated_max*(enthalpy(CH4, T=T_0)-w_CO2P*enthalpy(CO2, T=T_0)-w_H2OP*
..enthalpy(H2O, T=T_0)-w_O2P*enthalpy(O2, T=T_0)-w_N2P*enthalpy(N2, T=T_0))
E_air_heated=m_ng_heated_max*(w_O2R*enthalpy(O2, T=T_0)+w_N2R*enthalpy(N2, T=T_0))
"Energy Out"
E_steam_heated_max=m_water_heated_max*(enthalpy(water, P=P_steam, x=x_steam)-enthalpy(water, T=
..T_0, P=P_0))
E_exhaust_heated_max=m_ng_heated_max*(w_CO2P*enthalpy(CO2, T=T_exhaust)+w_H2OP*enthalpy(
..H2O, T=T_exhaust)+w_O2P*enthalpy(O2, T=T_exhaust)+w_N2P*enthalpy(N2, T=T_exhaust)-w_CO2P*
..enthalpy(CO2, T=T_0)-w_H2OP*enthalpy(H2O, T=T_0)-w_O2P*enthalpy(O2, T=T_0)-w_N2P*enthalpy(N2,
..T=T_0))
"Energy Balance"
E_ng_heated_max+E_air_heated_max=E_exhaust_heated_max+E_boiler_heated_max
E_boiler_heated_max+E_water_heated_max=E_steam_heated_max+E_loss_calc
Cost_savings_waterheat_max=(E_ng_calc-E_ng_heated)*cost_ng
"Power Generation"
"Summary of Typical Cost and Performance Characteristics by CHP Technology(EPA, 2008)"
eta_re=(0.27+0.41)/2
eta_st=0.8                                              {Overall efficiency of a steam turbine system}
eta_gt=0.725                                            {Overal efficiency of a gas turbine system +/-0.25}
```

Low Pressure Steam System Section 7.png

```
eta_mt=0.8                                       {Quoted efficiency from capstone turbine}
eta_fc=0.47                                      {Quoted efficiency from FuelCell Energy}
X_re=(0.5+1.2)/2
X_gt=1.25                                        {Typical power to heat ratio +/-0.75}
X_mt=0.93                                        {Quoted power to heat ratio from capstone turbine}
X_fc=1400/1092.183                               {Quoted power to heat ration from FuelCell Energy}
Cost_re_installed=1650[$/kW]                     {CHP installed for a recip. engine system +/-550}
Cost_mt_installed=2000[$/kW]                     {CHP cost for a microturbine system $1600-1800
                                                 per kW befor installation from capstone turbine}
Cost_fc_installed=5750[$/kW]                     {CHP installed cost for a fuel cell system +/-750}
Cost_re_OM=0.0155[$/kWh]                         {Non-fuel operation and maintenance costs for a
                                                 recip. engine system +/-0.0065}
Cost_fc_OM=0.035[$/kWh]                          {Non-fuel operation and maintenance costs for a
                                                 fuel cell system +/-0.003}
"RE"
eta_re=(P_re+E_water_heat)/F_re
X_re=P_re/E_water_heat
Cost_re_fuel_total=F_re*cost_ng
Cost_savings_re=P_re*convert(Btu, kWh)*(cost_elec-cost_re_OM)+Cost_savings_waterheat_max-
Cost_re_fuel_total
Cost_re=Cost_re_installed*P_re*convert(Btu/shift,kW)
Payback_re=Cost_re/(Cost_savings_re*convert($/shift,$/year))
"FC"
eta_fc=(P_fc+E_water_heat)/F_fc
X_fc=P_fc/E_water_heat
Cost_fc_fuel_total=F_fc*cost_ng
Cost_savings_fc=P_fc*convert(Btu, kWh)*(cost_elec-cost_fc_OM)+Cost_savings_waterheat_max-
Cost_fc_fuel_total
Cost_fc=Cost_fc_installed*P_fc*convert(Btu/shift,kW)
Payback_fc=Cost_fc/(Cost_savings_fc*convert($/shift,$/year))
```

APPENDIX D

CHILLED WATER SYSTEM EES CODE

