

9-9-2010

Second law analysis of a natural gas-fired steam boiler and cogeneration plant

Eric D. Conklin

Follow this and additional works at: https://digitalrepository.unm.edu/me_etds

Recommended Citation

Conklin, Eric D.. "Second law analysis of a natural gas-fired steam boiler and cogeneration plant." (2010).
https://digitalrepository.unm.edu/me_etds/45

This Thesis is brought to you for free and open access by the Engineering ETDs at UNM Digital Repository. It has been accepted for inclusion in Mechanical Engineering ETDs by an authorized administrator of UNM Digital Repository. For more information, please contact disc@unm.edu.

Eric Conklin

Candidate

Mechanical Engineering

Department

This thesis is approved, and it is acceptable in quality and form for publication:

Approved by the Thesis Committee:

Arsalan Razi

Chairperson

Randall Turner

N/A

**SECOND LAW ANALYSIS OF A NATURAL GAS-FIRED
STEAM BOILER AND COGENERATION PLANT**

BY

ERIC CONKLIN

B.S.M.E., UNIVERSITY OF NEW MEXICO, 2006

THESIS

Submitted in Partial Fulfillment of the
Requirements for the Degree of

**Master of Science
Mechanical Engineering**

The University of New Mexico
Albuquerque, New Mexico

July, 2010

ACKNOWLEDGMENTS

I acknowledge Dr. Arsalan Razani, my thesis committee chair, for the inspiration and knowledge to complete this work. His guidance has been essential throughout this process and I am grateful for his efforts.

I also thank Dr. Randall Truman for not only his insight in this particular work, but also for the years of guidance as my undergraduate advisor and professor of multiple courses.

To my other committee member and mentor, Michael Dexter, thank you. I admire the professionalism, work ethic and expertise that you display everyday and are thankful to have had the opportunity to learn so much from you over the last 4 years.

I acknowledge Steve Simon for the years of guidance and support. I am grateful for the knowledge and friendship you have given me from the first day we met.

I also thank Rice University and Doug Wells for his support of this work. The trending data and drawings provided have been invaluable and very much appreciated.

**SECOND LAW ANALYSIS OF A NATURAL GAS-FIRED
STEAM BOILER AND COGENERATION PLANT**

BY

ERIC CONKLIN

ABSTRACT OF THESIS

Submitted in Partial Fulfillment of the
Requirements for the Degree of

**Master of Science
Mechanical Engineering**

The University of New Mexico
Albuquerque, New Mexico

July, 2010

SECOND LAW ANALYSIS OF A NATURAL GAS-FIRED STEAM BOILER AND COGENERATION PLANT

By

Eric Conklin

B.S., Mechanical Engineering, University of New Mexico, 2006

M.S., Mechanical Engineering, University of New Mexico, 2010

ABSTRACT

A second law thermodynamic analysis of a natural gas-fired steam boiler and cogeneration plant at Rice University was conducted. The analysis included many components of the plant including piping, valves, boilers, turbines, piping specialties and various other pieces of equipment.

Typical steady state plant operating conditions were determined based on available trending data and the resulting conditions are representative of the bulk of the plant's operating hours. The exergy destruction from individual components in the plant was calculated based on these operating conditions to determine the true system losses. The largest source of exergy destruction within the plant was found to be the gas turbine system under typical operating conditions.

Recommendations for efficiency improvement based on the analysis are discussed. The addition of a back pressure steam turbine to the system is shown to improve the overall system efficiency from 21% to 22.4% while increasing the plant power generation capacity by 9.8%. A reduction in the plant steam header pressure in conjunction with the addition of the steam turbine improved the overall system efficiency to 23%, while increasing plant power generation by 12%. In addition, a first law thermodynamic analysis was performed and first and second law efficiencies are compared for several components.

TABLE OF CONTENTS

LIST OF FIGURES	VIII
LIST OF TABLES	IX
1. INTRODUCTION.....	1
2. OVERVIEW OF STEAM AND CHP PLANT	6
3. DETERMINATION OF PLANT OPERATING CONDITIONS	9
4. OVERVIEW OF ANALYSIS.....	11
4.1 First and Second Law Control Volume Governing Equations	11
4.2 First and Second Law Efficiency	13
4.3 Piping losses.....	14
4.4 Steam Turbine Calculations	15
5. ANALYSIS RESULTS	17
5.1 Plant Exergy Destruction	17
5.2 Exergetic efficiency	21
6. RECOMMENDATIONS.....	22
6.1 Addition of Back Pressure Steam Turbine.....	23
6.2 Reduction of Steam Header Pressure.....	24
7. CONCLUSIONS	27
LIST OF APPENDICES	29
APPENDIX A – ENGINEERING EQUATIONS SOLVER USER CREATED FUNCTIONS.....	30
APPENDIX B – ENGINEERING EQUATIONS SOLVER MAIN PROGRAMS ...	46

NOMENCLATURE.....	82
REFERENCES.....	84

LIST OF FIGURES

Figure 1. Schematic of the steam and cogeneration system analyzed at the North utility plant at Rice University.	8
Figure 2. Full year (2005) steam production trending data (normalized) at the North utility plant at Rice University.	10
Figure 3. Component contribution to the total exergy destruction for load scenario #1 and #2.	19
Figure 4. Exergy Flow Diagram of the steam and cogeneration plant for load scenario #2.	20
Figure 5. Energy flow diagram of the steam and cogeneration plant for load scenario #2.	20
Figure 6. Effect of reduction in steam header pressure on piping losses and power generation potential.	26

LIST OF TABLES

Table 1. Exergetic efficiency equations for plant components.....	14
Table 2. Exergy destruction for load scenario #1.	17
Table 3. Exergy destruction for load scenario #2.	18
Table 4. Component efficiency comparison.	21
Table 5. Exergy destruction - Addition of steam turbine for load scenario #1.....	23
Table 6. Exergy destruction - Addition of steam turbine for load scenario #2.....	24
Table 7. Exergy destruction - Reduction in plant header pressure for load scenario #1.	25
Table 8. Exergy destruction - Reduction in plant header pressure for load scenario #2.	25

1. Introduction

The effective use of natural resources in all aspects of society has become increasingly important, as technological advancement and population growth has increased the demand for high quality energy sources. The availability of these sources is limited, as the rate of replenishment is so slow that they are considered non-renewable. In addition, there is much debate over the environmental impact of the by-products produced by the use of these concentrated energy sources, but the general consensus has linked the prolific burning of fossil fuels with the onset of global climate change¹. These factors have and will continue to influence the cost of high quality energy sources, so efficient utilization of resources such as natural gas, coal and petroleum will be vital for the foreseeable future.

One of the largest single uses of fossil fuels today is in the power generation sector. It was reported in 2007 that approximately 71% and 67% of the total electricity production in the U.S. and worldwide, respectively, comes from conventional thermal, fossil fuel-based plants². With over two thirds of the electricity production worldwide derived from fossil fuels, effective resource utilization in this sector is critical. Combined heat and power (CHP) systems are one method in which thermal energy, which would otherwise be discharged to the environment in a conventional power plant, is captured to carry out a process heating need. The utilization of this waste heat makes the CHP system a more effective method of power generation and process heat production than two stand alone systems that accomplish the same goal. The waste heat can be utilized for processes such as domestic water heating, space heating, and absorption cooling or in district energy systems. It is in the sectors which have a high electricity demand and

typically consume a large quantity of thermal energy that benefit most from combined heat and power systems.

One method that is used to analyze thermodynamic processes is the concept of exergy, or a substance's availability to do useful work. This method can improve resource utilization by determining inefficient, wasteful processes within thermodynamic systems. Exergy is an extensive property of a substance like energy, but differs in that in a given process, it can be destroyed due to irreversibilities inherent to the process. While a First Law analysis might suggest that the amount of energy is conserved during a given process, it fails to identify the decline in the quality of the energy, or the reduced availability of the substance to do work, in its final state. It is therefore useful to perform an exergy analysis for the same process to determine the location, cause and magnitude of losses, so that opportunities to improve resource utilization in the process are identified.

This methodology can be used in the design of new systems or in analyzing existing systems to pinpoint inefficient or wasteful processes and to determine ways to improve resource utilization. The procedure for evaluating the Second Law performance for a typical combined heat and power system is shown by Bejan *et al.*³ Typical Second Law performance for various processes and methods of using exergy to make economic decisions in design are outlined by Gaggioli⁴. Applying Second Law techniques to specific processes such as combined heat and power systems has been done by many. Combined heat and power is a proven method to satisfy process heating loads in addition to generating electricity. Habib⁵ compared the performance of a cogeneration plant to that of a conventional plant with separate production of process heat and power to

determine that the total irreversibility for the cogeneration plant was significantly lower than that of the conventional plant. Dincer *et al.*⁶ investigated energy and exergy analyses for combined heat and power district energy systems, highlighting component efficiencies. Ahmadi *et al.*⁷ performed a Second Law analysis of a 420 MW combined heat and power plant to determine the main sources of inefficiency. Their research found that the combustion chamber in the gas turbine is the main source of inefficiency within the plant. The effect of utilizing a duct burner in the heat recovery steam boiler was analyzed and found to increase output but lower efficiency. The same concepts were utilized by Reddy and Butcher^{8,9} to analyze the effect of varying operating conditions on system performance for a natural gas-fired cogeneration system. Their research focused on the effect of intercooling and reheat on system performance. Another case study by Ahmadi *et al.*¹⁰ considered the effect of varying parameters such as ambient air temperature on system performance. Exergy costing was utilized to determine the value of exergy destruction in the plant. Another Second Law analysis was performed for a 1000 kW cogeneration system by Kim *et al.*¹¹ The effect of gas turbine inlet air temperature and humidity was analyzed. Law and Reddy¹² analyzed the effect of gas turbine pressure ratio, process heat loads and process steam extraction pressure for a combined cycle cogeneration system. It was determined that the gas turbine pressure ratio significantly influenced system performance. An exergy analysis of a gas and steam turbine cogeneration system was performed by Chuang and Sue¹³ for design and component selection purposes. The effect of varying the heat recovery steam generator pinch point was considered in their analysis. Exergetic and thermoeconomic analyses were performed for a 500 MW combined cycle plant by Jeon *et al.*¹⁴ Their research

resulted in the creation of a computer program that can determine the production costs of various types of power plants as well as thermodynamic performance of plant components. A parametric Second Law analysis of a coal-fired boiler-turbine plant by Dincer *et al.*¹⁵ was done to determine the parameters that maximized plant performance. Their analysis showed that the boiler and turbine yielded the highest exergy losses. The overall efficiency for a combined gas-steam cycle process was analyzed under varying cogeneration parameters such as supplemental firing at the gas turbine exhaust by Oman *et al.*¹⁶ A Second Law analysis of a cogeneration plant in Jordan was done by Aljundi *et al.*¹⁷ The variation of the reference environment state was considered in their analysis and it was found that it had little impact on the total exergy destruction in the components that involved combustion processes. A reduction in the air-to-fuel ratio had a greater impact on reducing the total exergy destruction. Casarosa and Franco¹⁸ found that by optimizing the heat recovery steam generator (HRSG) component of a cogeneration system was a feasible way to increase overall plant efficiency. A similar optimization of the HRSG component involving multiple steam generation pressure circuits was done by Pirone *et al.*¹⁹ Their work showed that the exergy losses associated with the exhaust flue gases was reduced by increasing the number of pressure circuits.

The objective of this study was to perform a Second Law analysis of the existing steam boiler and CHP plant at Rice University to determine the true system losses and to propose feasible ways to improve the second law efficiency of the system, thereby improving resource utilization. The first step of the analysis involved determining typical steady state operating conditions of the plant. This was accomplished by using actual trending data provided by the university. The First and Second Law balance equations

were then programmed into EES²⁰, a computer simulation program, for the various plant components to determine their performance. The sources of exergy destruction were determined and categorized so that feasible recommendations could be made. The effect of adding a back-pressure steam turbine to the system was analyzed and the effect on the overall plant efficiency was calculated. In addition, the effect of lowering the steam header pressure within the plant was investigated in conjunction with the addition of the steam turbine. A comparison of the First and Second Law efficiencies of the major system components is included.

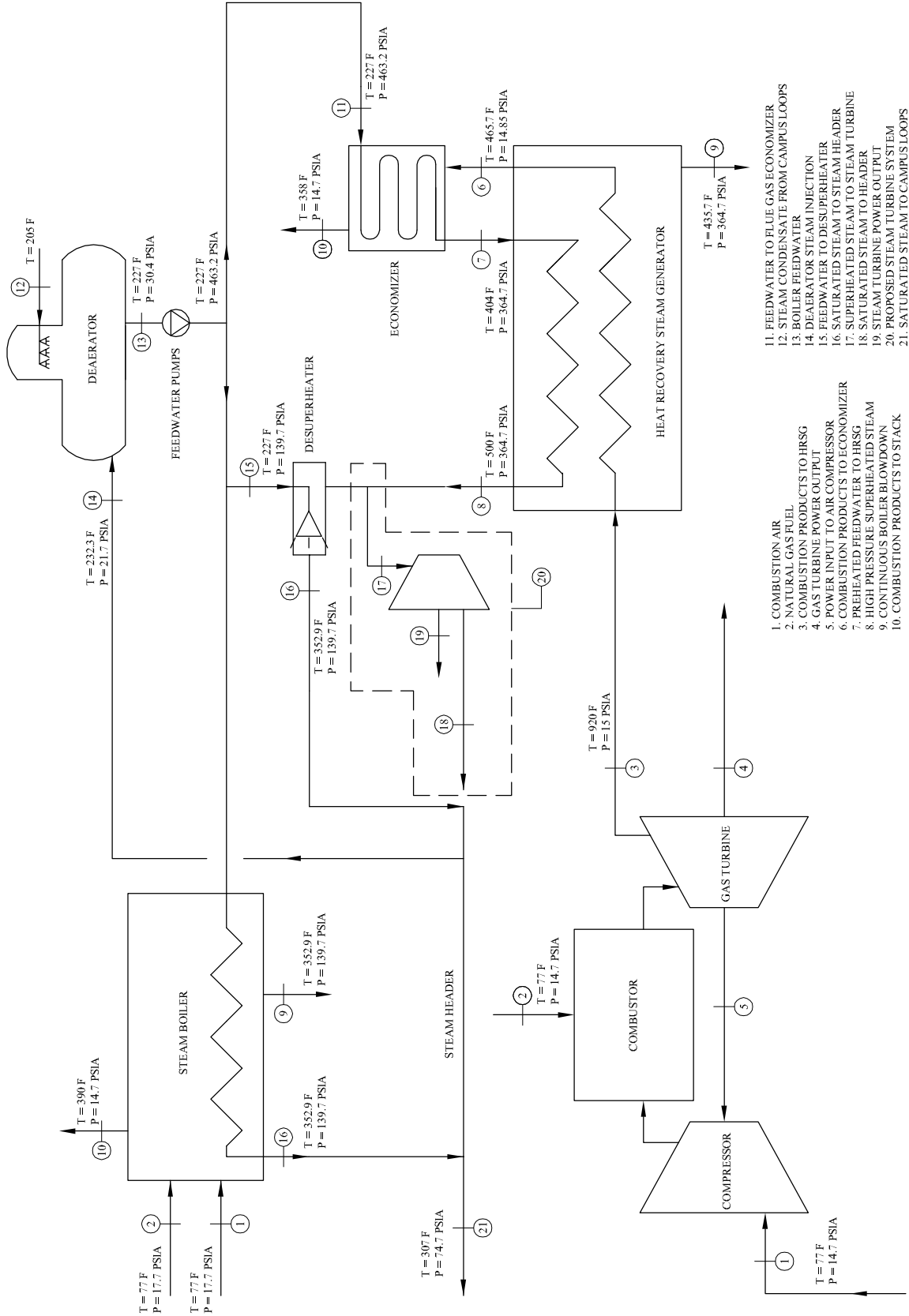
2. Overview of Steam and CHP Plant

A very common approach to providing electricity, heating and cooling for a university campus is from a central location, or utility plant. Combined heat and power systems and district energy are proven, cost-effective methods of delivering electricity, heating and cooling from a central location through a distribution system to serve a university campus. The heating, cooling and electricity production systems at Rice University employ this strategy, as two central utility plants serve the campus. Both plants provide campus steam and chilled water, with combined heat and power systems existing at the North utility plant.

The North utility plant consists of a combination of natural gas-fired steam generating boilers and natural gas turbines with heat recovery steam generators (HRSGs). The natural gas fired steam boilers are scotch-marine type fire-tube boilers that produce saturated steam at a pressure of 125 psig. Two natural gas-fired turbines have a combined power generation capacity of 7.4 MW and both have corresponding waste heat recovery boilers. HRSG #1 produces saturated steam at a pressure of 240 psig and HRSG #2 produces steam at a pressure of 350 psig. HRSG #2 contains a superheater section, in which the 350 psig steam is superheated to 500 °F. In total, the North utility plant at Rice has a total steam generation capacity of 135,000 lbs/hr. The steam header pressure in the plant is 125 psig, so the steam generated by the HRSGs is reduced in pressure prior to tying into the header. The pressure of the steam is reduced again to 60 psig prior to being sent out to the campus distribution system. Figure 1 below is a schematic of the steam and cogeneration system analyzed at the North utility plant. It is noteworthy that a back pressure steam turbine, installed downstream of HRSG #2, is

currently out of service, so the steam generated from this boiler instead bypasses around the turbine through a pressure regulating valve and a desuperheater to produce a higher quantity of saturated 125 psig steam prior to tying into the main steam header.