Chilled Water System Section 1.png

```
"Dead State Conditions"
T_0=converttemp('C','F',25)                        {Dead State Temperature in F}
P_0=1*convert('atm','psia')                        {Dead State Pressure in psia}
"Combustion Calculations"
"Used to Estimate Exergy Analysis"
n_O2R=(2[mol]+x)/((2[mol]+x)+(2[mol]+x)*3.76)      {mole fraction of O2 in the combustion reactants}
n_N2R=((2[mol]+x)*3.76)/((2[mol]+x)+(2[mol]+x)*3.76) {mole fraction of N2 in the combustion reactants}
n_CO2P=1[mol]/(1[mol]+2[mol]+x+(2[mol]+x)*3.76)    {mole fraction of CO2 in the combustion products}
n_H2OP=2[mol]/(1[mol]+2[mol]+x+(2[mol]+x)*3.76)    {mole fraction of H2O in the combustion products}
n_O2P=x/(1[mol]+2[mol]+x+(2[mol]+x)*3.76)          {mole fraction of O2 in the combustion products}
n_N2P=((2[mol]+x)*3.76)/(1[mol]+2[mol]+x+(2[mol]+x)*3.76){mole fraction of N2 in the combustion products}
w_O2R=((2[mol]+x)*molarmass(O2))/(1[mol]*molarmass(CH4)){mass fraction of O2 in the combustion
--                                                 reactants}
w_N2R=((2[mol]+x)*3.76*molarmass(N2))/(1[mol]*molarmass(CH4)){mass fraction of N2 in the combustion
--                                                 reactants}
w_CO2P=(1[mol]*molarmass(CO2))/(1[mol]*molarmass(CH4)){mass fraction of CO2 in the combustion
--                                                 products}
w_H2OP=(2[mol]*molarmass(H2O))/(1[mol]*molarmass(CH4)){mass fraction of H2O in the combustion
--                                                 products}
w_O2P=(x*molarmass(O2))/(1[mol]*molarmass(CH4)){mass fraction of O2 in the combustion products}
w_N2P=((2[mol]+x)*3.76*molarmass(N2))/(1[mol]*molarmass(CH4)){mass fraction of N2 in the combustion
--                                                 products}
p_O2R=n_O2R*P_0                                    {partial pressure of O2 in the combustion
--                                                 reactants}
p_N2R=n_N2R*P_0                                    {partial pressure of N2 in the combustion
--                                                 reactants}
p_CO2P=n_CO2P*P_0                                  {partial pressure of CO2 in the combustion
--                                                 products}
p_H2OP=n_H2OP*P_0                                  {partial pressure of H2O in the combustion
--                                                 products}
p_O2P=n_O2P*P_0                                    {partial pressure of O2 in the combustion products}
p_N2P=n_N2P*P_0                                    {partial pressure of N2 in the combustions
--                                                 producs}
T_exhaust=77                                       {Exhaust Temperature}
```

Chilled Water System Section 2.png

```
  phi_O2P=0.04                                   {volume fraction of O2 in the combustion products}
  phi_O2P=(x*MWO2*volume(O2, T=T_exhaust, P=P_0))/(1[mol]*MWCO2*volume(CO2, T=T_exhaust, P=P_0)
..+2[mol]*MWH2O*volume(H2O, T=T_exhaust, P=P_0)+x*MWO2*volume(O2, T=T_exhaust, P=P_0)+(2[mol]+
..x)*3.76*MWN2*volume(N2, T=T_exhaust, P=P_0))   {volume fraction of O2 in the combustion products}