Figure 1. Schematic of the steam and cogeneration system analyzed at the North utility plant at Rice University



3. Determination of Plant Operating Conditions

The first step in analyzing the North utility plant involved determining the conditions at which the plant typically operates. These typical operating conditions, or load scenarios, were extracted from available trending data provided by Rice University. The objective was to distinguish as many load scenarios as necessary to capture a high percentage of the operating hours of the North utility plant. The determined load scenarios are steady state conditions that represent a narrow range of steam and power production in the plant. In addition to quantifying the steam and power generation, it was necessary to determine the equipment being operated during these scenarios. Figure 2 graphs normalized steam production versus the time of year for the North utility plant.

Several conclusions can be extracted from Figure 2. First, the bell shaped steam production curve with the peak occurring around January corresponds to seasonal climate temperatures for this location, as expected. Secondly, the plant operates almost entirely below 50% capacity the entire year. From the trending data, two main operating ranges were established to categorize two load scenarios. It was found that 53% of the operating hours fell in a range of 12-26% full capacity and another 34% of the operating hours fell in a range of 26-38% full capacity. An average value for each of these two ranges was taken to determine two separate load scenarios that represent approximately 87% of Rice's operating hours. Average steam production values of 18,100 lbs/hr and 28,100 lbs/hr were established for the lower and upper ranges, respectively. These steam production values will be referred to as load scenario #1 (18,100 lbs/hr) and load scenario #2 (28,100 lbs/hr). The corresponding equipment combinations for each respective load scenario were then determined. For load scenario #1, it was found that Rice operates one

gas turbine at 80% load and produces the steam with HRSG #2. Load scenario #2 is accomplished by operating the gas turbine and HRSG #2 as in load scenario #1, with the additional steam production coming from Boiler #5 at part load. These established load scenarios are the boundary conditions used in the steady state analysis performed and represent the majority of the operating hours at the North utility plant.

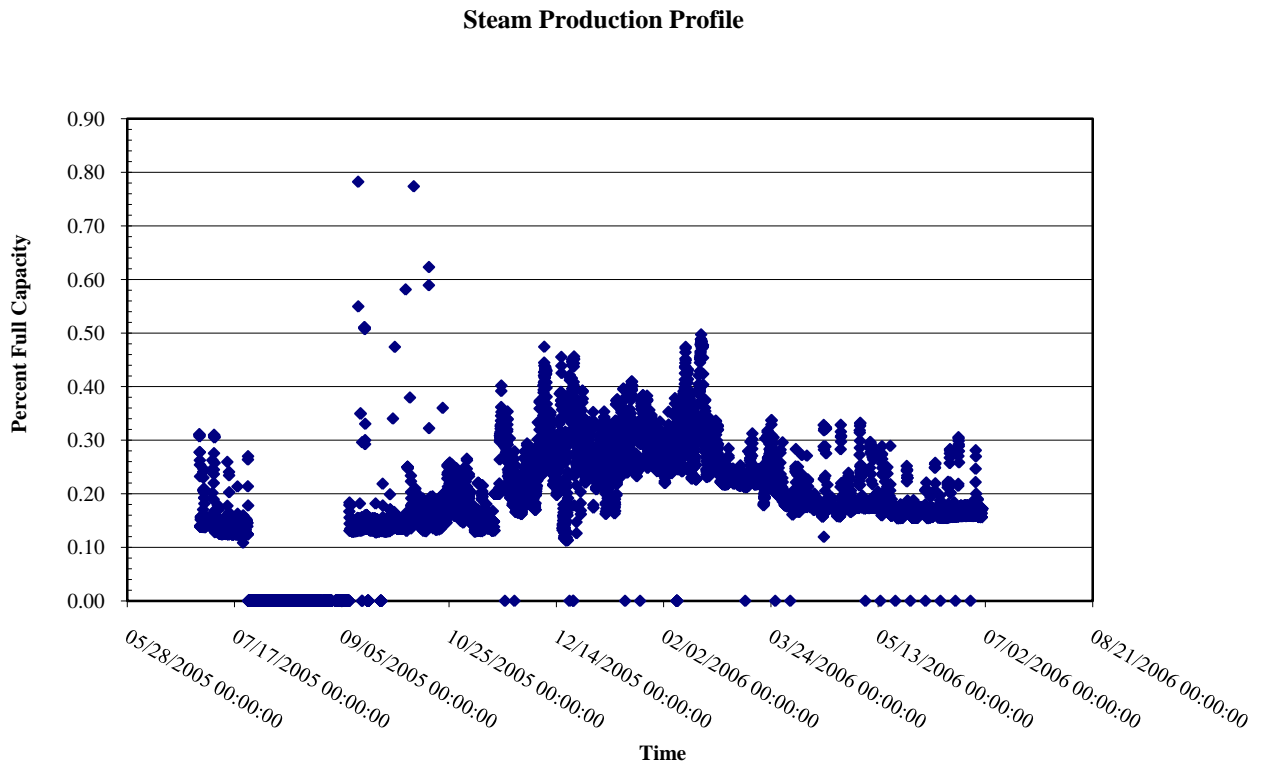


Figure 2. Full year (2005) steam production trending data (normalized) at the North utility plant at Rice University.

4. Overview of Analysis

The exergy of a system represents the departure of its state from that of the environment. For this study, standard atmospheric conditions at Rice University represent the environment. The total exergy of a system is comprised of four main components defined as the physical, chemical, kinetic and potential exergies. For the purposes of this study, the kinetic and potential exergy components are assumed to be negligible. The physical exergy represents the maximum theoretical work that can be obtained as a system goes from a state at temperature T and pressure P to the restricted dead state, or state at which the system and environment are in mechanical and thermal equilibrium, at the reference temperature T_o and P_o . The chemical exergy is defined as the maximum amount of work obtained as a system goes from the restricted dead state to the dead state, where the system is in complete equilibrium with the environment. It can be thought of as the chemical potential of the system to do work and is important when fuels and combustion are being considered. The subsections below represent several fundamental equations used in the analysis. The remaining, intermediate calculations for the components analyzed can be found in Appendix A and B.

4.1 First and Second Law Control Volume Governing Equations

Steady state control volume balance equations were used for the analysis. The steady state continuity equation and first law energy equations were used to calculate the mass flow and energy transfer rates across the boundaries of the control volumes.

Steady State Continuity Equation

$$\sum \dot{m}_i = \sum \dot{m}_e \quad (1)$$

Steady State Energy Balance Equation

$$\dot{Q}_{CV} - \dot{W}_{CV} = \sum \dot{m}_i h_i - \sum \dot{m}_e h_e \quad (2)$$

Similarly, the steady state exergy balance equation was used to calculate the rate of exergy destruction within the control volumes.

Steady State Exergy Balance Equation

$$\dot{E}_D = \sum_j \left(1 - \frac{T_o}{T_j} \right) \dot{Q}_j - \dot{W}_{cv} + \sum_i \dot{m}_i e_i - \sum_e \dot{m}_e e_e \quad (3)$$

The subscripts i , e , j and o refer to conditions at the inlets, exits, control volume boundaries and the reference state, respectively. Other quantities are defined in the nomenclature. As previously stated, the total exergy of inlet and exit streams has a physical and chemical component. The physical exergy of inlet and exit streams was calculated using the specific physical exergy equation.

Specific Physical Exergy Equation

$$e^{PH} = (h - h_o) - T_o (s - s_o) \quad (4)$$

The specific chemical exergy, e^{CH} , for the various substances analyzed was taken from published standard chemical exergies³. The total specific exergy of the inlet and exit streams is the sum of its physical and chemical components.

Total Specific Exergy Equation

$$e = e^{PH} + e^{CH} \quad (5)$$

The fuel for the boilers and gas turbines at the North utility plant is natural gas. For the purpose of this analysis, the physical and chemical properties of the fuel were assumed as

methane gas. For the combustion products, the total physical and chemical exergies of the gas mixtures were calculated on a molar fraction basis. The equations for specific physical and chemical exergies for the gas mixtures are given below.

Specific Physical Exergy – Gas Mixtures

$$e^{PH} = \frac{\bar{h} - \bar{h}_o - T_o (\bar{s} - \bar{s}_o)}{M} \quad (6)$$

$$\bar{h} = \sum_{k=1}^N x_k \bar{h}_k \quad (7)$$

$$\bar{s} = \sum_{k=1}^N x_k \bar{s}_k \quad (8)$$

$$M = \sum_{k=1}^N x_k M_k \quad (9)$$

Specific Chemical Exergy – Gas Mixtures

$$e^{CH} = \frac{\sum_{k=1}^N x_k \bar{e}_k^{CH} + \bar{R} T_o \sum_{k=1}^N x_k \ln x_k}{M} \quad (10)$$

The subscript k in the above equations refers to individual component in the gas mixture, and M is the calculated overall molecular weight of the mixture.

4.2 First and Second Law Efficiency

The exergetic efficiency, or Second Law efficiency, is a useful tool in evaluating the true thermodynamic performance of a particular system because it indicates how much of the available energy is translated to useful work. This parameter was calculated for the various plant components in the analysis and compared to the first law, or energy

efficiency. Table 1 summarizes the equations used to calculate first and second law efficiencies.

Table 1. Exergetic efficiency equations for plant components.^{3, 21}

	Second Law Efficiency	First Law Efficiency
Pump	$\eta_{II} = (\dot{E}_e - \dot{E}_i) / \dot{W}_m$	$\eta_I = \eta_{pump} P_{hyd} / \dot{W}_m$
Gas Turbine	$\eta_{II} = \dot{W}_{out} / \dot{E}_f$	$\eta_I = \dot{W}_{out} / \dot{m}_{in} LHV$
Mixing Tank	$\eta_{II} = \dot{E}_e / (\dot{E}_i + \dot{E}_e)$	$\eta_I = \sum \dot{m}_e h_e / \sum \dot{m}_i h_i$
Boiler	$\eta_{II} = (\dot{E}_e - \dot{E}_i) / (\dot{E}_f + \dot{W}_{in})$	$\eta_I = \dot{m}_e (h_{c,e} - h_{c,i}) / \dot{m}_m LHV$
Heat Exch.	$\eta_{II} = (\dot{E}_{c,e} - \dot{E}_{c,i}) / (\dot{E}_{h,i} - \dot{E}_{h,e})$	$\eta_I = \dot{m}_c (h_{c,e} - h_{c,i}) / \dot{m}_h (h_{h,i} - h_{h,e})$

4.3 Piping losses

Piping losses due to friction irreversibilities and heat transfer to the environment were accounted for in the analysis. Friction losses were calculated using the Darcy-Weisbach equation for fluid flow in a closed conduit. Incompressible fluid flow was assumed for all piping loss calculations since the pressure drop across any given length of pipe was small enough that the fluid density variations were negligible. Minor losses due to pipe elbows, valves, tees, etc. were accounted for using tabulated minor loss coefficients²².

Darcy-Weisbach Equation

$$\Delta p = f \cdot \frac{L}{D} \cdot \frac{\rho v^2}{2} + \sum K \frac{v^2}{2} \quad (11)$$

The pipe friction factor was solved for explicitly using the Churchill correlation, which is valid for all flow regimes and pipe relative roughness values.

*Churchill Correlation for Closed Conduit Flow*²³

$$f = 8 \cdot \left(\left(\frac{8}{\text{Re}} \right)^{12} + \left(\left(2.457 \cdot \ln \left(\frac{1}{\left(\frac{7}{\text{Re}} \right)^{0.9} + 0.27 \cdot \left(\frac{\varepsilon}{D} \right)} \right) \right)^{16} + \left(\frac{37530}{\text{Re}} \right)^{16} \right)^{-1.5} \right)^{1/12} \quad (12)$$

Piping losses due to heat transfer were calculated by a First Law energy balance, equation (2) above. Losses due to heat transfer were only considered for pipes carrying fluids at a significant temperature difference from the reference environment.

4.4 Steam Turbine Calculations

The steam turbine output is a function of the inlet temperature and pressure of the steam as well as the mass flow rate of steam through the turbine. The estimated steam turbine power output was calculated by relating the isentropic turbine efficiency based on the entering conditions to the actual process. The isentropic turbine efficiency was determined by equation (13).

Isentropic Turbine Efficiency

$$\eta_s = \frac{h_{in} - h_{out}}{h_{in} - h_{out,s}} \quad (13)$$

The required turbine steam rate was then determined by relating the theoretical steam rate²¹ based on the inlet conditions to the isentropic turbine efficiency.

Actual Turbine Steam Rate

$$SR_a = \frac{SR_{th}}{\eta_s} \quad (14)$$

The power output generated by the steam turbine was then determined using the actual steam rate and mass flow rate into the turbine.

Turbine Power Output

$$\dot{W} = \frac{\dot{m}_{in}}{SR_a} \quad (15)$$

The exergy destruction within the steam turbine was calculated using the steady state exergy balance equation (3).

5. Analysis Results

All the governing equations for the analysis were entered and solved in a computer simulation program²⁰, the input and output of which are included in Appendices A and B. The load scenarios for the analysis were set by the procedure described in section 3 and the variables for these conditions were set as parametric values, so that the simulation of both load scenarios could be run together.

5.1 Plant Exergy Destruction

Tables 2 and 3 summarize the exergy destruction by component for load scenarios #1 and #2. In addition to the exergy destruction for each component, the ratio of the exergy destruction with respect to the total exergy of the fuel entering the system is tabulated. For load scenario #1, it was found that the gas turbine system possessed the largest rate of exergy destruction. The high rate of exergy destruction in the gas turbine system can be attributed to the combustion process within the turbine system.

Table 2. Exergy destruction for load scenario #1.

Load Scenario #1		
	\dot{E}_D (Btu / hr)	\dot{E}_D / \dot{E}_F
Piping	42,391	0.001
PRVs	852,450	0.024
Desuperheater	802,000	0.023
Gas Turbine System	21,800,000	0.623
HRSG#2	2,340,000	0.067
Economizer	1,283,000	0.037
Deaerator	503,721	0.014
Pumping Losses	13,866	0.0004
Total	27,639,072	0.79

Table 3. Exergy destruction for load scenario #2.

Load Scenario #2		
	\dot{E}_D (Btu / hr)	\dot{E}_D / \dot{E}_F
Piping	47,144	0.001
PRVs	1,424,215	0.03
Desuperheater	802,000	0.017
Gas Turbine	21,800,000	0.47
HRSG#2	2,340,000	0.051
Economizer	1,283,000	0.028
Pumping Losses	336,651	0.007
Deaerator	13,866	0.0003
Aux. Blr. #5	5,912,000	0.128
Total	33,960,520	0.74

Simulation results for load scenario #2 show a similar trend to load scenario #1, with the exception of the added exergy destruction from the operation of Boiler #5. The effect of the added steam production in load scenario #2 on piping and PRV losses is very minor, as seen in table 3. The moderate contribution of the desuperheater to the total exergy destruction is prevalent in both load scenarios. Figure 3 shows the component contribution to the total exergy destruction for each load scenario. The cogeneration system, which includes the gas turbine and corresponding heat recovery steam generator, is the largest driving force for electricity and steam generation in the plant and is also the largest contributor to the total exergy destruction within the plant for both load scenarios. The exergy flow diagram in figure 4 gives a breakdown of the exergy destroyed within individual components as well as the useful exergy delivered in the product streams and the effluent losses associated with individual components. The exergetic efficiency for the plant is the ratio of the exergy streams of useful product to input fuel and for load scenario #2 was found to be 50%. In comparison, the energy flow diagram shown in

figure 5 implies that a much higher percentage of the input fuel energy is transferred to the combustion products within the gas turbine and gas-fired boiler. The exergy diagram is more revealing of the actual losses in this case because the quality of the energy in the combustion products is accounted for.

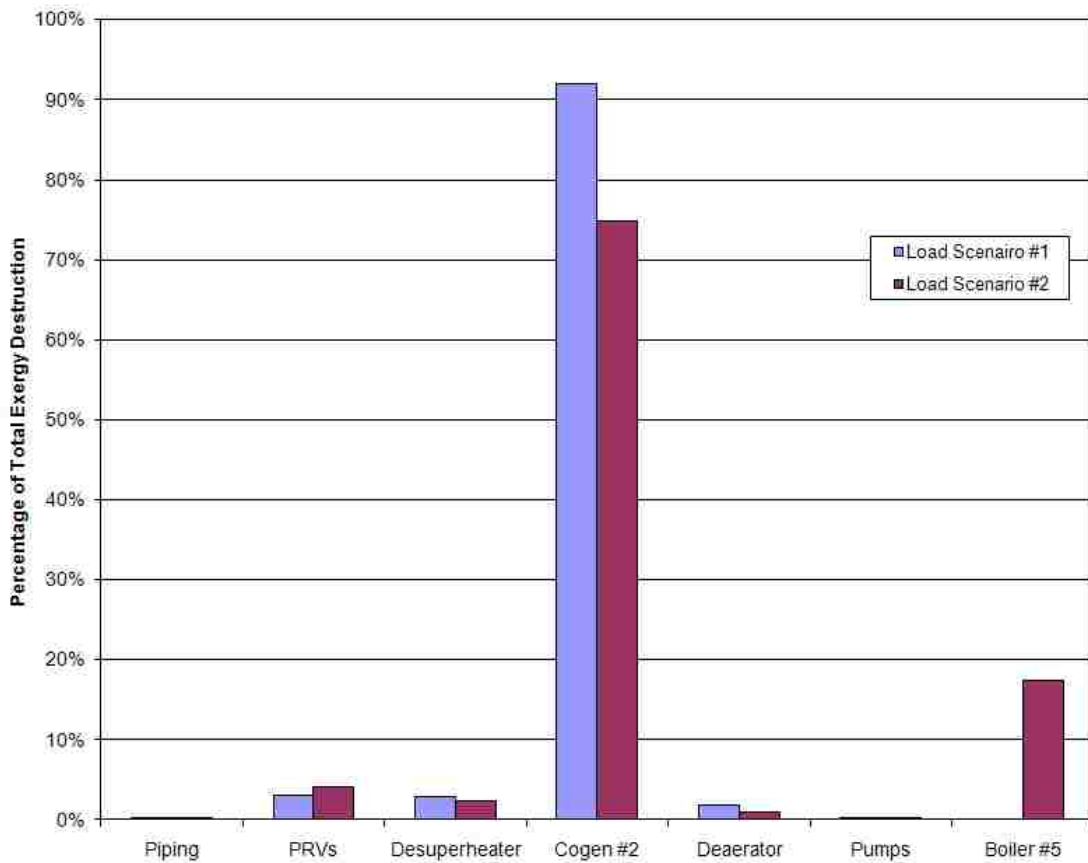


Figure 3. Component contribution to the total exergy destruction for load scenario #1 and #2.