  MWO2=molarmass(O2)*convert(lb_m/lbmol,lb_m/mol)   {molar mass of O2 in lb_m/mol}
  MWCO2=molarmass(CO2)*convert(lb_m/lbmol,lb_m/mol){molar mass of CO2 in lb_m/mol}
  MWH2O=molarmass(H2O)*convert(lb_m/lbmol,lb_m/mol){molar mass of H2O in lb_m/mol}
  MWN2=molarmass(N2)*convert(lb_m/lbmol,lb_m/mol)   {molar mass of N2 in lb_m/mol}
  P_CH4=(16+101.325)*convert('kPa','psia')       {The pressure of the natural gas in psia as
..                                               received by the Boilers}
  "Utility Costs"
  cost_ng=0.0000076[$/Btu]                       {average natural gas price for FY14 minus June}
  cost_elec=(cost_nonpeak+(cost_demand/(30.5*24[h]))+cost_peak+(cost_demand/(30.5*24[h]))+(
..cost_demand_peak/(30.5*12[h])))/2              {average of peak and non-peak}
  cost_elec_p=cost_peak+(cost_demand/(30.5*24[h])+(cost_demand_peak/(30.5*12[h])))
  cost_elec_np=cost_nonpeak+(cost_demand/(30.5*24[h]))
  cost_nonpeak=0.05104[$/kWh]                    {non-peak electrical rate}
  cost_demand=1.306[$/kW]                        {monthly non-peak demand charge}
  cost_peak=0.07118[$/kWh]                       {peak electrical rate}
  cost_demand_peak=7.501[$/kW]                   {monthly peak demand charge}
  cost_LMP_average=31.94[$/MWh]                  {average price payed for excess power
..generation, https://www.misoenergy.org/Library/Repository/Report/Annual%20Market%20Report/
..2013%20Annual%20Market%20Assessment%20Report.pdf}
  cost_facilitiescharge=0.11507[$/day]           {facilities charge for interconnection, https://
..www.we-energies.com/pdfs/etariffs/wisconsin/ewi_sheet131-132.pdf}
  "Current Chiller Information"
  Q_i_h=0.897[kW/Ton]*Chiller_h*y                {Power used by current chillers scaled up to future
..                                               size during fully loaded operation}
  eta_II_i_l=X_chiller_utilized_h/(Q_i_h*convert(kW,Btu/s)) {Second law efficiency of mechanical chiller}
  Q_i_l=0.897[kW/Ton]*Chiller_l*y                {Power used by current chillers scaled up to future
..                                               size during fully loaded operation}
  eta_II_i_h=X_chiller_utilized_h/(Q_i_l*convert(kW,Btu/s)) {Second law efficiency of mechanical chiller}
  "Theoretical Chiller Information"
  Q_se=Chiller_l*y*convert(ton,Btu/s)/COP_se     {Thermal load for single stage lp steam fired
```

Chilled Water System Section 3.png

```
                                                absorption chiller}
Q_dh=Chiller_h*y*convert(ton,Btu/s)/COP_dh      {Thermal load for two stage direct fire absorption
                                                chiller}
Chiller_l=300[Ton]
Chiller_h=500[Ton]
COP_se=0.793                                    {Coefficient of performance for a single stage
absorption chiller, http://cgproducts.johnsoncontrols.com/YorkDoc/155.16-EG1.pdf}
COP_dh=1.1293                                   {Coefficient of performance for a two stage direct
fire absorption chiller, http://cgproducts.johnsoncontrols.com/YorkDoc/155.17-EG4.pdf}
COP_ds=1.38                                     {Coefficient of performance for a two stage high