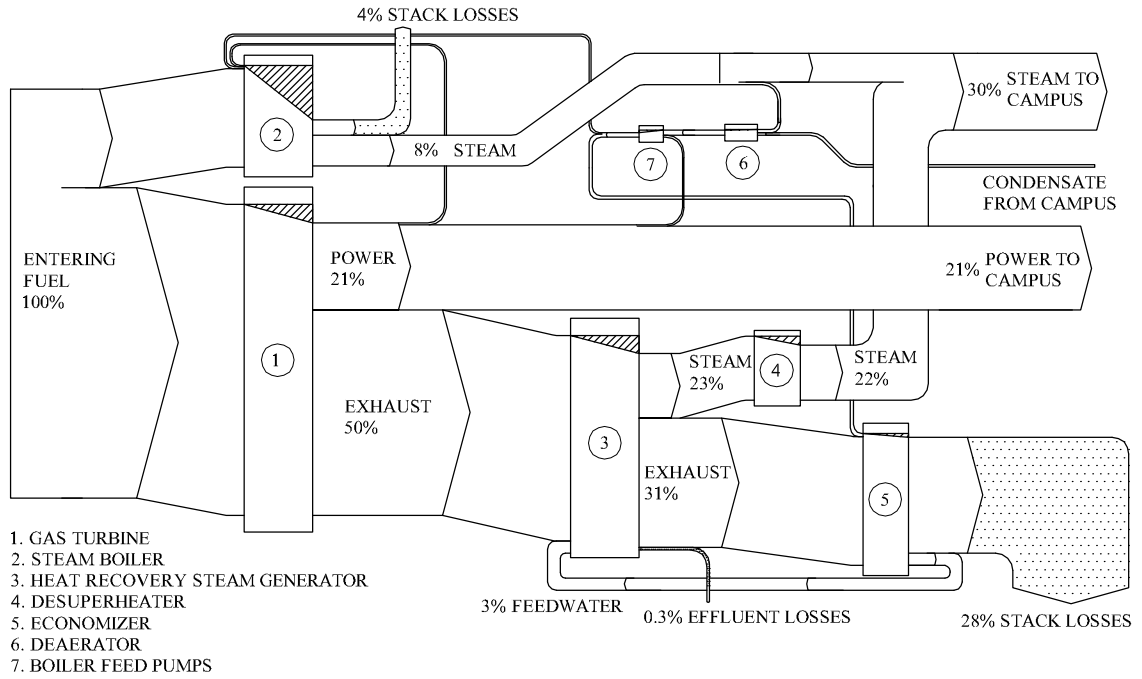


Figure 4. Exergy Flow Diagram of the steam and cogeneration plant for load scenario #2

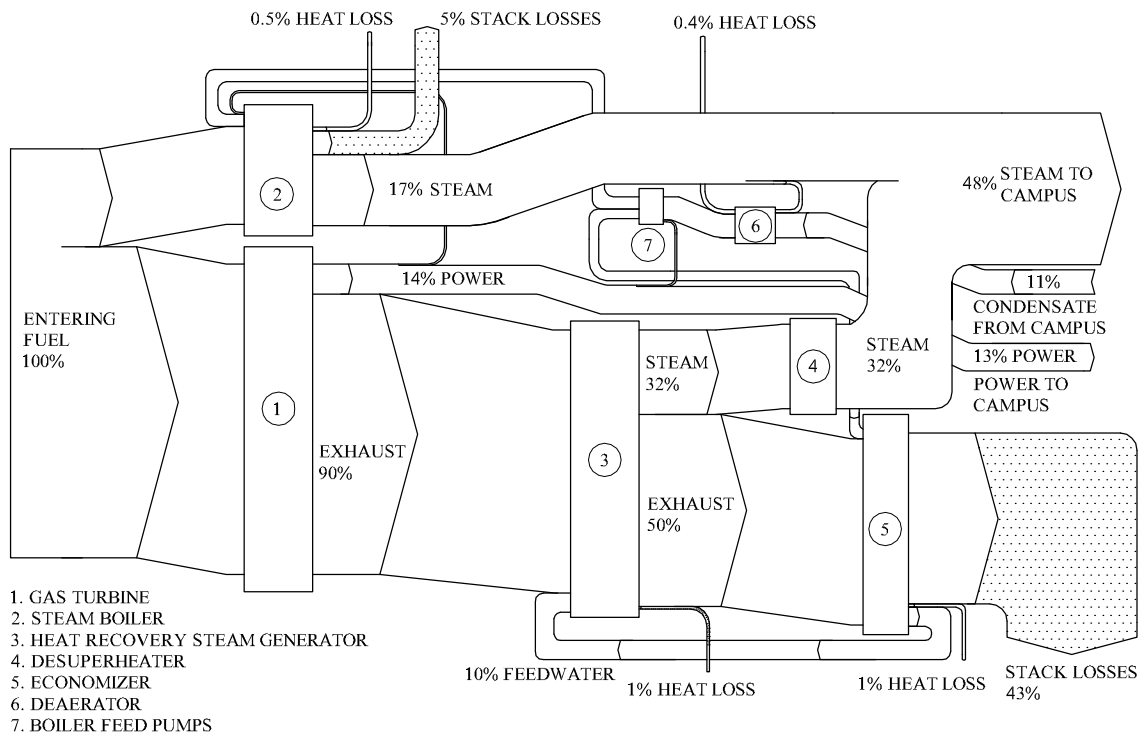


Figure 5. Energy flow diagram of the steam and cogeneration plant for load scenario #2

5.2 Exergetic efficiency

The second law, exergetic efficiency was calculated for several major components as another means of identifying the true sources of inefficiencies within the plant. Table 4 is a comparison of the first law and second law efficiency values for several of the components within the plant. The components that involve combustion have the lowest second law efficiency values, as the majority of the exergy in the fuel is wasted in the conversion from chemical to thermal and mechanical energy. Another notable inefficient component is the deaerator, which is used to remove dissolved air and other gases from the feed water to the boilers. This air removal process involves the mixing of hot steam with a colder feed water stream. Although a wasteful process, it is necessary to reduce system corrosion and is common practice.

Table 4. Component efficiency comparison.

	1st Law Efficiency	2nd Law Efficiency
Gas Turbine System	27%	28%
HRSG#2	97%	73%
Economizer	86%	70%
Deaerator	95%	88%
Pumps	76%	79%
Boiler #5	82%	30%

6. Recommendations

The exergy analysis identified numerous sources of inefficiencies and wasteful processes, but the objective of the study was to focus on specific areas of inefficiency to identify feasible opportunities to improve resource utilization and ultimately reduce operating costs. The largest source of exergy destruction for both load scenarios is the combustion process in the gas turbine cycle. Previous analyses have shown that gains in cogeneration efficiency can be achieved by optimizing the operating conditions of the cycle, such as reheating the combustion products in a multistage gas turbine system⁶. This option may be feasible, but modifications to improve the combustion efficiency in the gas turbine and gas boiler proved to not be the most attractive option economically.

Another significant source of exergy destruction is due to the desuperheater valve. The mixing of relatively cold feed water with the superheated, high pressure steam generated from the heat recovery steam generator is a wasteful process in which no useful work is done. The opportunity exists to install steam turbine service in the plant to extract useful work from the valuable superheated steam while reducing the steam temperature and pressure.

A second attractive option, employed in conjunction with the steam turbine option, is to reduce the steam turbine exhaust pressure and the corresponding pressure of the campus distribution system. The main advantage of this option is the increased power generation potential created by lowering the exhaust pressure of the steam turbine. This option is further discussed in section 6.2.

6.1 Addition of Back Pressure Steam Turbine

The second law analysis uncovered the magnitude of the losses realized by the desuperheater. This wasteful process was focused on to determine that restoring steam turbine service in the North utility plant is the most feasible and attractive option to improve resource utilization and reduce operating costs. This option would require bypassing the desuperheater and flowing instead through a new back-pressure steam turbine with similar exhaust conditions. The effect of restoring steam turbine service for load scenarios #1 and #2 can be seen in tables 5 and 6. The total exergy destruction is reduced since useful work is being produced, in this case electricity, by the steam turbine and generator. The result is an increase in power generation of approximately 280 kW and an increase in second law efficiency for the entire plant from 21.1% to 22.4% and from 26.3% to 27.3%, for load scenarios #1 and #2, respectively.

Table 5. Exergy destruction - Addition of steam turbine for load scenario #1.

Load Scenario #1 - Table 5		
	\dot{E}_D (Btu / hr)	\dot{E}_D / \dot{E}_F
Piping	42,277	0.001
PRVs	839,018	0.024
Steam Turbine	370,830	0.011
Gas Turbine System	21,800,000	0.622
HRSG#2	2,342,000	0.067
Economizer	1,283,000	0.037
Pumping Losses	13,866	0.0004
Deaerator	503,721	0.014
Total	27,194,712	0.776

Table 6. Exergy destruction - Addition of steam turbine for load scenario #2.

Load Scenario #2 - Table 6		
	\dot{E}_D (Btu / hr)	\dot{E}_D / \dot{E}_F
Piping	47,030	0.001
PRVs	1,403,618	0.030
Steam Turbine	370,830	0.008
Gas Turbine System	21,800,000	0.473
HRSG#2	2,342,000	0.051
Economizer	1,283,000	0.028
Pumping Losses	13,866	0.0003
Deaerator	336,651	0.007
Aux. Blr. #5	5,912,000	0.128
Total	33,508,995	0.73

6.2 Reduction of Steam Header Pressure

A reduction in steam header pressure from 125 psig to 60 psig in the plant would provide several advantages when implemented in conjunction with the steam turbine option. The main advantage would be the increase in power generation potential of the steam turbine. By reducing the exhaust pressure of the steam turbine from 125 psig to 60 psig, the potential power generation rate would increase from 280 kW to approximately 344 kW. In addition, the gas boilers in the plant could be operated at 60 psig instead of 125 psig. The effect of the reduction in steam header pressure, in conjunction with the addition of the steam turbine, for load scenarios #1 and #2 can be seen in tables 7 and 8. An increase in second law efficiency for the overall plant to 22.9% and 28.4% is realized for load scenarios #1 and #2, respectively.

Table 7. Exergy destruction - Reduction in plant header pressure for load scenario #1.

Load Scenario #1 - Table 7		
	\dot{E}_D (Btu / hr)	\dot{E}_D / \dot{E}_F
Piping	44,658	0.001
PRVs	199,240	0.006
Steam Turbine	852,352	0.024
Gas Turbine System	21,800,000	0.622
HRSG#2	2,342,000	0.067
Economizer	1,283,000	0.037
Pumping Losses	13,866	0.0004
Deaerator	503,721	0.014
Total	27,038,837	0.771

Table 8. Exergy destruction - Reduction in plant header pressure for load scenario #2.

Load Scenario #2 - Table 8		
	\dot{E}_D (Btu / hr)	\dot{E}_D / \dot{E}_F
Piping	51,544	0.001
PRVs	408,235	0.009
Steam Turbine	852,352	0.018
Gas Turbine System	21,800,000	0.473
HRSG#2	2,342,000	0.051
Economizer	1,283,000	0.028
Pumping Losses	13,866	0.0003
Deaerator	336,651	0.007
Aux. Blr. #5	5,912,000	0.128
Total	32,999,648	0.716

The exergy destruction due to piping losses increased by 5-10% due to the elevated specific volume of the steam, but the contribution of piping to the total exergy destruction in the plant is slight; therefore the opportunity for increased power generation far outweighs the increase in piping losses. The estimated turbine power generation rate calculation is included in Appendix B. A comparison between the increased piping

losses and power generation potential is shown in figure 4. There is a small requirement for 125 psig steam in the building adjacent to the plant, so this option would require new piping to be routed from upstream of the steam turbine to the building to serve that relatively minor demand.

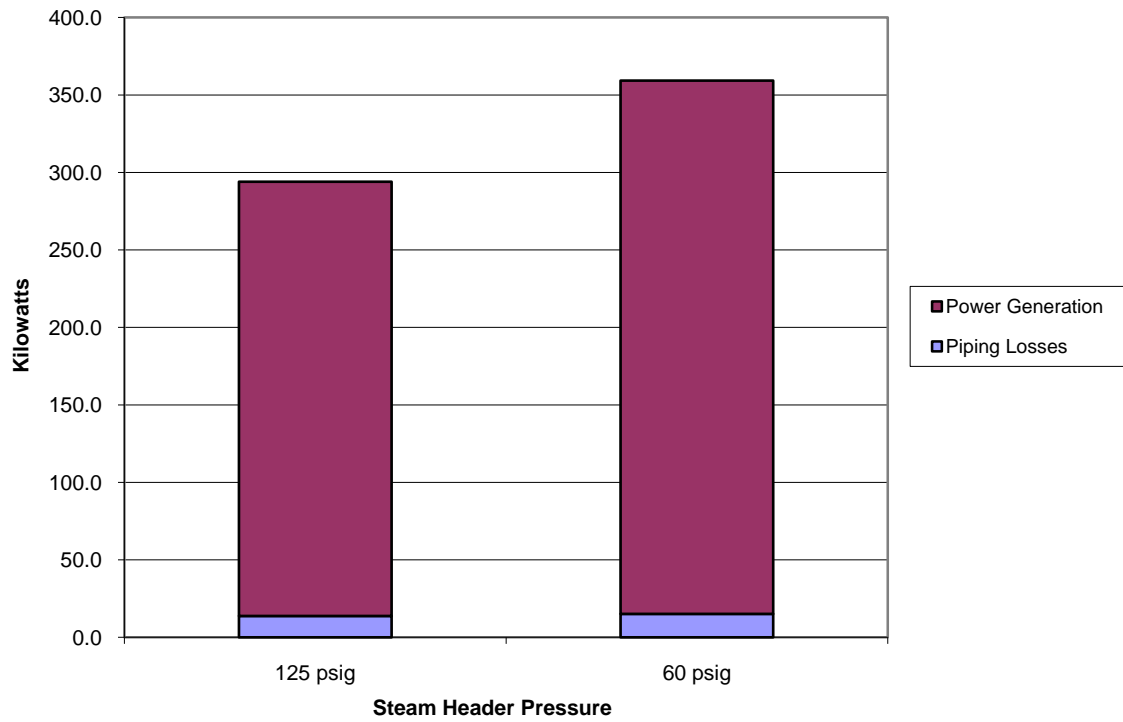


Figure 6. Effect of reduction in steam header pressure on piping losses and power generation potential.

7. Conclusions

Improving resource utilization is becoming increasingly important today, as the demand for high quality energy sources continues to grow. The practical application of the second law of thermodynamics is a useful tool in analyzing the quality of energy sources and how efficiently those sources are utilized in processes. While First Law concepts are valuable in analyzing thermodynamic processes, they do not provide the insight necessary to determine how efficiently resources are being utilized. Quantifying the quality of energy, or a substance's availability to do useful work, is beneficial in the design of new systems as well as increasing the efficiency of existing systems.

This study examined the existing steam and combined heat and power plant at Rice University from a Second Law perspective to determine the true system losses. Sources of exergy destruction were categorized and examined to determine feasible opportunities for efficiency improvements to enhance resource utilization. The major source of exergy destruction within the plant was determined to be the gas turbine, primarily due to the irreversibilities associated with the combustion process. The combustion process within boiler #5 contributed to the total exergy destruction similarly during load scenario #2. However, the focus of the study was not on improving the combustion efficiency of the gas turbine or gas-fired boiler, but rather on reducing exergy destruction per the system. Another notable source of exergy destruction was found to be the deaerator. The contribution of this component to the overall exergy destruction is a wasteful but necessary process; therefore it was not the most attractive area for efficiency improvement. The most feasible opportunity for improvement in plant efficiency was associated with the exergy destroyed by the desuperheater valve.

The replacement of the desuperheater valve with a back-pressure steam turbine downstream of the heat recovery steam generator, HRSG #2, was analyzed. There is virtually no exergetic penalty associated with the power generation capacity obtained by installing the back pressure steam turbine. In conjunction with the installation of the steam turbine, the effect of reducing the steam header pressure in the plant was analyzed. A reduction in steam header pressure resulted in an increase in steam turbine power generation of 23% and a 70% reduction in pressure reducing valve losses, while only increasing the losses associated with piping by 5-10% as shown in figure 4. The benefits associated with a reduction in steam header pressure far outweigh the exergetic penalty, and the initial capital cost for the installation of the back-pressure steam turbine is further justified. The two options combined for an improvement in Second Law overall plant efficiency from 21.1% to 22.9% for load scenario #1 and from 26.3% to 28.4% for load scenario #2.

Currently, the plant exiting condition of the combustion products generated by the gas turbine system and steam boiler is far from being in physical equilibrium with the reference environment. The excess heat in the combustion products could be extracted to serve additional thermal loads such as domestic water heating or space heating for nearby buildings. While these options were not explored, further improvements in Second Law efficiency would be achievable due to the increase in useful product exergy without increasing the amount of fuel consumed.

LIST OF APPENDICES

APPENDIX A – ENGINEERING EQUATIONS SOLVER (EES) USER CREATED FUNCTIONS	31
APPENDIX B – ENGINEERING EQUATIONS SOLVER (EES) MAIN PROGRAMS	47

**APPENDIX A – ENGINEERING EQUATIONS SOLVER USER CREATED
FUNCTIONS**

Equations

$$\text{function } \dot{E}_{ph,fg}(T, m) \quad (1)$$

Auxiliary Blr. #5 - Physical Exergy of exhaust gases leaving

$$\rho_{CO_2} = \frac{44 \cdot 2116.8}{(1545 \cdot (460 + T))} \quad \text{density calc. - ideal gas law} \quad (2)$$

$$\rho_{N_2} = \frac{28.01 \cdot 2116.8}{1545 \cdot (460 + T)} \quad (3)$$

$$\rho_{H_2O} = \frac{18 \cdot 2116.8}{1545 \cdot (460 + T)} \quad (4)$$

$$\rho_{O_2} = \frac{16 \cdot 2116.8}{1545 \cdot (460 + T)} \quad (5)$$

$$\rho_{ex} = .132 \cdot \rho_{CO_2} + .722 \cdot \rho_{N_2} + 0.028 \cdot \rho_{O_2} + 0.118 \cdot \rho_{H_2O} \quad (6)$$

$$\dot{m}_{ex} = m \quad \text{exhaust flow rate (lb/hr) at full load} \quad (7)$$

$$CFH_{ex} = \frac{\dot{m}_{ex}}{(\rho_{ex})} \quad \text{volumetric flow rate (CFH) of exhaust at full load} \quad (8)$$

$$\dot{m}_{CO_2} = .132 \cdot CFH_{ex} \cdot \rho_{CO_2} \quad \text{mass flow rate of CO}_2 \text{ (lb/hr) at full load} \quad (9)$$

$$\dot{m}_{N_2} = .722 \cdot CFH_{ex} \cdot \rho_{N_2} \quad (10)$$

$$\dot{m}_{O_2} = .028 \cdot CFH_{ex} \cdot \rho_{O_2} \quad (11)$$

$$\dot{m}_{H_2O} = .118 \cdot CFH_{ex} \cdot \rho_{H_2O} \quad (12)$$

Mass fractions of exhaust gas

$$MF_{CO_2} = 0.132 \quad \text{Mass fractions from Johnston Boiler Website Emmissions data} \quad (13)$$

$$MF_{N_2} = 0.722 \quad (14)$$

$$MF_{O_2} = 0.028 \quad (15)$$

$$MF_{H_2O} = 0.118 \quad (16)$$

enthalpy of exhaust gases

$$h_{cp} = MF_{CO_2} \cdot h(\text{carbondioxide}, T = T, P = 14.7) + MF_{N_2} \cdot h(\text{nitrogen}, T = T, P = 14.7) + MF_{O_2} \cdot c_p(O_2, T = T) \cdot (T + 460) + MF_{H_2O} \cdot h(\text{water}, T = T, P = 14.7) \quad (17)$$

entropy of exhaust gases

$$s_{cp} = MF_{CO_2} \cdot s(CO_2, T = T, P = 14.7) + MF_{N_2} \cdot s(N_2, T = T, P = 14.7) + MF_{O_2} \cdot s(O_2, T = T, P = 14.7) + MF_{H_2O} \cdot s(H_2O, T = T, P = 14.7) \quad (18)$$

analysis of how much water will condense from exhaust gases

$$p_v = MF_{H_2O} \cdot 14.7 \quad \text{partial pressure of water vapor in combustion products} \quad (19)$$

$$p_{water} = P_{sat}(water, T = 77) \quad \text{partial pressure of water vapor at } T = T_o = 77 \text{ F} \quad (20)$$

$$n_v = 0 \quad \text{mass fraction of water vapor in comb. products at dead state} \quad (21)$$

$$n_w = MF_{H_2O} - n_v \quad (22)$$

enthalpy of exhaust gases at dead state

$$h_o = MF_{CO_2} \cdot h(carbondioxide, T = 77, P = 14.7) + MF_{N_2} \cdot h(nitrogen, T = 77, P = 14.7) + MF_{O_2} \cdot h(oxygen, T = 77, P = 14.7) + n_v \cdot 1095.1 + n_w \cdot h(water, T = 77, P = 14.7) \quad (23)$$

entropy of exhaust gases at dead state

$$s_o = MF_{CO_2} \cdot s(CO_2, T = 77, P = 14.7) + MF_{N_2} \cdot s(N_2, T = 77, P = 14.7) + MF_{O_2} \cdot s(O_2, T = 77, P = 14.7) + n_w \cdot s(H_2O, T = 77, P = 14.7) + n_v \cdot 8.12 \quad (24)$$

$$\dot{E}_{ph,fg} = \dot{m}_{ex} \cdot ((h_{cp} - h_o) - 537 \cdot (s_{cp} - s_o)) \quad (25)$$

end (26)

function $\dot{E}_{ch,fg}(T, m)$ (27)

Auxiliary Blr. #5 - Chemical Exergy of flue gases leaving

$$\rho_{CO_2} = \frac{44 \cdot 2116.8}{(1545 \cdot (460 + T))} \quad \text{density calc. - ideal gas law} \quad (28)$$

$$\rho_{N_2} = \frac{28.01 \cdot 2116.8}{1545 \cdot (460 + T)} \quad (29)$$

$$\rho_{H_2O} = \frac{18 \cdot 2116.8}{1545 \cdot (460 + T)} \quad (30)$$

$$\rho_{O_2} = \frac{16 \cdot 2116.8}{1545 \cdot (460 + T)} \quad (31)$$

$$\rho_{ex} = .132 \cdot \rho_{CO_2} + .722 \cdot \rho_{N_2} + 0.028 \cdot \rho_{O_2} + 0.118 \cdot \rho_{H_2O} \quad (32)$$

$$\dot{m}_{ex} = m \quad \text{exhaust flow rate (lb/hr) at full load} \quad (33)$$

$$CFH_{ex} = \frac{\dot{m}_{ex}}{(\rho_{ex})} \quad \text{volumetric flow rate (CFH) of exhaust at full load} \quad (34)$$

$$\dot{m}_{CO_2} = .0285 \cdot CFH_{ex} \cdot \rho_{CO_2} \quad \text{mass flow rate of CO}_2 \text{ (lb/hr) at full load} \quad (35)$$

$$\dot{m}_{N_2} = .7517 \cdot CFH_{ex} \cdot \rho_{N_2} \quad (36)$$

$$\dot{m}_{O_2} = .1462 \cdot CFH_{ex} \cdot \rho_{O_2} \quad (37)$$

$$\dot{m}_{H_2O} = .0647 \cdot CFH_{ex} \cdot \rho_{H_2O} \quad (38)$$

Mass fractions of exhaust gas

$$MF_{CO_2} = 0.132 \quad \text{Mass fractions from Johnston Boiler Website Emmissions data} \quad (39)$$

$$MF_{N_2} = 0.722 \quad (40)$$

$$MF_{O_2} = 0.028 \quad (41)$$

$$MF_{H_2O} = 0.118 \quad (42)$$

analysis of how much water will condense from exhaust gases

$$p_v = MF_{H_2O} \cdot 14.7 \quad \text{partial pressure of water vapor in combustion products} \quad (43)$$

$$p_{water} = P_{sat}(water, T = 77) \quad \text{partial pressure of water vapor at } T = T_o = 77 \text{ F} \quad (44)$$

$$n_v = 0 \quad \text{mass fraction of water vapor in comb. products at dead state} \quad (45)$$

$$n_w = MF_{H_2O} - n_v \quad (46)$$

Mass fractions of gases

$$MF_{CO_2g} = \frac{MF_{CO_2}}{(1 - n_w)} \quad (47)$$

$$MF_{N_2g} = \frac{MF_{N_2}}{1 - n_w} \quad (48)$$

$$MF_{O_2g} = \frac{MF_{O_2}}{1 - n_w} \quad (49)$$

$$MF_{H_2Og} = n_v \quad (50)$$

Standard Chemical Exergies of flue gases and liquid water

$$E_{ch,CO_2} = 14167/2.326 \quad \text{standard chemical exergy of CO2 using Table C.2 - Model I - BTU/lb} \quad (51)$$

$$E_{ch,N_2} = 639/2.326 \quad (52)$$

$$E_{ch,O_2} = 3951/2.326 \quad (53)$$

$$E_{ch,H_2Og} = 8636/2.326 \quad (54)$$

$$E_{ch,H_2Ol} = 45/2.326 \quad (55)$$

$$M_{tot} = MF_{CO_2} \cdot 44.01 + MF_{N_2} \cdot 28.01 + MF_{O_2} \cdot 32 + MF_{H_2O} \cdot 18.02 \quad \text{Molecular weight of exhaust in lb/lbmol} \quad (56)$$

chemical exergy of gases

$$E_{ch,gas} = MF_{CO_2g} \cdot E_{ch,CO_2} + MF_{N_2g} \cdot E_{ch,N_2} + MF_{O_2g} \cdot E_{ch,O_2} + MF_{H_2Og} \cdot E_{ch,H_2Og} + (1.986) \cdot (537) \cdot (MF_{CO_2g} \cdot \ln(MF_{CO_2g}) + MF_{N_2g} \cdot \ln(MF_{N_2g}) + MF_{O_2g} \cdot \ln(MF_{O_2g})) \quad (57)$$

chemical exergy of liquid water

$$E_{ch,water} = n_w \cdot E_{ch,H_2Ol} \quad (58)$$

$$E_{ch,total} = \frac{(MF_{CO_2} + MF_{N_2} + MF_{O_2} + n_w) \cdot E_{ch,gas} + E_{ch,water}}{M_{tot}} \quad \text{Total chemical exergy of exhaust in BTU/lb} \quad (59)$$

$$\dot{E}_{ch,fg} = \dot{m}_{ex} \cdot E_{ch,total} \quad (60)$$

$$\text{end} \quad (61)$$

Equations

$$\text{function } ff_{gas}(CFH, T, P, d) \quad (1)$$

$$\text{If}(CFH = 0) \text{ then} \quad (2)$$

$$ff_{gas} = 0 \quad (3)$$

$$\text{else} \quad (4)$$

$$u = \frac{\mu(CH4, T = T)}{3600} \quad (5)$$

$$\rho = \rho(CH4, T = T, P = P) \quad (6)$$

$$\rho_s = \rho(CH4, T = 77, P = 14.7) \quad (7)$$

$$CFH_a = CFH \cdot \rho / \rho_s \quad (8)$$

$$Re = \frac{0.16 \cdot CFH_a \cdot \rho}{\pi \cdot d \cdot u} \quad (9)$$

$$RR = \frac{0.00015}{d/12} \quad (10)$$

$$ff_{gas} = 8 \cdot \left((8/Re)^{12} + \left(\left(2.457 \cdot \ln \left(\frac{1}{(7/Re)^{0.9} + 0.27 \cdot (RR)} \right) \right)^{16} + (37530/Re)^{16} \right)^{-1.5} \right)^{1/12} \quad (11)$$

$$\text{endif} \quad (12)$$

$$\text{end} \quad (13)$$

$$\text{function } ff_{steam}(m_{flow}, T, d) \quad (14)$$

$$\text{If}(m_{flow} = 0) \text{ then} \quad (15)$$

$$ff_{steam} = 0 \quad (16)$$

$$\text{else} \quad (17)$$

$$u = \frac{\mu(H2O, T = T)}{3600} \quad (18)$$

$$Re = \frac{m_{flow}}{75 \cdot \pi \cdot d \cdot u} \quad (19)$$

$$RR = \frac{0.00015}{d/12} \quad (20)$$

$$ff_{steam} = 8 \cdot \left((8/Re)^{12} + \left(\left(2.457 \cdot \ln \left(\frac{1}{(7/Re)^{0.9} + 0.27 \cdot (RR)} \right) \right)^{16} + (37530/Re)^{16} \right)^{-1.5} \right)^{1/12} \quad (21)$$

endif (22)

end (23)

function $ff_{water}(gpm, T, P, d)$ (24)

If($gpm = 0$) then (25)

$ff_{water} = 0$ (26)

else (27)

$u = \frac{\mu(water, T = T, P = P)}{3600}$ (28)

$\rho = \rho(water, T = T, P = P)$ (29)

$Re = \frac{1.283 \cdot \rho \cdot gpm}{\pi \cdot d \cdot u}$ (30)

$RR = \frac{0.00015}{d/12}$ (31)

$ff_{water} = 8 \cdot \left((8/Re)^{12} + \left(\left(2.457 \cdot \ln \left(\frac{1}{(7/Re)^{0.9} + 0.27 \cdot (RR)} \right) \right)^{16} + (37530/Re)^{16} \right)^{-1.5} \right)^{1/12}$ (32)

endif (33)

end (34)

Exergy thru Pipe Heat Loss.LIB

Equations

```
function  $\dot{E}q(d, L, T, Q)$  (1)
  If( $T > 150$ )and( $T < 251$ ) then (2)
     $k = 0.024$  (3)
     $ins = 2$  (4)
  else (5)
    If( $T > 251$ )and( $T < 351$ ) then (6)
       $k = 0.03$  (7)
       $ins = 3$  (8)
    else (9)
      If( $T > 351$ )and( $T < 451$ ) and ( $(d/2) > 1.49$ ) and ( $(d/2) < 3.01$ ) then (10)
         $k = 0.0376$  (11)
         $ins = 3$  (12)
      else (13)
        If( $T > 351$ )and( $T < 451$ ) and ( $(d/2) > 3.99$ ) then (14)
           $k = 0.0376$  (15)
           $ins = 4$  (16)
        else (17)
          If( $T > 451$ )and ( $(d/2) > 1.49$ ) and ( $(d/2) < 3.01$ ) then (18)
             $k = 0.0491$  (19)
             $ins = 3$  (20)
          else (21)
            If( $T > 451$ )and ( $(d/2) > 3.99$ ) then (22)
               $k = 0.0491$  (23)
               $ins = 4$  (24)
            else (25)
              call Error('no k or ins' ,  $k$ ) (26)
            endif (27)
          endif (28)
```

endif (29)

endif (30)

endif (31)

endif (32)

$$R_{tot} = \frac{\ln\left(\frac{ins+(d/2)}{d/2}\right)}{(2 \cdot \pi \cdot k \cdot L)} + (2 \cdot \pi \cdot (ins + (d/2)) \cdot 0.7 \cdot L)^{-1} \quad (33)$$

$$T_o = \frac{\ln\left(\frac{ins+(d/2)}{d/2}\right)}{2 \cdot \pi \cdot k \cdot L} \cdot (77 - T) + T \quad (34)$$

$$T_{avg} = \frac{T_o + 77}{2} \quad (35)$$

$$\dot{E}q = (1 - (77/T_{avg})) \cdot Q \quad (36)$$

end (37)