pressure steam absorption chiller, http://cgproducts.johnsoncontrols.com/YorkDoc/155.19-EG3.pdf}
Chiller_h*convert(ton,Btu/s)=m_water_h*(enthalpy(water, T=54[F], x=0)-enthalpy(water, T=50[F], x=0))
{Calculating mass flow rate of water, based on current chiller operating temperatures}
X_chiller_utilized_h=m_water_h*(enthalpy(water, T=50[F], x=0)-enthalpy(water, T=54[F], x=0)-converttemp(F,
R,T_0)*(entropy(water, T=50[F], x=0)-entropy(water, T=54[F], x=0)))
{Calculating exergy utilized in the form of chilled water}
Chiller_l*convert(ton,Btu/s)=m_water_l*(enthalpy(water, T=54[F], x=0)-enthalpy(water, T=50[F], x=0))
{Calculating mass flow rate of water, based on current chiller operating temperatures}
X_chiller_utilized_l=m_water_l*(enthalpy(water, T=50[F], x=0)-enthalpy(water, T=54[F], x=0)-converttemp(F,R,
T_0)*(entropy(water, T=50[F], x=0)-entropy(water, T=54[F], x=0)))
{Calculating exergy utilized in the form of chilled water}
y=.4                                            {Chiller load factor, between .4 and .7}
"Summary of Typical Cost and Performance Characteristics by CHP Technology(EPA, 2008)"
eta_st=0.8                                      {Overall efficiency of a steam turbine system}
eta_gt=0.725                                    {Overal efficiency of a gas turbine system +/-0.25}
eta_mt=0.8                                      {Quoted efficiency from capstone turbine}
eta_fc=0.47                                     {Quoted efficiency from FuelCell Energy}
eta_re=0.785
X_st=0.2                                        {Typical power to heat ratio +/-0.1}
X_gt=1.25                                       {Typical power to heat ratio +/-0.75}
X_mt=0.93                                       {Quoted power to heat ratio from capstone turbine}
X_fc=1400/1092.183                              {Quoted power to heat ratio from FuelCell Energy}
X_re=0.85
Cost_st_installed=765[$/kW]                     {CHP installed cost for a steam turbine system +/-
```

Chilled Water System Section 4.png

```
 335}
 {Cost_re_installed=1650[$/kW]}                      {CHP installed cost for a recip. engine system +/-
..550}
 Cost_gt_installed=1135[$/kW]                        {CHP installed cost for a gas turbine system +/-
..165}
 Cost_mt_installed=2000[$/kW]                        {CHP cost for a microturbine system $1600-1800
..per kW befor installation from capstone turbine}
 Cost_fc_installed=5750[$/kW]                        {CHP installed cost for a fuel cell system +/-750}
 Cost_st_OM=0.005[$/kWh]                             {Non-fuel operation and maintenance costs for a
..steam turbine system -0.005}
 Cost_re_OM=0.0155[$/kWh]                            {Non-fuel operation and maintenance costs for a
..recip. engine system +/-0.0065}
 Cost_gt_OM=0.0075[$/kWh]                            {Non-fuel operation and maintenance costs for a
..gas turbine system +/-0.0035}
 Cost_mt_OM=0.0175[$/kWh]                            {Quoted non-fuel operation and maintenance
..costs for a microturbine system +/-0.0025}
 Cost_fc_OM=0.035[$/kWh]                             {Non-fuel operation and maintenance costs for a
..fuel cell system +/-0.003}