HRSG#2 - Ph. and Ch. exergy-cp.LIB

Equations

$$\text{function } \dot{E}_{ph,cp}(T, m) \quad (1)$$

HRSG#2 - Physical Exergy of exhaust gases entering or leaving

$$\rho_{CO_2} = \frac{44 \cdot 2116.8}{(1545 \cdot (460 + T))} \quad \text{density calc. - ideal gas law} \quad (2)$$

$$\rho_{N_2} = \frac{28.01 \cdot 2116.8}{1545 \cdot (460 + T)} \quad (3)$$

$$\rho_{Ar} = \frac{39.95 \cdot 2116.8}{1545 \cdot (460 + T)} \quad (4)$$

$$\rho_{H_2O} = \frac{18 \cdot 2116.8}{1545 \cdot (460 + T)} \quad (5)$$

$$\rho_{O_2} = \frac{16 \cdot 2116.8}{1545 \cdot (460 + T)} \quad (6)$$

$$\rho_{ex} = .0285 \cdot \rho_{CO_2} + .7517 \cdot \rho_{N_2} + 0.1462 \cdot \rho_{O_2} + 0.0647 \cdot \rho_{H_2O} + 0.0089 \cdot \rho_{Ar} \quad \text{overall density of exhaust gases} \quad (7)$$

$$\dot{m}_{ex} = m \quad \text{exhaust flow rate (lb/hr) at full load} \quad (8)$$

$$CFH_{ex} = \frac{\dot{m}_{ex}}{(\rho_{ex})} \quad \text{volumetric flow rate (CFH) of exhaust at full load} \quad (9)$$

$$\dot{m}_{CO_2} = .0285 \cdot CFH_{ex} \cdot \rho_{CO_2} \quad \text{mass flow rate of CO}_2 \text{ (lb/hr) at full load} \quad (10)$$

$$\dot{m}_{N_2} = .7517 \cdot CFH_{ex} \cdot \rho_{N_2} \quad (11)$$

$$\dot{m}_{O_2} = .1462 \cdot CFH_{ex} \cdot \rho_{O_2} \quad (12)$$

$$\dot{m}_{H_2O} = .0647 \cdot CFH_{ex} \cdot \rho_{H_2O} \quad (13)$$

$$\dot{m}_{Ar} = .0089 \cdot CFH_{ex} \cdot \rho_{Ar} \quad (14)$$

Mass fractions of exhaust gas

$$MF_{CO_2} = \dot{m}_{CO_2} / \dot{m}_{ex} \quad (15)$$

$$MF_{N_2} = \dot{m}_{N_2} / \dot{m}_{ex} \quad (16)$$

$$MF_{O_2} = \dot{m}_{O_2} / \dot{m}_{ex} \quad (17)$$

$$MF_{H_2O} = \dot{m}_{H_2O} / \dot{m}_{ex} \quad (18)$$

$$MF_{Ar} = \dot{m}_{Ar} / \dot{m}_{ex} \quad (19)$$

enthalpy of exhaust gases

$$h_{cp} = MF_{CO_2} \cdot h(\text{carbondioxide, } T = T, P = 14.7) + MF_{N_2} \cdot h(\text{nitrogen, } T = T, P = 14.7) +$$

$$MF_{O_2} \cdot c_p(O_2, T = T) \cdot (T + 460) + MF_{H_2O} \cdot h(\text{water, } T = T, P = 14.7) + MF_{Ar} \cdot c_p(Ar, T = T) \cdot (T + 460) \quad (20)$$

entropy of exhaust gases

$$s_{cp} = MF_{CO_2} \cdot s(CO_2, T = T, P = 14.7) + MF_{N_2} \cdot s(N_2, T = T, P = 14.7) + MF_{O_2} \cdot s(O_2, T = T, P = 14.7) + MF_{H_2O} \cdot s(H_2O, T = T, P = 14.7) + MF_{Ar} \cdot \text{entropy}(\text{argon}, T=T, P = 14.7) \quad (21)$$

analysis of how much water will condense from exhaust gases

$$p_v = MF_{H_2O} \cdot 14.7 \quad \text{partial pressure of water vapor in combustion products} \quad (22)$$

$$p_{water} = P_{sat}(water, T = 77) \quad \text{partial pressure of water vapor at } T = T_o = 77 \text{ F} \quad (23)$$

$$n_v = p_{water} \cdot \frac{1 - p_v}{(14.7 - p_{water})} \quad \text{mass fraction of water vapor in comb. products at dead state} \quad (24)$$

$$n_w = MF_{H_2O} - n_v \quad \text{mass fraction of liquid water at dead state} \quad (25)$$

enthalpy of exhaust gases at dead state

$$h_o = MF_{CO_2} \cdot h(\text{carbondioxide}, T = 77, P = 14.7) + MF_{N_2} \cdot h(\text{nitrogen}, T = 77, P = 14.7) + MF_{O_2} \cdot h(\text{oxygen}, T = 77, P = 14.7) + n_v \cdot 1095.1 + MF_{Ar} \cdot h(\text{argon}, T = 77, P = 14.7) + n_w \cdot h(\text{water}, T = 77, P = 14.7) \quad (26)$$

entropy of exhaust gases at dead state

$$s_o = MF_{CO_2} \cdot s(CO_2, T = 77, P = 14.7) + MF_{N_2} \cdot s(N_2, T = 77, P = 14.7) + MF_{O_2} \cdot s(O_2, T = 77, P = 14.7) + n_w \cdot s(H_2O, T = 77, P = 14.7) + MF_{Ar} \cdot s(\text{argon}, T = 77, P = 14.7) + n_v \cdot 8.12 \quad (27)$$

$$\dot{E}_{ph,cp} = \dot{m}_{ex} \cdot ((h_{cp} - h_o) - 537 \cdot (s_{cp} - s_o)) \quad (28)$$

end (29)

function $\dot{E}_{ch,cp}(T, m)$ (30)

HRS#2 - Chemical Exergy of exhaust gases - entering or leaving

$$\rho_{CO_2} = \frac{44 \cdot 2116.8}{(1545 \cdot (460 + T))} \quad \text{density calc. - ideal gas law} \quad (31)$$

$$\rho_{N_2} = \frac{28.01 \cdot 2116.8}{1545 \cdot (460 + T)} \quad (32)$$

$$\rho_{Ar} = \frac{39.95 \cdot 2116.8}{1545 \cdot (460 + T)} \quad (33)$$

$$\rho_{H_2O} = \frac{18 \cdot 2116.8}{1545 \cdot (460 + T)} \quad (34)$$

$$\rho_{O_2} = \frac{16 \cdot 2116.8}{1545 \cdot (460 + T)} \quad (35)$$

$$\rho_{ex} = .0285 \cdot \rho_{CO_2} + .7517 \cdot \rho_{N_2} + 0.1462 \cdot \rho_{O_2} + 0.0647 \cdot \rho_{H_2O} + 0.0089 \cdot \rho_{Ar} \quad (36)$$

$$\dot{m}_{ex} = m \quad \text{exhaust flow rate (lb/hr) at full load} \quad (37)$$

$$CFH_{ex} = \frac{\dot{m}_{ex}}{(\rho_{ex})} \quad \text{volumetric flow rate (CFH) of exhaust at full load} \quad (38)$$

$$\dot{m}_{CO_2} = .0285 \cdot CFH_{ex} \cdot \rho_{CO_2} \quad \text{mass flow rate of CO}_2 \text{ (lb/hr) at full load} \quad (39)$$

$$\dot{m}_{N_2} = .7517 \cdot CFH_{ex} \cdot \rho_{N_2} \quad (40)$$

$$\dot{m}_{O_2} = .1462 \cdot CFH_{ex} \cdot \rho_{O_2} \quad (41)$$

$$\dot{m}_{H_2O} = .0647 \cdot CFH_{ex} \cdot \rho_{H_2O} \quad (42)$$

$$\dot{m}_{Ar} = .0089 \cdot CFH_{ex} \cdot \rho_{Ar} \quad (43)$$

Mass fractions of exhaust gas

$$MF_{CO_2} = \dot{m}_{CO_2} / \dot{m}_{ex} \quad (44)$$

$$MF_{N_2} = \dot{m}_{N_2} / \dot{m}_{ex} \quad (45)$$

$$MF_{O_2} = \dot{m}_{O_2} / \dot{m}_{ex} \quad (46)$$

$$MF_{H_2O} = \dot{m}_{H_2O} / \dot{m}_{ex} \quad (47)$$

$$MF_{Ar} = \dot{m}_{Ar} / \dot{m}_{ex} \quad (48)$$

analysis of how much water will condense from exhaust gases

$$p_v = MF_{H_2O} \cdot 14.7 \quad \text{partial pressure of water vapor in combustion products} \quad (49)$$

$$p_{water} = P_{sat}(water, T = 77) \quad \text{partial pressure of water vapor at } T = T_o = 77 \text{ F} \quad (50)$$

$$n_v = p_{water} \cdot \frac{1 - p_v}{(14.7 - p_{water})} \quad \text{mass fraction of water vapor in comb. products at dead state} \quad (51)$$

$$n_w = MF_{H_2O} - n_v \quad (52)$$

Mass fractions of gases

$$MF_{CO_2g} = \frac{MF_{CO_2}}{(1 - n_w)} \quad (53)$$

$$MF_{N_2g} = \frac{MF_{N_2}}{1 - n_w} \quad (54)$$

$$MF_{O_2g} = \frac{MF_{O_2}}{1 - n_w} \quad (55)$$

$$MF_{H_2Og} = n_v \quad (56)$$

$$MF_{Arg} = \frac{MF_{Ar}}{1 - n_w} \quad (57)$$

Standard Chemical Exergies of exhaust gases and liquid water

$$E_{ch,CO_2} = 14167/2.326 \quad \text{standard chemical exergy of CO}_2 \text{ using Table C.2 - Model I - BTU/lb} \quad (58)$$

$$E_{ch,N_2} = 639/2.326 \quad (59)$$

$$E_{ch,O_2} = 3951/2.326 \quad (60)$$

$$E_{ch,H_2Og} = 8636/2.326 \quad (61)$$

$$E_{ch,Ar} = 11622/2.326 \quad (62)$$

$$E_{ch,H_2Ol} = 45/2.326 \quad (63)$$

$$M_{tot} = MF_{CO_2} \cdot 44.01 + MF_{N_2} \cdot 28.01 + MF_{O_2} \cdot 32 + MF_{H_2O} \cdot 18.02 + MF_{Ar} \cdot 39.95 \quad \text{Molecular weight of exhaust in lb/lbmol}$$

chemical exergy of gases

$$\begin{aligned} E_{ch,gas} = & MF_{CO_2g} \cdot E_{ch,CO_2} + MF_{N_2g} \cdot E_{ch,N_2} + MF_{O_2g} \cdot E_{ch,O_2} + MF_{H_2Og} \cdot E_{ch,H_2Og} + \\ & MF_{Arg} \cdot E_{ch,Ar} + (1.986) \cdot (537) \cdot (MF_{CO_2g} \cdot \ln(MF_{CO_2g}) + MF_{N_2g} \cdot \ln(MF_{N_2g}) + MF_{O_2g} \cdot \ln(MF_{O_2g}) + \\ & MF_{H_2Og} \cdot \ln(MF_{H_2Og}) + MF_{Arg} \cdot \ln(MF_{Arg})) \end{aligned} \quad (65)$$

chemical exergy of liquid water

$$E_{ch,water} = n_w \cdot E_{ch,H_2Ol} \quad (66)$$

$$E_{ch,total} = \frac{(MF_{CO_2} + MF_{N_2} + MF_{O_2} + MF_{Ar} + n_w) \cdot E_{ch,gas} + E_{ch,water}}{M_{tot}} \quad \text{Total chemical exergy of exhaust in BTU/lbmol}$$

$$\dot{E}_{ch,cp} = \dot{m}_{ex} \cdot E_{ch,total} \quad (68)$$

$$\text{end} \quad (69)$$

Equations

$$\text{function } Eph(T, P) \quad (1)$$

$$T_o = 77 \quad \text{standard temperature F} \quad (2)$$

$$p_o = 14.7 \quad \text{standard pressure psia} \quad (3)$$

$$h_o = h(\text{water}, T = T_o, P = p_o) \quad (4)$$

$$s_o = s(\text{water}, T = T_o, P = p_o) \quad (5)$$

$$h = h(\text{steam}, T = T, P = (P + 14.5)) \quad (6)$$

$$s = s(\text{steam}, T = T, P = (P + 14.5)) \quad (7)$$

$$Eph = (h - h_o) - (T_o + 460) \cdot (s - s_o) \quad (8)$$

$$\text{end} \quad (9)$$

$$\text{function } Eph_{gas}(T, P) \quad (10)$$

$$T_o = 77 \quad \text{standard temperature F} \quad (11)$$

$$p_o = 14.7 \quad \text{standard pressure psia} \quad (12)$$

$$h_o = h(\text{Methane}, T = T_o, P = p_o) \quad (13)$$

$$s_o = s(\text{Methane}, T = T_o, P = p_o) \quad (14)$$

$$h = h(\text{Methane}, T = T, P = (P + 14.7)) \quad (15)$$

$$s = s(\text{Methane}, T = T, P = (P + 14.7)) \quad (16)$$

$$Eph_{gas} = (h - h_o) - (T_o + 460) \cdot (s - s_o) \quad (17)$$

$$\text{end} \quad (18)$$

Pipe dPLIB

Equations

$$\text{function } HL_{water}(gpm, length, K_{tot}, f, d) \quad (1)$$

$$V = 1.283 \cdot \frac{gpm}{(\pi \cdot d^2)} \quad \text{velocity calc} \quad (2)$$

$$HL_{water} = \frac{\left(f \cdot \frac{length}{d/12}\right) \cdot \left(\frac{V^2}{2}\right) + K_{tot} \cdot \left(\frac{V^2}{2}\right)}{32.174} \cdot .433 \quad \text{Head loss in psi} \quad (3)$$

$$\text{end} \quad (4)$$

$$\text{function } HL_{steam}(m_{flow}, T, P, length, K_{tot}, f, d) \quad (5)$$

$$\rho = \rho(H_2O, T = T, P = (P + 14.7)) \quad \text{density calc} \quad (6)$$

$$HL_{steam} = 0.000336 \cdot f \cdot \frac{m_{flow}^2}{\rho \cdot d^5} \cdot length/100 \cdot .433 + 0.000000280 \cdot K_{tot} \cdot \frac{m_{flow}^2}{(\rho \cdot d^4)} \quad \text{head loss in psi} \quad (7)$$

$$\text{end} \quad (8)$$

$$\text{function } HL_{gas}(CFH, T, P, length, K_{tot}, f, d) \quad (9)$$

$$\rho = \rho(CH_4, T = T, P = (P + 14.7)) \quad \text{density calc} \quad (10)$$

$$\rho_s = \rho(CH_4, T = 77, P = 14.7) \quad \text{density at dead state} \quad (11)$$

$$CFH_a = CFH \cdot \rho_s / \rho \quad (12)$$

$$HL_{gas} = 0.000336 \cdot f \cdot CFH_a^2 \cdot \frac{\rho}{d^5} \cdot length/100 \cdot .433 + 0.000000280 \cdot K_{tot} \cdot CFH_a^2 \cdot \frac{\rho}{d^4} \quad \text{head loss in psi} \quad (13)$$

$$\text{end} \quad (14)$$

Pipe Heat Loss.LIB

Equations

```
function  $\dot{Q}(d, L, T)$  (1)
  If( $T > 150$ )and( $T < 251$ ) then (2)
     $k = 0.024$  (3)
     $ins = 2$  (4)
  else (5)
    If( $T > 251$ )and( $T < 351$ ) then (6)
       $k = 0.03$  (7)
       $ins = 3$  (8)
    else (9)
      If( $T > 351$ )and( $T < 451$ ) and ( $(d/2) > 1.49$ ) and ( $(d/2) < 3.01$ ) then (10)
         $k = 0.0376$  (11)
         $ins = 3$  (12)
      else (13)
        If( $T > 351$ )and( $T < 451$ ) and ( $(d/2) > 3.99$ ) then (14)
           $k = 0.0376$  (15)
           $ins = 4$  (16)
        else (17)
          If( $T > 451$ )and ( $(d/2) > 1.49$ ) and ( $(d/2) < 3.01$ ) then (18)
             $k = 0.0491$  (19)
             $ins = 3$  (20)
          else (21)
            If( $T > 451$ )and ( $(d/2) > 3.99$ ) then (22)
               $k = 0.0491$  (23)
               $ins = 4$  (24)
            else (25)
              call Error('no k or ins' ,  $k$ ) (26)
            endif (27)
          endif (28)
```

endif (29)

endif (30)

endif (31)

endif (32)

$$R_{tot} = \frac{\ln\left(\frac{ins+(d/2)}{d/2}\right)}{(2 \cdot \pi \cdot k \cdot L)} + (2 \cdot \pi \cdot (ins + (d/2)) \cdot 0.7 \cdot L)^{-1} \quad (33)$$

$$T_o = \frac{\ln\left(\frac{ins+(d/2)}{d/2}\right)}{2 \cdot \pi \cdot k \cdot L} \cdot (77 - T) + T \quad (34)$$

$$T_{avg} = \frac{T_o + 77}{2} \quad (35)$$

$$\dot{Q} = \frac{T_{avg} - T}{R_{tot}} \quad (36)$$

end (37)

APPENDIX B – ENGINEERING EQUATIONS SOLVER MAIN PROGRAMS

Aux Blr #5

Equations

Auxiliary Boiler #5

User created functions used:

$\dot{E}_{ph,fg}$ - Calculation of physical exergy of boiler flue gases (BTU/hr)

$\dot{E}_{ch,fg}$ - Calculation of chemical exergy of boiler flue gases (BTU/hr)

E_{ph} - Calculation of physical exergy of water liquid or vapor (BTU/lb)

mass flow rates

$$\dot{m}_1 = 10028 \text{ [lb/hr]} \quad \text{Combustion Air into boiler for 3\% excess O}_2 \text{ at 10,000 lb/hr steam production} \quad (1)$$

$$\dot{m}_2 = 10523 \text{ [lb/hr]} \quad \text{Flue gas flow rate} \quad (2)$$

$$\dot{m}_3 = 10200 \text{ [lb/hr]} \quad \text{Feedwater flow rate} \quad (3)$$

$$\dot{m}_4 = 10000 \text{ [lb/hr]} \quad \text{Steam flow rate leaving boiler} \quad (4)$$

$$\dot{m}_5 = 200 \text{ [lb/hr]} \quad \text{Continuous blowoff leaving boiler - 2\% of steam rate} \quad (5)$$

$$\dot{m}_6 = \dot{m}_2 - \dot{m}_1 \quad \text{Natural Gas flow rate into boiler - Continuity} \quad (6)$$