 Delta_chiller_cost=50[$/Ton]                        {Difference in cost between a single stage
..absorption chiller and a water cooled rotary scroll chiller per ton http://www.trane.com/commercial/uploads/
..pdf/                                                    865/ctv-trt-001-en.pdf}
 Delta_chiller_cost_1=225[$/Ton]                     {Difference in cost between a  direct fire
..absorption chiller and a water cooled rotary scroll chiller per ton http://www.trane.com/commercial/uploads/
..pdf/                                                    865/ctv-trt-001-en.pdf}
 Cost_chiller_installed=60[$/Ton]                    {Cost to install a chiller http://www.trane.com/
..commercial/uploads/pdf/865/ctv-trt-001-en.pdf}
 Cost_chiller_se=350[$/Ton]                          {Cost of a single stage absorption chiller}
 Cost_chiller_dh=525[$/Ton]                          {Cost of a direct fire absorption chiller}
 "Calculations for Steam Turbine System with Single Stage Absorption Chiller"
 eta_st=(P_st_se+Q_se)/F_st_se                       {Relating overall efficiency, thermal load and
..power to heat ratio to solve for fuel usage and power production}
 X_st=P_st_se/Q_se                                   {Relating overall efficiency, thermal load and
..power to heat ratio to solve for fuel usage and power production}
 "Calculations for Steam Turbine System with Single Stage Absorption Chiller"
```

Chilled Water System Section 5.png

```
  eta_st=(P_st_se+Q_se)/F_st_se                     {Relating overall efficiency, thermal load and
..power to heat ratio to solve for fuel usage and power production}
  X_st=P_st_se/Q_se                                 {Relating overall efficiency, thermal load and
..power to heat ratio to solve for fuel usage and power production}
  "Calculations for Steam Turbine System with Single Stage Absorption Chiller"
  eta_re=(P_re_se+Q_se)/F_re_se                     {Relating overall efficiency, thermal load and
..power to heat ratio to solve for fuel usage and power production}
  X_re=P_re_se/Q_se                                 {Relating overall efficiency, thermal load and
..power to heat ratio to solve for fuel usage and power production}
  "Calculations for Microturbine System with Single Stage Hot Water Fired Absorption Chiller"
  eta_mt=(P_mt_se+Q_se)/F_mt_se                     {See comments in section above}
  eta_mt_se_e=P_mt_se/F_mt_se
  X_mt=P_mt_se/Q_se
  Cost_mt_fuel_elec_se=(F_mt_se*P_mt_se*cost_ng*3600[s])/(P_mt_se*convert(Btu/s,kW)*1[h]*(P_mt_se+
..Q_se))
  Cost_mt_fuel_therm_se=(F_mt_se*Q_se*cost_ng*3600[s])/(1[h]*(P_mt_se+Q_se))
  Cost_mt_fuel_total_se=F_mt_se*cost_ng
  Cost_mt_fuel_elec_only_se=(F_mt_se*cost_ng*convert(Btu/s,Btu/h))/(P_mt_se*convert(Btu/s,kW))
  Total_costsavings_mt_se=(Q_i_h*cost_elec-Cost_mt_fuel_therm_se)+P_mt_se*convert(Btu/s,kW)*(
..Cost_elec-Cost_mt_fuel_elec_se+Cost_mt_OM)
  Payback_mt_se=(P_mt_se*convert(Btu/s,kW)*Cost_mt_installed+Delta_chiller_cost*Chiller_h-
..TaxCredit_mt_se-FocusOnEnergy)/Total_costsavings_mt_se
  m_ng_mt_se=F_mt_se/(enthalpy(CH4, T=T_0)-w_CO2P*enthalpy(CO2, T=T_0)-w_H2OP*enthalpy(H2O, T=
..T_0)-w_O2P*enthalpy(O2, T=T_0)-w_N2P*enthalpy(N2, T=T_0))
  X_in_mt_se=m_ng_mt_se*(enthalpy(CH4, T=T_0)+w_O2R*enthalpy(O2, T=T_0)+w_N2R*enthalpy(N2, T=
..T_0)-w_CO2P*enthalpy(CO2, T=T_0)-w_H2OP*enthalpy(H2O, T=T_0)-w_O2P*enthalpy(O2, T=T_0)-w_N2P*
..enthalpy(N2, T=T_0)-converttemp(F,R,T_0)*(entropy(CH4, T=T_0, P=P_CH4)+w_O2R*entropy(O2, T=T_0,
..P=P_O2R)+w_N2R*entropy(N2, T=T_0, P=P_N2R)-w_CO2P*entropy(CO2, T=T_0, P=P_CO2P)-w_H2OP*
..entropy(H2O, T=T_0, P=P_H2OP)-w_O2P*entropy(O2, T=T_0, P=P_O2P)-w_N2P*entropy(N2, T=T_0, P=
..P_N2P)))
  X_utilized_mt_se=X_chiller_utilized_h+P_mt_se
  eta_II_mt_se=X_utilized_mt_se/X_in_mt_se
  eta_I_mt_se=(Chiller_h*y*convert(ton,Btu/s)+P_mt_se)/F_mt_se
  TaxCredit_mt_se=.1*(P_mt_se*convert(Btu/s,kW)*Cost_mt_installed+Chiller_h*(Cost_chiller_installed+
```

Chilled Water System Section 6.png

```
Cost_chiller_se))                                    {CHP system with an efficiency greater than 60%}
FocusOnEnergy=200000                                 {Max rebate from Focus on Energy Program}
"Calculations for Microturbine System with Two Stage Direct Heat Fired Absorption Chiller"
eta_mt=(P_mt_dh+Q_dh)/F_mt_dh                        {See comments in section above}
eta_mt_dh_e=P_mt_dh/F_mt_dh
X_mt=P_mt_dh/Q_dh
Cost_mt_fuel_elec_dh=(F_mt_dh*P_mt_dh*cost_ng*3600[s])/(P_mt_dh*convert(Btu/s,kW)*1[h]*(P_mt_dh+
..Q_dh))
Cost_mt_fuel_therm_dh=(F_mt_dh*Q_dh*cost_ng*3600[s])/(1[h]*(P_mt_dh+Q_dh))
Cost_mt_fuel_total_dh=F_mt_dh*cost_ng
Cost_mt_fuel_elec_only_dh=(F_mt_dh*cost_ng*convert(Btu/s,Btu/h))/(P_mt_dh*convert(Btu/s,kW))
Total_costsavings_mt_dh=(Q_i_h*cost_elec-Cost_mt_fuel_therm_dh)+P_mt_dh*convert(Btu/s,kW)*(
..Cost_elec-Cost_mt_fuel_elec_dh+Cost_mt_OM)
Payback_mt_dh=(P_mt_dh*convert(Btu/s,kW)*Cost_mt_installed+Delta_chiller_cost_1*Chiller_h-
..TaxCredit_mt_dh-FocusOnEnergy)/Total_costsavings_mt_dh
m_ng_mt_dh=F_mt_dh/(enthalpy(CH4, T=T_0)-w_CO2P*enthalpy(CO2, T=T_0)-w_H2OP*enthalpy(H2O, T=
..T_0)-w_O2P*enthalpy(O2, T=T_0)-w_N2P*enthalpy(N2, T=T_0))
X_in_mt_dh=m_ng_mt_dh*(enthalpy(CH4, T=T_0)+w_O2R*enthalpy(O2, T=T_0)+w_N2R*enthalpy(N2, T=
..T_0)-w_CO2P*enthalpy(CO2, T=T_0)-w_H2OP*enthalpy(H2O, T=T_0)-w_O2P*enthalpy(O2, T=T_0)-w_N2P*
..enthalpy(N2, T=T_0)-converttemp(F,R,T_0)*(entropy(CH4, T=T_0, P=P_CH4)+w_O2R*entropy(O2, T=T_0,
..P=P_O2R)+w_N2R*entropy(N2, T=T_0, P=P_N2R)-w_CO2P*entropy(CO2, T=T_0, P=P_CO2P)-w_H2OP*
..entropy(H2O, T=T_0, P=P_H2OP)-w_O2P*entropy(O2, T=T_0, P=P_O2P)-w_N2P*entropy(N2, T=T_0, P=
..P_N2P)))
X_utilized_mt_dh=X_chiller_utilized_h+P_mt_dh
eta_II_mt_dh=X_utilized_mt_dh/X_in_mt_dh
eta_I_mt_dh=(Chiller_h*y*convert(ton,Btu/s)+P_mt_dh)/F_mt_se
TaxCredit_mt_dh=.1*(P_mt_dh*convert(Btu/s,kW)*Cost_mt_installed+Chiller_h*(Cost_chiller_installed+
..Cost_chiller_dh))                                  {CHP system with an efficiency greater than 60%}
"Calculations for Capstone Microturbine System with 300 Ton Two Stage Direct Fire Thermax Absorptions
..Chiller"
P_mt_300=1000[kW]*convert(kW,Btu/s)
Q_300=297[Tons]*convert(Tons,Btu/s)
eta_mt_300_e=0.33
Cost_mt_300=1832130[$]
```

Chilled Water System Section 7.png

```
eta_mt_300=(P_mt_300+Q_300)/F_mt_300
eta_mt_300_e=P_mt_300/F_mt_300
X_mt_300=P_mt_300/Q_300