Temperature and Pressure Conditions

$$T_1 = 77 \text{ [F]} \quad \text{Temperature of combustion air into boiler} \quad (7)$$

$$P_1 = 14.7 \text{ [psia]} \quad \text{Pressure of combustion air entering boiler} \quad (8)$$

$$T_2 = 390 \text{ [F]} \quad \text{Temperature of flue gases exiting boiler} \quad (9)$$

$$P_2 = 14.7 \text{ [psia]} \quad \text{Pressure of flue gases exiting boiler to atmosphere} \quad (10)$$

$$T_3 = 227 \text{ [F]} \quad \text{Temperature of feedwater into boiler} \quad (11)$$

$$P_3 = 139.7 \text{ [psia]} \quad \text{Pressure of feedwater into boiler} \quad (12)$$

$$T_4 = T_{\text{sat}}(\text{steam}, P = P_4) \quad \text{Temperature of saturated steam leaving blr. \#5} \quad (13)$$

$$P_4 = 139.7 \text{ [psia]} \quad \text{Boiler operating pressure} \quad (14)$$

$$T_5 = T_4 \quad \text{Temperature of continuous blowoff exiting boiler} \quad (15)$$

$$P_5 = P_4 + .1 \text{ [psia]} \quad (16)$$

$$T_6 = 77 \text{ [F]} \quad \text{Temperature of natural gas entering boiler} \quad (17)$$

$$P_6 = 17.7 \text{ [psia]} \quad \text{Pressure of natural gas entering boiler} \quad (18)$$

Physical Exergy Conditions at Inlets and Outlets

$$\dot{E}_{1,ph} = 0 \quad \text{Combustion air at thermal \& chemical equilibrium with dead state} \quad (19)$$

$$\dot{E}_{2,ph} = \dot{E}_{ph,fg}(T_2, \dot{m}_2) \quad \text{Physical exergy of combustion products from function} \quad (20)$$

$$\dot{E}_{3,ph} = \dot{m}_3 \cdot Eph(T_3, (P_3 - 14.7)) \quad \text{Phys. exergy of feedwater} \quad (21)$$

$$\dot{E}_{4,ph} = \dot{m}_4 \cdot Eph(T_4, (P_4 - 14.7)) \quad \text{Phys. exergy of steam} \quad (22)$$

$$\dot{E}_{5,ph} = \dot{m}_5 \cdot Eph(T_5, (P_5 - 14.7)) \quad \text{Phys. exergy of blowoff} \quad (23)$$

$$\dot{E}_{6,ph} = \dot{m}_6 \cdot Eph_{gas}(T_6, (P_6 - 14.7)) \quad \text{Phys. exergy of natural gas} \quad (24)$$

Chemical Exergy Conditions at Inlets and Outlets

$$\dot{E}_{1,ch} = 0 \quad (25)$$

$$\dot{E}_{2,ch} = \dot{E}_{ch,fg}(T_2, \dot{m}_2) \quad \text{Chem. exergy of combustion products from function} \quad (26)$$

$$\dot{E}_{3,ch} = \dot{m}_3 \cdot \left(\frac{45}{2.326 \cdot 18.02} \right) \quad \text{Chem. exergy of feedwater converted to BTU/lb} \quad (27)$$

$$\dot{E}_{4,ch} = \dot{m}_4 \cdot \left(\frac{45}{2.326 \cdot 18.02} \right) \quad \text{Chem. exergy of steam leaving converted to BTU/lb} \quad (28)$$

$$\dot{E}_{5,ch} = \dot{m}_5 \cdot \left(\frac{45}{2.326 \cdot 18.02} \right) \quad \text{Chem. exergy of continuous blowoff converted to BTU/lb} \quad (29)$$

$$\dot{E}_{6,ch} = \dot{m}_6 \cdot 22150.23 \quad \text{Chem. exergy of natural gas in BTU/lb} \quad (30)$$

Total Exergy at Inlets and Outlets

$$\dot{E}_1 = \dot{E}_{1,ph} + \dot{E}_{1,ch} \quad (31)$$

$$\dot{E}_2 = \dot{E}_{2,ph} + \dot{E}_{2,ch} \quad (32)$$

$$\dot{E}_3 = \dot{E}_{3,ph} + \dot{E}_{3,ch} \quad (33)$$

$$\dot{E}_4 = \dot{E}_{4,ph} + \dot{E}_{4,ch} \quad (34)$$

$$\dot{E}_5 = \dot{E}_{5,ph} + \dot{E}_{5,ch} \quad (35)$$

$$\dot{E}_6 = \dot{E}_{6,ph} + \dot{E}_{6,ch} \quad (36)$$

Work Input for forced draft fan

$$\dot{W}_{in} = -15 \cdot 2545 \text{ [BTU/hr]} \quad 15 \text{ HP blower motor} \quad (37)$$

Total Exergy Destruction

$$\dot{E}_d = (\dot{E}_1 + \dot{E}_3 + \dot{E}_6) - (\dot{E}_2 + \dot{E}_4 + \dot{E}_5) - \dot{W}_{in} \quad \text{Exergy destruction for boiler #5} \quad (38)$$

First Law Efficiency for Aux. Blr. #5

$$h_3 = h(\text{steam}, T = T_3, P = P_3) \quad (39)$$

$$h_4 = h(\text{steam}, T = T_4, P = (P_4 - .1)) \quad (40)$$

$$\eta_I = \dot{m}_4 \cdot \frac{h_4 - h_3}{(\dot{m}_6 \cdot 936/0.04102) - \dot{W}_{in}} \quad (41)$$

Solution

$\eta_I = -9999$	$\dot{E}_1 = 0$
$\dot{E}_{1,ch} = 0$	$\dot{E}_{1,ph} = 0$
$\dot{E}_2 = -9999$	$\dot{E}_{2,ch} = -9999$
$\dot{E}_{2,ph} = -9999$	$\dot{E}_3 = -9999$
$\dot{E}_{3,ch} = 10951$	$\dot{E}_{3,ph} = -9999$
$\dot{E}_4 = -9999$	$\dot{E}_{4,ch} = 10736$
$\dot{E}_{4,ph} = -9999$	$\dot{E}_5 = -9999$
$\dot{E}_{5,ch} = 214.7$	$\dot{E}_{5,ph} = -9999$
$\dot{E}_6 = -9999$	$\dot{E}_{6,ch} = 1.096 \times 10^7$
$\dot{E}_{6,ph} = -9999$	$\dot{E}_d = -9999$
$h_3 = 195.6$	$h_4 = -9999$
$\dot{m}_1 = 10028$ [lb/hr]	$\dot{m}_2 = 10523$ [lb/hr]
$\dot{m}_3 = 10200$ [lb/hr]	$\dot{m}_4 = 10000$ [lb/hr]
$\dot{m}_5 = 200$ [lb/hr]	$\dot{m}_6 = 495$
$P_1 = 14.7$ [psia]	$P_2 = 14.7$ [psia]
$P_3 = 139.7$ [psia]	$P_4 = 139.7$ [psia]
$P_5 = 139.8$	$P_6 = 17.7$ [psia]
$T_1 = 77$ [F]	$T_2 = 390$ [F]
$T_3 = 227$ [F]	$T_4 = -9999$
$T_5 = -9999$	$T_6 = 77$ [F]
$\dot{W}_{in} = -38175$	

Equations

Solar Gas Turbine

Input Parametric Values

$energy_{fuel}$ = Fuel input to Gas Turbine (BTU/hr)

\dot{m}_{ex} = Mass flow rate of Combustion Products Exiting turbine (lb/hr)

\dot{W}_{out} = Electricity Generation Rate (BTU/hr)

T_{ex} = Temperature of Combustion Products (F)

\dot{m}_3 = HRSG#2 Feedwater mass flow rate (lb/hr)

T_7 = Temperature of Combustion Products Exiting Economizer (F)

Custom functions used in calculations:

$E_{ph,gas}$ - Calculation of physical exergy of natural gas

$\dot{E}_{ph,cp}$ - Calculation of physical exergy of combustion products

$\dot{E}_{ch,cp}$ - Calculation of chemical exergy of combustion products

E_{ph} - Calculation of physical exergy of water in liquid or vapor state

Properties of fuel and combustion products for gas turbine

$$density_{fuel} = \rho(\text{Methane}, T = 77, P = 14.7) \quad \text{Methane assumed for calculation of fuel density (lb/ft}^3\text{)} \quad (1)$$

$$\dot{m}_{fuel} = (energy_{fuel}/1040) \cdot density_{fuel} \quad \text{mass flow rate of fuel (lb/hr)} \quad (2)$$

$$\dot{E}_{fuel} = \dot{m}_{fuel} \cdot (E_{ph,gas}(77, 199.1) + 22150.23) \quad \text{Exergy flow rate of entering fuel (BTU/hr)} \quad (3)$$

$$\dot{m}_{air} = \dot{m}_{ex} - \dot{m}_{fuel} \quad \text{Continuity} \quad (4)$$

$$h_{air} = h(\text{air}, T = 77) \quad (5)$$

$$\dot{E}_{air} = 0 \quad \text{no physical or chemical exergy in entering combustion air at } T_o, P_o \quad (6)$$

$$P_{ex} = 15 \text{ [psia]} \quad \text{exhaust pressure leaving turbine} \quad (7)$$

$$\dot{E}_{ex,ph} = \dot{E}_{ph,cp}(T_{ex}, \dot{m}_{ex}) \quad \text{Physical exergy of exhaust gases} \quad (8)$$

$$\dot{E}_{ex,ch} = \dot{E}_{ch,cp}(T_{ex}, \dot{m}_{ex}) \quad \text{Chem. Exergy of Exhaust Gases} \quad (9)$$

$$\dot{E}_{ex} = \dot{E}_{ex,ph} + \dot{E}_{ex,ch} \quad \text{Total Exergy of exhaust gases} \quad (10)$$

$$\dot{E}_{d1} = (\dot{E}_{fuel} + \dot{E}_{air}) - \dot{E}_{ex} + \dot{W}_{out} \quad \text{Exergy destruction of gas turbine} \quad (11)$$

$$\eta_{gt,i} = \frac{\dot{W}_{out}}{(\dot{m}_{fuel} \cdot 936/0.04102)} \quad \text{First Law Efficiency for gas turbine} \quad (12)$$

$$\eta_{gt,ii} = \dot{W}_{out}/\dot{E}_{fuel} \quad \text{Second Law efficiency for gas turbine} \quad (13)$$

HRSG#2 Analysis

enthalpy of exhaust gases

$$h_1 = 389.4 \quad \text{enthalpy of exhaust gases entering HRSG\#2 (BTU/lb)} \quad (14)$$

$$h_2 = 266.8 \quad \text{enthalpy of exhaust gases leaving HRSG\#2 (BTU/lb)} \quad (15)$$

$$\dot{m}_1 = \dot{m}_{ex} \quad \text{exhaust mass flow rate into HRSG\#2 from Solar Turbine} \quad (16)$$

$$T_1 = T_{ex} \quad \text{exhaust temperature entering HRSG\#2} \quad (17)$$

$$P_1 = P_{ex} \quad \text{exhaust pressure entering HRSG\#2} \quad (18)$$

$$\dot{m}_2 = \dot{m}_1 \quad \text{unfired continuity balance} \quad (19)$$

$$T_2 = 465.7 \quad \text{exhaust temperature leaving HRSG\#2 - set parametric} \quad (20)$$

$$P_2 = 14.85 \text{ [psia]} \quad (21)$$

$$T_3 = 404 \quad \text{feedwater temp entering HRSG\#2 from economizer} \quad (22)$$

$$P_3 = 364.7 \text{ [psia]} \quad \text{feedwater pressure entering HRSG \#2} \quad (23)$$

$$h_3 = h(\text{steam}, T = T_3, P = P_3) \quad (24)$$

$$\dot{m}_4 = \dot{m}_3/1.02 \quad \text{steam leaving HRSG \#2 (lb/hr) - set parametric} \quad (25)$$

$$P_4 = 364.7 \text{ [psia]} \quad \text{steam pressure leaving HRSG\#2 (350 psig)} \quad (26)$$

$$T_4 = 500 \quad \text{steam temp leaving HRSG\#2 (unfired)} \quad (27)$$

$$h_4 = h(\text{steam}, T = T_4, P = P_4) \quad (28)$$

$$\dot{m}_5 = \dot{m}_3 - \dot{m}_4 \quad \text{continuous blowdown from HRSG\#2 - 2\% of feedwater rate (lb/hr)} \quad (29)$$

$$T_5 = T_{\text{sat}}(\text{steam}, P = P_5) \quad (30)$$

$$P_5 = P_4 \quad (31)$$

$$h_5 = h(\text{steam}, T = T_5, P = P_5) \quad (32)$$

First Law Energy Balance

$$\dot{Q}_{hrsg} = \dot{m}_1 \cdot (h_1 - h_2) + \dot{m}_3 \cdot h_3 - \dot{m}_4 \cdot h_4 - \dot{m}_5 \cdot h_5 \quad \text{Heat transfer from HSRG\#2 to the Environment (BTU/hr)} \quad (33)$$

$$\eta_{hrsg,i} = \dot{m}_4 \cdot \frac{h_4 - h_3}{(\dot{m}_1 \cdot (h_1 - h_2))} \quad \text{First Law efficiency of HRSG\#2} \quad (34)$$

Physical and Chemical Exergy for Inlet and Exit Flows

$$\dot{E}_{1,ph} = \dot{E}_{ex,ph} \quad (35)$$

$$\dot{E}_{2,ph} = \dot{E}_{ph,cp}(T_2, \dot{m}_{ex}) \quad (36)$$

$$\dot{E}_{3,ph} = \dot{m}_3 \cdot Eph(T_3, (P_3 - 14.7)) \quad (37)$$

$$\dot{E}_{4,ph} = \dot{m}_4 \cdot Eph(T_4, (P_4 - 14.7)) \quad (38)$$

$$\dot{E}_{5,ph} = \dot{m}_5 \cdot Eph(T_5, (P_5 - 14.7)) \quad (39)$$

$$\dot{E}_{1,ch} = \dot{E}_{ex,ch} \quad (40)$$

$$\dot{E}_{2,ch} = \dot{E}_{ch,cp}(T_2, \dot{m}_{ex}) \quad (41)$$

$$\dot{E}_{3,ch} = \dot{m}_3 \cdot \left(\frac{45}{2.326 \cdot 18.02} \right) \quad \text{Chem. exergy of feedwater converted to BTU/lb from standard table data} \quad (42)$$

$$\dot{E}_{4,ch} = \dot{m}_4 \cdot \left(\frac{45}{2.326 \cdot 18.02} \right) \quad \text{Chem. exergy of steam leaving converted to BTU/lb from standard table data} \quad (43)$$

$$\dot{E}_{5,ch} = \dot{m}_5 \cdot \left(\frac{45}{2.326 \cdot 18.02} \right) \quad \text{Chem. exergy of blowoff water leaving converted to BTU/lb from standard table data} \quad (44)$$

$$\dot{E}_1 = \dot{E}_{1,ph} + \dot{E}_{1,ch} \quad (45)$$

$$\dot{E}_2 = \dot{E}_{2,ph} + \dot{E}_{2,ch} \quad (46)$$

$$\dot{E}_3 = \dot{E}_{3,ph} + \dot{E}_{3,ch} \quad (47)$$

$$\dot{E}_4 = \dot{E}_{4,ph} + \dot{E}_{4,ch} \quad (48)$$

$$\dot{E}_5 = \dot{E}_{5,ph} + \dot{E}_{5,ch} \quad (49)$$

$$\dot{E}_{d2} = \left(\dot{E}_1 + \dot{E}_3 \right) - \left(\dot{E}_2 + \dot{E}_4 + \dot{E}_5 \right) + (1 - 537/610) \cdot \dot{Q}_{hrsg} \quad \text{Exergy destruction rate of HRSG#2 - heat loss accounted for} \quad (50)$$

$$\eta_{hrsg,ii} = \frac{\dot{E}_4 - \dot{E}_3}{\left(\dot{E}_1 - \dot{E}_2 - \dot{E}_5 \right)} \quad \text{Second Law efficiency of HRSG#2} \quad (51)$$

Economizer - Unfired

$$T_6 = T_2 \quad \text{Exhaust temp entering Economizer} \quad (52)$$

$$P_6 = P_2 \quad \text{Exhaust pressure entering Economizer} \quad (53)$$

$$P_7 = 14.7 \text{ [psia]} \quad \text{Discharge to atmosphere} \quad (54)$$

$$T_8 = 227 \quad \text{Economizer feedwater inlet temp (F)} \quad (55)$$

$$P_8 = 463.2 \text{ [psia]} \quad \text{Economizer feedwater inlet pressure} \quad (56)$$

$$T_9 = 404 \quad \text{Economizer outlet feedwater temperature} \quad (57)$$

$$P_9 = 461.7 \text{ [psia]} \quad \text{Economizer outlet feedwater pressure - 1.5 psi drop} \quad (58)$$

First Law Balance for Economizer

$$h_6 = 266.8 \quad \text{enthalpy of exhaust gases entering economizer (BTU/lb)} \quad (59)$$

$$h_7 = 237.9 \quad \text{enthalpy of exhaust gases exiting economizer (BTU/lb)} \quad (60)$$

$$h_8 = h(\text{steam}, T = T_8, P = P_8) \quad \text{enthalpy of feedwater entering economizer (BTU/lb)} \quad (61)$$

$$h_9 = h(\text{steam}, T = T_9, P = P_9) \quad \text{enthalpy of feedwater exiting economizer (BTU/lb)} \quad (62)$$

$$\dot{Q}_{econ} = \dot{m}_4 \cdot (h_9 - h_8) + \dot{m}_1 \cdot (h_6 - h_7) \quad (63)$$

$$\eta_{econ,i} = \dot{m}_4 \cdot \frac{h_9 - h_8}{(\dot{m}_1 \cdot (h_6 - h_7))} \quad \text{First Law Efficiency for Economizer} \quad (64)$$