Cost_mt_fuel_elec_300=(F_mt_300*P_mt_300*cost_ng*3600[s])/(P_mt_300*convert(Btu/s,kW)*1[h]*(
..P_mt_300+Q_300))
Cost_mt_fuel_therm_300=(F_mt_300*Q_300*cost_ng*3600[s])/(1[h]*(P_mt_300+Q_300))
Cost_mt_fuel_total_300=F_mt_300*cost_ng
Cost_mt_fuel_elec_only_300=(F_mt_300*cost_ng*convert(Btu/s,Btu/h))/(P_mt_300*convert(Btu/s,kW))
Total_costsavings_mt_300=(Q_300*convert(Btu/s,Tons)*0.897[kW/Ton]*cost_elec-Cost_mt_
..fuel_therm_300)+P_mt_300*convert(Btu/s,kW)*(Cost_elec-Cost_mt_fuel_elec_300+Cost_mt_OM)
Payback_mt_300=(Cost_mt_300+Delta_chiller_cost_1*Q_300*convert(Btu/s,Tons)-TaxCredit_mt_300-
..FocusOnEnergy)/Total_costsavings_mt_300
TaxCredit_mt_300=.1*(Cost_mt_300+Q_300*convert(Btu/s,Tons)*(Cost_chiller_installed+Cost_chiller_dh))
"Calculations for Capstone Microturbine System with 500 Ton Two Stage Direct Fire Thermax Absorptions
..Chiller"
P_mt_500=1000[kW]*2*.83*convert(kW,Btu/s)
Q_500=297[Tons]*2*.83*convert(Tons,Btu/s)
eta_mt_500_e=0.33
Cost_mt_500=3346120[$]
eta_mt_500=(P_mt_500+Q_500)/F_mt_500
eta_mt_500_e=P_mt_500/F_mt_500
X_mt_500=P_mt_500/Q_500
Cost_mt_fuel_elec_500=(F_mt_500*P_mt_500*cost_ng*3600[s])/(P_mt_500*convert(Btu/s,kW)*1[h]*(
..P_mt_500+Q_500))
Cost_mt_fuel_therm_500=(F_mt_500*Q_500*cost_ng*3600[s])/(1[h]*(P_mt_500+Q_500))
Cost_mt_fuel_total_500=F_mt_500*cost_ng
Cost_mt_fuel_elec_only_500=(F_mt_500*cost_ng*convert(Btu/s,Btu/h))/(P_mt_500*convert(Btu/s,kW))
Total_costsavings_mt_500=(Q_500*convert(Btu/s,Tons)*0.897[kW/Ton]*cost_elec-Cost_mt_
..fuel_therm_500)+P_mt_500*convert(Btu/s,kW)*(Cost_elec-Cost_mt_fuel_elec_500+Cost_mt_OM)
Payback_mt_500=(Cost_mt_500+Delta_chiller_cost_1*Q_500*convert(Btu/s,Tons)-TaxCredit_mt_500-
..FocusOnEnergy)/Total_costsavings_mt_500
TaxCredit_mt_500=.1*(Cost_mt_500+Q_500*convert(Btu/s,Tons)*(Cost_chiller_installed+Cost_chiller_dh))
"Calculations for Capstone Microturbine System with 500 Ton Two Stage Direct Fire Thermax Absorptions
..Chiller with Peak Time Over Production"
```

Chilled Water System Section 8.png

```
 P_mt_500_t=1000[kW]*2*convert(kW,Btu/s)
 Q_500_t=297[Tons]*2*convert(Tons,Btu/s)
 eta_mt_500_e_t=0.33
 Cost_mt_500_t=3346120[$]
 eta_mt_500_t=(P_mt_500_t+Q_500_t)/F_mt_500_t
 eta_mt_500_e_t=P_mt_500_t/F_mt_500_t
 X_mt_500_t=P_mt_500_t/Q_500_t
 Cost_mt_fuel_elec_500_t=(F_mt_500_t*P_mt_500_t*cost_ng*3600[s])/(P_mt_500_t*convert(Btu/s,kW)*1[h]*(
..P_mt_500_t+Q_500_t))
 Cost_mt_fuel_therm_500_t=(F_mt_500_t*Q_500_t*cost_ng*3600[s])/(1[h]*(P_mt_500_t+Q_500_t))
 Cost_mt_fuel_total_500_t=F_mt_500_t*cost_ng
 Cost_mt_fuel_elec_only_500_t=(F_mt_500_t*cost_ng*convert(Btu/s,Btu/h))/(P_mt_500_t*convert(Btu/s,kW))
 Total_costsavings_mt_500_t=(Q_500*convert(Btu/s,Tons)*0.8414[kW/Ton]*cost_elec-Cost_m
..t_fuel_therm_500)+P_mt_500*convert(Btu/s,kW)*(Cost_elec-Cost_mt_fuel_elec_500+Cost_mt_OM)+(
..P_mt_500_t-P_mt_500)*convert(Btu/s,kW)*(Cost_elec_p-Cost_mt_fuel_elec_500_t+Cost_mt_OM)*0.5
 Payback_mt_500_t=(Cost_mt_500_t+Delta_chiller_cost_1*Q_500_t*convert(Btu/s,Tons)-TaxC
..redit_mt_500_t-FocusOnEnergy)/Total_costsavings_mt_500_t
 TaxCredit_mt_500_t=.1*(Cost_mt_500_t+Q_500_t*convert(Btu/s,Tons)*(Cost_chiller_installed+
..Cost_chiller_dh))