Inlet and Exit Exergy Flow Rates (BTU/hr)

$$\dot{E}_{6,ph} = \dot{E}_{2,ph} \quad (65)$$

$$\dot{E}_{6,ch} = \dot{E}_{2,ch} \quad (66)$$

$$\dot{E}_{7,ph} = \dot{E}_{ph,cp}(T_7, \dot{m}_{ex}) \quad (67)$$

$$\dot{E}_{7,ch} = \dot{E}_{ch,cp}(T_7, \dot{m}_{ex}) \quad (68)$$

$$\dot{E}_{8,ph} = \dot{m}_3 \cdot Eph(T_8, (P_8 - 14.7)) \quad (69)$$

$$\dot{E}_{8,ch} = \dot{E}_{3,ch} \quad (70)$$

$$\dot{E}_{9,ph} = \dot{m}_3 \cdot Eph(T_9, (P_9 - 14.7)) \quad (71)$$

$$\dot{E}_{9,ch} = \dot{E}_{8,ch} \quad (72)$$

$$\dot{E}_6 = \dot{E}_{6,ph} + \dot{E}_{6,ch} \quad (73)$$

$$\dot{E}_7 = \dot{E}_{7,ph} + \dot{E}_{7,ch} \quad (74)$$

$$\dot{E}_8 = \dot{E}_{8,ph} + \dot{E}_{8,ch} \quad (75)$$

$$\dot{E}_9 = \dot{E}_{9,ph} + \dot{E}_{9,ch} \quad (76)$$

$$\dot{E}_{d3} = (\dot{E}_6 + \dot{E}_8) - (\dot{E}_7 + \dot{E}_9) + (1 - 537/610) \cdot \dot{Q}_{econ} \quad \text{Exergy destruction rate of Economizer - heat loss accounted for (77)}$$

$$\eta_{econ,ii} = \frac{\dot{E}_9 - \dot{E}_8}{(\dot{E}_6 - \dot{E}_7)} \quad \text{Second Law efficiency of economizer} \quad (78)$$

Total Exergy Destruction for Cogeneration System (BTU/hr)

$$\dot{E}_{d,total} = \dot{E}_{d1} + \dot{E}_{d2} + \dot{E}_{d3} \quad (79)$$

$$\eta_{total,i} = \frac{\dot{W}_{out} + \dot{m}_4 \cdot (h_4 - h_8)}{\dot{m}_{fuel} \cdot 936/0.04102} \quad \text{First Law efficiency for overall cogeneration system} \quad (80)$$

$$\eta_{total,ii} = \frac{\dot{W}_{out} + \dot{E}_4 - \dot{E}_8}{\dot{E}_{fuel}} \quad \text{Second Law efficiency of overall cogeneration system} \quad (81)$$

Solution

$$density_{fuel} = 0.04102 \quad energy_{fuel} = -9999$$

$$\eta_{econ,i} = -9999 \quad \eta_{econ,ii} = -9999$$

$$\eta_{gt,i} = -9999 \quad \eta_{gt,ii} = -9999$$

$$\eta_{hrsg,i} = -9999 \quad \eta_{hrsg,ii} = -9999$$

$$\eta_{total,i} = -9999 \quad \eta_{total,ii} = -9999$$

$$\dot{E}_1 = -9999 \quad \dot{E}_{1,ch} = -9999$$

$$\dot{E}_{1,ph} = -9999 \quad \dot{E}_2 = -9999$$

$$\dot{E}_{2,ch} = -9999 \quad \dot{E}_{2,ph} = -9999$$

$$\dot{E}_3 = -9999 \quad \dot{E}_{3,ch} = -9999$$

$$\dot{E}_{3,ph} = -9999 \quad \dot{E}_4 = -9999$$

$$\dot{E}_{4,ch} = -9999 \quad \dot{E}_{4,ph} = -9999$$

$\dot{E}_5 = -9999$	$\dot{E}_{5,ch} = -9999$
$\dot{E}_{5,ph} = -9999$	$\dot{E}_6 = -9999$
$\dot{E}_{6,ch} = -9999$	$\dot{E}_{6,ph} = -9999$
$\dot{E}_7 = -9999$	$\dot{E}_{7,ch} = -9999$
$\dot{E}_{7,ph} = -9999$	$\dot{E}_8 = -9999$
$\dot{E}_{8,ch} = -9999$	$\dot{E}_{8,ph} = -9999$
$\dot{E}_9 = -9999$	$\dot{E}_{9,ch} = -9999$
$\dot{E}_{9,ph} = -9999$	$\dot{E}_{air} = 0$
$\dot{E}_{d1} = -9999$	$\dot{E}_{d2} = -9999$
$\dot{E}_{d3} = -9999$	$\dot{E}_{d,total} = -9999$
$\dot{E}_{ex} = -9999$	$\dot{E}_{ex,ch} = -9999$
$\dot{E}_{ex,ph} = -9999$	$\dot{E}_{fuel} = -9999$
$h_1 = 389.4$	$h_2 = 266.8$
$h_3 = 379.5$	$h_4 = 1249$
$h_5 = -9999$	$h_6 = 266.8$
$h_7 = 237.9$	$h_8 = 196.3$
$h_9 = 379.6$	$h_{air} = 128.4$
$\dot{m}_1 = -9999$	$\dot{m}_2 = -9999$
$\dot{m}_3 = -9999$	$\dot{m}_4 = -9999$
$\dot{m}_5 = -9999$	$\dot{m}_{air} = -9999$
$\dot{m}_{ex} = -9999$	$\dot{m}_{fuel} = -9999$
$P_1 = 15$ [psia]	$P_2 = 14.85$ [psia]
$P_3 = 364.7$ [psia]	$P_4 = 364.7$ [psia]
$P_5 = 364.7$	$P_6 = 14.85$
$P_7 = 14.7$ [psia]	$P_8 = 463.2$ [psia]
$P_9 = 461.7$ [psia]	$P_{ex} = 15$ [psia]
$\dot{Q}_{econ} = -9999$	$\dot{Q}_{hrsg} = -9999$
$T_1 = -9999$	$T_2 = 465.7$
$T_3 = 404$	$T_4 = 500$
$T_5 = -9999$	$T_6 = 465.7$
$T_7 = -9999$	$T_8 = 227$
$T_9 = 404$	$T_{ex} = -9999$
$\dot{W}_{out} = -9999$	

NG_piping losses

Equations

Natural Gas Piping Losses - all CFH values are SCFH

Parametric Input Values

CFH1 - Natural gas volumetric flowrate into plant (standard ft³/hr)

CFH2 to CFH6 - Natural gas volumetric flowrates (SCFH)

User created functions used:

HL_{gas} - Pressure drop calculation (ψ) for natural gas piping

ff_{gas} - Darcy friction factor calculation for natural gas piping

Eph_{gas} - Physical exergy calculation for natural gas

Gas Pipe 001

$$P_{N,001} = 200 \text{ [psig]} \quad \text{inlet pressure to plant (psig)} \quad (1)$$

$$T = 77 \text{ [F]} \quad \text{inlet temperature to plant (F)} \quad (2)$$

$$\rho_{gas} = \rho(\text{methane}, T = T, P = 14.7) \quad \text{density of natural gas at dead state} \quad (3)$$

$$K_{001} = 0.18 \cdot 11 + 0.3 \cdot 1 + 0.27 \cdot 1 \quad (4)$$

$$P_{N,002} = P_{N,001} - HL_{gas}(CFH1, T, P_{N,001}, 185, K_{001}, ff_{gas}(CFH1, T, P_{N,001}, 6), 6) \quad (5)$$

$$E_{001} = Eph_{gas}(T, P_{N,001}) + 22150.23 \quad \text{physical + chemical exergy} \quad (6)$$

$$E_{002} = Eph_{gas}(T, P_{N,002}) + 22150.23 \quad (7)$$

$$\dot{E}_{d,001} = CFH1 \cdot \rho_{gas} \cdot (E_{001} - E_{002}) \quad \text{Exergy destruction due to pressure drop. No } E_{ch} \text{ change, heat transfer} \quad (8)$$

Gas Pipe 002

$$K_{002} = 0.3 \cdot 1 \quad (9)$$

$$P_{N,003} = P_{N,002} - HL_{gas}(CFH2, T, P_{N,002}, 3, K_{002}, ff_{gas}(CFH2, T, P_{N,002}, 6), 6) \quad (10)$$

$$E_{003} = Eph_{gas}(T, P_{N,003}) + 22150.23 \quad (11)$$

$$\dot{E}_{d,002} = CFH2 \cdot \rho_{gas} \cdot (E_{002} - E_{003}) \quad (12)$$

Gas Pipe 003

$$K_{003} = 0.3 \cdot 1 \quad (13)$$

$$P_{N,004} = P_{N,003} - HL_{gas}(CFH3, T, P_{N,003}, 15, K_{003}, ff_{gas}(CFH3, T, P_{N,003}, 6), 6) \quad (14)$$

$$E_{004} = Eph_{gas}(T, P_{N,004}) + 22150.23 \quad (15)$$

$$\dot{E}_{d,003} = CFH3 \cdot \rho_{gas} \cdot (E_{003} - E_{004}) \quad (16)$$

Gas Pipe 004

$$K_{004} = 0.3 \cdot 1 \quad (17)$$

$$P_{N,005} = P_{N,004} - HL_{gas}(CFH4, T, P_{N,004}, 4, K_{004}, ff_{gas}(CFH4, T, P_{N,004}, 6), 6) \quad (18)$$

$$E_{005} = Eph_{gas}(T, P_{N,005}) + 22150.23 \quad (19)$$

$$\dot{E}_{d,004} = CFH4 \cdot \rho_{gas} \cdot (E_{004} - E_{005}) \quad (20)$$

Gas Pipe 005

$$K_{005} = 0.3 \cdot 1 \quad (21)$$

$$P_{N,006} = P_{N,005} - HL_{gas}(CFH5, T, P_{N,005}, 10, K_{005}, ff_{gas}(CFH5, T, P_{N,005}, 6), 6) \quad (22)$$

$$E_{006} = Eph_{gas}(T, P_{N,006}) + 22150.23 \quad (23)$$

$$\dot{E}_{d,005} = CFH5 \cdot \rho_{gas} \cdot (E_{005} - E_{006}) \quad (24)$$

Gas Pipe 006

$$K_{006} = 0.22 \cdot 3 + 0.32 \cdot 3 + 0.36 \cdot 1 \quad (25)$$

$$P_{N,007} = P_{N,006} - HL_{gas}(CFH6, T, P_{N,006}, 30, K_{006}, ff_{gas}(CFH6, T, P_{N,006}, 3), 3) \quad (26)$$

$$E_{007} = Eph_{gas}(T, P_{N,007}) + 22150.23 \quad (27)$$

$$\dot{E}_{d,006} = CFH6 \cdot \rho_{gas} \cdot (E_{006} - E_{007}) \quad (28)$$

Gas Pipe 007

$$K_{007} = 0.25 \cdot 3 + 0.15 \cdot 1 \quad (29)$$

$$P_{N,008} = P_{N,007} - HL_{gas}(CFH6, T, P_{N,007}, 12, K_{007}, ff_{gas}(CFH6, T, P_{N,007}, 2), 2) \quad (30)$$

$$E_{008} = Eph_{gas}(T, P_{N,008}) + 22150.23 \quad (31)$$

$$\dot{E}_{d,007} = CFH6 \cdot \rho_{gas} \cdot (E_{007} - E_{008}) \quad (32)$$

Gas Pipe 008

$$K_{008} = 0.22 \cdot 8 + 0.32 \cdot 2 \quad (33)$$

$$CFH7 = CFH1 - CFH2 \quad (34)$$

$$P_{N,009} = P_{N,002} - HL_{gas}(CFH7, T, P_{N,002}, 148, K_{008}, ff_{gas}(CFH7, T, P_{N,002}, 3), 3) \quad (35)$$

$$E_{009} = Eph_{gas}(T, P_{N,009}) + 22150.23 \quad (36)$$

$$\dot{E}_{d,008} = CFH7 \cdot \rho_{gas} \cdot (E_{002} - E_{009}) \quad (37)$$

Gas Pipe 009

$$K_{009} = 0.22 \cdot 1 + 0.32 \cdot 2 \quad (38)$$

$$P_{N,011} = P_{N,009} - HL_{gas}(CFH7, T, P_{N,009}, 22, K_{009}, ff_{gas}(CFH7, T, P_{N,009}, 3), 3) \quad (39)$$

$$E_{011} = Eph_{gas}(T, P_{N,011}) + 22150.23 \quad (40)$$

$$\dot{E}_{d,009} = CFH7 \cdot \rho_{gas} \cdot (E_{009} - E_{011}) \quad (41)$$

Gas Pipe 010

$$K_{010} = 0.23 \cdot 2 \quad (42)$$

$$P_{N,012} = P_{N,011} - HL_{gas}(CFH7, T, P_{N,011}, 6, K_{010}, ff_{gas}(CFH7, T, P_{N,011}, 2), 2) - 0.5 \quad 0.5 \text{ psig drop assumed for y}$$

$$E_{012} = Eph_{gas}(T, P_{N,012}) + 22150.23 \quad (44)$$

$$\dot{E}_{d,010} = CFH7 \cdot \rho_{gas} \cdot (E_{011} - E_{012}) \quad (45)$$

$$\rho_{012} = \rho(\text{Methane}, T = T, P = (14.7)) \quad +P_{N,011} \quad (46)$$

Gas Pipe 011

$$K_{011} = 0.22 \cdot 6 + 0.11 \cdot 1 + 0.32 \cdot 1 \quad (47)$$

$$CFH8 = CFH2 - CFH3 \quad (48)$$

$$P_{N,013} = P_{N,003} - HL_{gas}(CFH8, T, P_{N,003}, 23, K_{011}, ff_{gas}(CFH8, T, P_{N,003}, 3), 3) \quad (49)$$

$$E_{013} = Eph_{gas}(T, P_{N,013}) + 22150.23 \quad (50)$$

$$\dot{E}_{d,011} = CFH8 \cdot \rho_{gas} \cdot (E_{003} - E_{013}) \quad (51)$$

$$P_{N,014} = P_{N,013} - 125 \quad \text{PRV - 200 psig to 75 psig} \quad (52)$$

$$E_{014} = Eph_{gas}(T, P_{N,014}) + 22150.23 \quad (53)$$

$$\dot{E}_{d,PRV1} = CFH8 \cdot \rho_{gas} \cdot (E_{013} - E_{014}) \quad (54)$$

Gas Pipe 012

$$K_{012} = 0 \quad (55)$$

$$P_{N,015} = P_{N,014} - HL_{gas}(CFH8, T, P_{N,014}, 3, K_{012}, ff_{gas}(CFH8, T, P_{N,014}, 3), 3) \quad (56)$$

$$E_{015} = Eph_{gas}(T, P_{N,015}) + 22150.23 \quad (57)$$

$$\dot{E}_{d,012} = CFH8 \cdot \rho_{gas} \cdot (E_{014} - E_{015}) \quad (58)$$

$$P_{N,016} = P_{N,015} - 60 \quad \text{PRV - 75 psig to 15 psig} \quad (59)$$

$$E_{016} = Eph_{gas}(T, P_{N,016}) + 22150.23 \quad (60)$$

$$\dot{E}_{d,PRV2} = CFH8 \cdot \rho_{gas} \cdot (E_{015} - E_{016}) \quad (61)$$

Gas Pipe 013

$$K_{013} = 0.32 \cdot 2 + 0.14 \cdot 1 \quad (62)$$

$$P_{N,017} = P_{N,016} - HL_{gas}(CFH8, T, P_{N,016}, 11, K_{013}, ff_{gas}(CFH8, T, P_{N,016}, 3), 3) \quad (63)$$

$$E_{017} = Eph_{gas}(T, P_{N,017}) + 22150.23 \quad (64)$$

$$\dot{E}_{d,013} = CFH8 \cdot \rho_{gas} \cdot (E_{016} - E_{017}) \quad (65)$$

$$P_{N,018} = P_{N,017} - 12 \quad \text{FCV - 15 psig to 3 psig} \quad (66)$$

$$E_{018} = Eph_{gas}(T, P_{N,018}) + 22150.23 \quad (67)$$

$$\dot{E}_{d,PRV3} = CFH8 \cdot \rho_{gas} \cdot (E_{017} - E_{018}) \quad (68)$$