 "Calculations for Capstone Microturbine System with 500 Ton Two Stage Direct Fire Thermax Absorptions
..Chiller with Peak Time Over Production Ideal Payback"
 P_mt_500_t_i=1000[kW]*2*convert(kW,Btu/s)
 Q_500_t_i=297[Tons]*2*convert(Tons,Btu/s)
 eta_mt_500_e_t_i=0.33
 Cost_mt_500_t_i=3346120[$]
 eta_mt_500_t_i=(P_mt_500_t_i+Q_500_t_i)/F_mt_500_t_i
 eta_mt_500_e_t_i=P_mt_500_t_i/F_mt_500_t_i
 X_mt_500_t_i=P_mt_500_t_i/Q_500_t_i
 Cost_mt_fuel_elec_500_t_i=(F_mt_500_t_i*P_mt_500_t_i*cost_ng*3600[s])/(P_mt_500_t_i*convert(Btu/s,kW)*
..1[h]*(P_mt_500_t_i+Q_500_t_i))
 Cost_mt_fuel_therm_500_t_i=(F_mt_500_t_i*Q_500_t_i*cost_ng*3600[s])/(1[h]*(P_mt_500_t_i+Q_500_t_i))
 Cost_mt_fuel_total_500_t_i=F_mt_500_t_i*cost_ng
 Cost_mt_fuel_elec_only_500_t_i=(F_mt_500_t_i*cost_ng*convert(Btu/s,Btu/h))/(P_mt_500_t_i*convert(Btu/s,
..kW))
```

Chilled Water System Section 9.png

```
 ratio_elec=cost_elec*convert($/kWh, $/Btu)/cost_ng
 ratio_elec_i=cost_elec_i*convert($/kWh, $/Btu)/cost_ng
 Total_costsavings_mt_500_t_i=(Q_500*convert(Btu/s,Tons)*0.8414[kW/Ton]*cost_elec_i-Cos
..t_mt_fuel_therm_500)+P_mt_500*convert(Btu/s,kW)*(Cost_elec_i-Cost_mt_fuel_elec_500+Cost_mt_OM)+(
..P_mt_500_t-P_mt_500)*convert(Btu/s,kW)*(Cost_elec_i*1.3-Cost_mt_fuel_elec_500_t_i+Cost_mt_OM)*0.5
 (4*365*24)[h]=(Cost_mt_500_t_i+Delta_chiller_cost_1*Q_500_t_i*convert(Btu/s,Tons)-TaxCredit_mt_500_t_i-
..FocusOnEnergy)/Total_costsavings_mt_500_t_i
 TaxCredit_mt_500_t_i=.1*(Cost_mt_500_t_i+Q_500_t_i*convert(Btu/s,Tons)*(Cost_chiller_installed+
..Cost_chiller_dh))
 "Calculations for Fuel Cell System with Single Effect Absorption Chiller"
 eta_fc=(P_fc_se+Q_se)/F_fc_se                                {See comments in section above}
 eta_fc_e=P_fc_se/F_fc_se
 X_fc=P_fc_se/Q_se
 Cost_fc_fuel_elec_se=(F_fc_se*P_fc_se*cost_ng*3600[s])/(P_fc_se*convert(Btu/s,kW)*1[h]*(P_fc_se+Q_se)
 )
..Cost_fc_fuel_therm_se=(F_fc_se*Q_se*cost_ng*3600[s])/(1[h]*(P_fc_se+Q_se))
 Cost_fc_fuel_total_se=F_fc_se*cost_ng
 Total_costsavings_fc_se=(Q_i_h*cost_elec-Cost_fc_fuel_therm_se)+P_fc_se*convert(Btu/s,kW)*(
..Cost_elec-Cost_fc_fuel_elec_se+Cost_fc_OM)
 Payback_fc_se=(P_fc_se*convert(Btu/s,kW)*Cost_fc_installed+Delta_chiller_cost*Chiller_h-
..TaxCredit_fc_se)/Total_costsavings_fc_se
 m_ng_fc_se=F_fc_se/(enthalpy(CH4, T=T_0)-w_CO2P*enthalpy(CO2, T=T_0)-w_H2OP*enthalpy(H2O, T=
..T_0)-w_O2P*enthalpy(O2, T=T_0)-w_N2P*enthalpy(N2, T=T_0))
 X_in_fc_se=m_ng_fc_se*(enthalpy(CH4, T=T_0)+w_O2R*enthalpy(O2, T=T_0)+w_N2R*enthalpy(N2, T=T_0)
..-w_CO2P*enthalpy(CO2, T=T_0)-w_H2OP*enthalpy(H2O, T=T_0)-w_O2P*enthalpy(O2, T=T_0)-w_N2P*
..enthalpy(N2, T=T_0)-converttemp(F,R,T_0)*(entropy(CH4, T=T_0, P=P_CH4)+w_O2R*entropy(O2, T=T_0,
..P=P_O2R)+w_N2R*entropy(N2, T=T_0, P=P_N2R)-w_CO2P*entropy(CO2, T=T_0, P=P_CO2P)-w_H2OP*
..entropy(H2O, T=T_0, P=P_H2OP)-w_O2P*entropy(O2, T=T_0, P=P_O2P)-w_N2P*entropy(N2, T=T_0, P=
..P_N2P)))
 X_utilized_fc_se=X_chiller_utilized_h+P_fc_se
 eta_II_fc_se=X_utilized_fc_se/X_in_fc_se
 eta_I_fc_se=(Chiller_h*convert(ton,Btu/s)+P_fc_se)/F_fc_se
 TaxCredit_fc_se=.3*P_mt_dh*convert(Btu/s,kW)*Cost_mt_installed
 {Fuel Cell system with an electricity-only generation efficiency greater than 30%}
```