Gas Pipe 014

$$K_{014} = 0.38 \cdot 1 \quad (69)$$

$$P_{N,019} = P_{N,018} - HL_{gas}(CFH8, T, P_{N,018}, 1, K_{014}, ff_{gas}(CFH8, T, P_{N,018}, 2), 2) \quad (70)$$

$$E_{019} = Eph_{gas}(T, P_{N,019}) + 22150.23 \quad (71)$$

$$\dot{E}_{d,014} = CFH8 \cdot \rho_{gas} \cdot (E_{018} - E_{019}) \quad (72)$$

Gas Pipe 015

$$K_{015} = 0.23 \cdot 1 + 0.15 \cdot 1 \quad (73)$$

$$CFH9 = CFH8/2 \quad (74)$$

$$P_{N,020} = P_{N,019} - HL_{gas}(CFH9, T, P_{N,019}, 6, K_{015}, ff_{gas}(CFH9, T, P_{N,019}, 2), 2) \quad (75)$$

$$E_{020} = Eph_{gas}(T, P_{N,020}) + 22150.23 \quad (76)$$

$$\dot{E}_{d,015} = CFH9 \cdot \rho_{gas} \cdot (E_{019} - E_{020}) \quad (77)$$

Gas Pipe 016

$$K_{016} = 0.34 \cdot 2 \quad (78)$$

$$P_{N,021} = P_{N,020} - HL_{gas}(CFH9, T, P_{N,020}, 2, K_{016}, ff_{gas}(CFH9, T, P_{N,020}, 4), 4) \quad (79)$$

$$E_{021} = Eph_{gas}(T, P_{N,021}) + 22150.23 \quad (80)$$

$$\dot{E}_{d,016} = CFH9 \cdot \rho_{gas} \cdot (E_{020} - E_{021}) \quad (81)$$

Gas Pipe 017

$$K_{017} = 0 \quad (82)$$

$$P_{N,021b} = P_{N,021} - HL_{gas}(CFH9, T, P_{N,021}, 3, K_{017}, ff_{gas}(CFH9, T, P_{N,021}, 2), 2) \quad (83)$$

$$E_{021b} = Eph_{gas}(T, P_{N,021b}) + 22150.23 \quad (84)$$

$$\dot{E}_{d,017} = 2 \cdot CFH9 \cdot \rho_{gas} \cdot (E_{021} - E_{021b}) \quad (85)$$

Gas Pipe 019

$$K_{019} = 0.23 \cdot 2 + 0.15 \cdot 1 \quad (86)$$

$$P_{N,022} = P_{N,019} - HL_{gas}(CFH9, T, P_{N,019}, 20, K_{019}, ff_{gas}(CFH9, T, P_{N,019}, 2), 2) \quad (87)$$

$$E_{022} = Eph_{gas}(T, P_{N,022}) + 22150.23 \quad (88)$$

$$\dot{E}_{d,019} = CFH9 \cdot \rho_{gas} \cdot (E_{019} - E_{022}) \quad (89)$$

Gas Pipe 020

$$K_{020} = 0.34 \cdot 2 \quad (90)$$

$$P_{N,023} = P_{N,022} - HL_{gas}(CFH9, T, P_{N,022}, 2, K_{020}, ff_{gas}(CFH9, T, P_{N,022}, 4), 4) \quad (91)$$

$$E_{023} = Eph_{gas}(T, P_{N,023}) + 22150.23 \quad (92)$$

$$\dot{E}_{d,020} = CFH9 \cdot \rho_{gas} \cdot (E_{022} - E_{023}) \quad (93)$$

Gas Pipe 021

$$K_{021} = 0 \quad (94)$$

$$P_{N,023b} = P_{N,023} - HL_{gas}(CFH9, T, P_{N,023}, 2, K_{021}, ff_{gas}(CFH9, T, P_{N,023}, 2), 2) \quad (95)$$

$$E_{023b} = Eph_{gas}(T, P_{N,023b}) + 22150.23 \quad (96)$$

$$\dot{E}_{d,021} = 2 \cdot CFH9 \cdot \rho_{gas} \cdot (E_{023} - E_{023b}) \quad (97)$$

Gas Pipe 022

$$K_{022} = 0.32 \cdot 1 \quad (98)$$

$$CFH10 = CFH3 - CFH4 \quad (99)$$

$$P_{N,024} = P_{N,004} - HL_{gas}(CFH10, T, P_{N,004}, 5, K_{022}, ff_{gas}(CFH10, T, P_{N,004}, 2.5), 2.5) \quad (100)$$

$$E_{024} = Eph_{gas}(T, P_{N,024}) + 22150.23 \quad (101)$$

$$\dot{E}_{d,022} = CFH10 \cdot \rho_{gas} \cdot (E_{004} - E_{024}) \quad (102)$$

$$P_{N,025} = P_{N,024} - 190 \quad \text{PRV - 200 psig to 10 psig} \quad (103)$$

$$E_{025} = Eph_{gas}(T, P_{N,025}) + 22150.23 \quad (104)$$

$$\dot{E}_{d,PRV4} = CFH10 \cdot \rho_{gas} \cdot (E_{024} - E_{025}) \quad (105)$$

Gas Pipe 023

$$K_{023} = 0.32 \cdot 2 \quad (106)$$

$$P_{N,026} = P_{N,025} - HL_{gas}(CFH10, T, P_{N,025}, 4, K_{023}, ff_{gas}(CFH10, T, P_{N,025}, 3), 3) \quad (107)$$

$$E_{026} = Eph_{gas}(T, P_{N,026}) + 22150.23 \quad (108)$$

$$\dot{E}_{d,023} = CFH10 \cdot \rho_{gas} \cdot (E_{025} - E_{026}) \quad (109)$$

$$P_{N,027} = P_{N,026} - 7 \quad \text{FCV - 10 psig to 3 psig} \quad (110)$$

$$E_{027} = Eph_{gas}(T, P_{N,027}) + 22150.23 \quad (111)$$

$$\dot{E}_{d,PRV5} = CFH10 \cdot \rho_{gas} \cdot (E_{026} - E_{027}) \quad (112)$$

Gas Pipe 024

$$K_{024} = 0.22 \cdot 2 + 0.14 \cdot 3 + 0.32 \cdot 1 \quad (113)$$

$$P_{N,028} = P_{N,027} - HL_{gas}(CFH10, T, P_{N,027}, 4, K_{023}, ff_{gas}(CFH10, T, P_{N,027}, 2.5), 2.5) \quad (114)$$

$$E_{028} = Eph_{gas}(T, P_{N,028}) + 22150.23 \quad (115)$$

$$\dot{E}_{d,024} = CFH10 \cdot \rho_{gas} \cdot (E_{027} - E_{028}) \quad (116)$$

$$\rho_{028} = \rho(\text{Methane}, T = T, P = (14.7)) \quad (117)$$

Gas Pipe 025

$$K_{025} = 0.22 \cdot 11 + 0.32 \cdot 1 \quad (118)$$

$$CFH11 = CFH4 - CFH5 \quad (119)$$

$$P_{N,029} = P_{N,005} - HL_{gas}(CFH11, T, P_{N,005}, 88, K_{025}, ff_{gas}(CFH11, T, P_{N,005}, 3), 3) \quad (120)$$

$$E_{029} = Eph_{gas}(T, P_{N,029}) + 22150.23 \quad (121)$$

$$\dot{E}_{d,025} = CFH11 \cdot \rho_{gas} \cdot (E_{005} - E_{029}) \quad (122)$$

$$P_{N,030} = P_{N,029} - 125 \quad \text{PRV - 200 psig to 75 psig} \quad (123)$$

$$E_{030} = Eph_{gas}(T, P_{N,030}) + 22150.23 \quad (124)$$

$$\dot{E}_{d,PRV6} = CFH11 \cdot \rho_{gas} \cdot (E_{029} - E_{030}) \quad (125)$$

$$P_{N,031} = P_{N,030} - 45 \quad \text{PRV - 75 psig to 30 psig} \quad (126)$$

$$E_{031} = Eph_{gas}(T, P_{N,031}) + 22150.23 \quad (127)$$

$$\dot{E}_{d,PRV7} = CFH11 \cdot \rho_{gas} \cdot (E_{030} - E_{031}) \quad (128)$$

Gas Pipe 026

$$K_{026} = 0.32 \cdot 1 \quad (129)$$

$$P_{N,032} = P_{N,031} - HL_{gas}(CFH11, T, P_{N,031}, 9, K_{026}, ff_{gas}(CFH11, T, P_{N,031}, 3), 3) \quad (130)$$

$$E_{032} = Eph_{gas}(T, P_{N,032}) + 22150.23 \quad (131)$$

$$\dot{E}_{d,026} = CFH11 \cdot \rho_{gas} \cdot (E_{031} - E_{032}) \quad (132)$$

$$P_{N,033} = P_{N,032} - 21 \quad \text{PRV - 30 psig to 9 psig} \quad (133)$$

$$E_{033} = Eph_{gas}(T, P_{N,033}) + 22150.23 \quad (134)$$

$$\dot{E}_{d,PRV8} = CFH11 \cdot \rho_{gas} \cdot (E_{032} - E_{033}) \quad (135)$$

Gas Pipe 027

$$K_{027} = 0.22 \cdot 2 + 0.14 \cdot 2 + 0.32 \cdot 1 \quad (136)$$

$$P_{N,034} = P_{N,033} - HL_{gas}(CFH11, T, P_{N,033}, 10, K_{027}, ff_{gas}(CFH11, T, P_{N,033}, 3), 3) \quad (137)$$

$$E_{034} = Eph_{gas}(T, P_{N,034}) + 22150.23 \quad (138)$$

$$\dot{E}_{d,027} = CFH11 \cdot \rho_{gas} \cdot (E_{033} - E_{034}) \quad (139)$$

Solution

$CFH1 = -9999$	$CFH10 = -9999$
$CFH11 = -9999$	$CFH2 = -9999$
$CFH3 = -9999$	$CFH4 = -9999$
$CFH5 = -9999$	$CFH6 = -9999$
$CFH7 = -9999$	$CFH8 = -9999$
$CFH9 = -9999$	$E_{001} = -9999$
$E_{002} = -9999$	$E_{003} = -9999$
$E_{004} = -9999$	$E_{005} = -9999$
$E_{006} = -9999$	$E_{007} = -9999$
$E_{008} = -9999$	$E_{009} = -9999$
$E_{011} = -9999$	$E_{012} = -9999$
$E_{013} = -9999$	$E_{014} = -9999$
$E_{015} = -9999$	$E_{016} = -9999$
$E_{017} = -9999$	$E_{018} = -9999$
$E_{019} = -9999$	$E_{020} = -9999$
$E_{021} = -9999$	$E_{021b} = -9999$
$E_{022} = -9999$	$E_{023} = -9999$
$E_{023b} = -9999$	$E_{024} = -9999$
$E_{025} = -9999$	$E_{026} = -9999$
$E_{027} = -9999$	$E_{028} = -9999$
$E_{029} = -9999$	$E_{030} = -9999$
$E_{031} = -9999$	$E_{032} = -9999$
$E_{033} = -9999$	$E_{034} = -9999$
$\dot{E}_{d,001} = -9999$	$\dot{E}_{d,002} = -9999$
$\dot{E}_{d,003} = -9999$	$\dot{E}_{d,004} = -9999$
$\dot{E}_{d,005} = -9999$	$\dot{E}_{d,006} = -9999$
$\dot{E}_{d,007} = -9999$	$\dot{E}_{d,008} = -9999$
$\dot{E}_{d,009} = -9999$	$\dot{E}_{d,010} = -9999$
$\dot{E}_{d,011} = -9999$	$\dot{E}_{d,012} = -9999$
$\dot{E}_{d,013} = -9999$	$\dot{E}_{d,014} = -9999$
$\dot{E}_{d,015} = -9999$	$\dot{E}_{d,016} = -9999$
$\dot{E}_{d,017} = -9999$	$\dot{E}_{d,019} = -9999$
$\dot{E}_{d,020} = -9999$	$\dot{E}_{d,021} = -9999$
$\dot{E}_{d,022} = -9999$	$\dot{E}_{d,023} = -9999$
$\dot{E}_{d,024} = -9999$	$\dot{E}_{d,025} = -9999$
$\dot{E}_{d,026} = -9999$	$\dot{E}_{d,027} = -9999$
$\dot{E}_{d,PRV1} = -9999$	$\dot{E}_{d,PRV2} = -9999$
$\dot{E}_{d,PRV3} = -9999$	$\dot{E}_{d,PRV4} = -9999$
$\dot{E}_{d,PRV5} = -9999$	$\dot{E}_{d,PRV6} = -9999$
$\dot{E}_{d,PRV7} = -9999$	$\dot{E}_{d,PRV8} = -9999$
$K_{001} = 2.55$	$K_{002} = 0.3$
$K_{003} = 0.3$	$K_{004} = 0.3$
$K_{005} = 0.3$	$K_{006} = 1.98$
$K_{007} = 0.9$	$K_{008} = 2.4$
$K_{009} = 0.86$	$K_{010} = 0.46$
$K_{011} = 1.75$	$K_{012} = 0$
$K_{013} = 0.78$	$K_{014} = 0.38$
$K_{015} = 0.38$	$K_{016} = 0.68$
$K_{017} = 0$	$K_{019} = 0.61$
$K_{020} = 0.68$	$K_{021} = 0$
$K_{022} = 0.32$	$K_{023} = 0.64$
$K_{024} = 1.18$	$K_{025} = 2.74$
$K_{026} = 0.32$	$K_{027} = 1.04$

$P_{N,001} = 200$ [psig]	$P_{N,002} = -9999$
$P_{N,003} = -9999$	$P_{N,004} = -9999$
$P_{N,005} = -9999$	$P_{N,006} = -9999$
$P_{N,007} = -9999$	$P_{N,008} = -9999$
$P_{N,009} = -9999$	$P_{N,011} = -9999$
$P_{N,012} = -9999$	$P_{N,013} = -9999$
$P_{N,014} = -9999$	$P_{N,015} = -9999$
$P_{N,016} = -9999$	$P_{N,017} = -9999$
$P_{N,018} = -9999$	$P_{N,019} = -9999$
$P_{N,020} = -9999$	$P_{N,021} = -9999$
$P_{N,021b} = -9999$	$P_{N,022} = -9999$
$P_{N,023} = -9999$	$P_{N,023b} = -9999$
$P_{N,024} = -9999$	$P_{N,025} = -9999$
$P_{N,026} = -9999$	$P_{N,027} = -9999$
$P_{N,028} = -9999$	$P_{N,029} = -9999$
$P_{N,030} = -9999$	$P_{N,031} = -9999$
$P_{N,032} = -9999$	$P_{N,033} = -9999$
$P_{N,034} = -9999$	$\rho_{012} = 0.04102$
$\rho_{028} = 0.04102$	$\rho_{gas} = 0.04102$
$T = 77$ [F]	

Equations

Deerator and Feed Pumps

Mass flow parametric values

\dot{m}_3 - Required Steam Flowrate

User created functions used:

Eph - Calculation of physical exergy of water in liquid or vapor state

Temperature and Pressure conditions

$$T_1 = 205 \text{ [F]} \quad \text{Temperature of feedwater entering deaerator} \quad (1)$$

$$P_1 = 21.7 \text{ [psia]} \quad \text{Operating pressure of deaerator tank} \quad (2)$$

$$T_2 = T_{\text{sat}}(\text{steam}, P = P_2) \quad \text{Temperature of entering steam} \quad (3)$$

$$P_2 = 21.7 \text{ [psia]} \quad \text{Pressure of entering steam} \quad (4)$$

$$T_3 = 227 \text{ [F]} \quad \text{Temperature of feedwater exiting deaerator} \quad (5)$$

$$P_3 = 30.4 \text{ [psia]} \quad \text{Pressure at suction side of feed pumps - 7 psig + 20' water column} \quad (6)$$

Enthalpies of inlet and outlet streams

$$h_1 = h(\text{steam}, T = T_1, P = P_1) \quad (7)$$

$$h_2 = h(\text{steam}, T = T_2, P = (P_2 - .1)) \quad (8)$$

$$h_3 = h(\text{steam}, T = T_3, P = P_3) \quad (9)$$

First Law balance for deaerator

$$\dot{Q}_{DA} = 0.05 \cdot \dot{m}_3 \cdot h_3 \quad 5\% \text{ heat loss from DA tank assumed} \quad (10)$$

$$\dot{m}_2 = \frac{\dot{m}_3 \cdot (h_3 - h_1) + \dot{Q}_{DA}}{(h_2 - h_3)} \quad \text{Required steam rate for DA - Energy balance equation} \quad (11)$$

$$\dot{m}_1 = \dot{m}_3 - \dot{m}_2 \quad \text{Continuity} \quad (12)$$

$$\eta_{da,i} = \frac{\dot{m}_3 \cdot h_3}{(\dot{m}_1 \cdot h_1 + \dot{m}_2 \cdot h_2)} \quad \text{First Law Efficiency for Deaerator Tank} \quad (13)$$

Physical exergies of inlet and outlet streams

$$\dot{E}_{1,ph} = \dot{m}_1 \cdot Eph(T_1, (P_1 - 14.5)) \quad (14)$$

$$\dot{E}_{2,ph} = \dot{m}_2 \cdot Eph(T_2, (P_2 - 14.5)) \quad (15)$$

$$\dot{E}_{3,ph} = \dot{m}_3 \cdot Eph(T_3, (P_3 - 14.5)) \quad (16)$$

Chemical exergies of inlet and outlet streams

$$\dot{E}_{1,ch} = \dot{m}_1 \cdot \left(\frac{45}{2.326 \cdot 18.02} \right) \quad \text{Chem. exergy of water entering converted to BTU/lb} \quad (17)$$

$$\dot{E}_{2,ch} = \dot{m}_2 \cdot \left(\frac{8636}{2.326 \cdot 18.02} \right) \quad \text{Chem. exergy of steam entering converted to BTU/lb} \quad (18)$$

$$\dot{E}_{3,ch} = \dot{m}_3 \cdot \left(\frac{45}{2.326 \cdot 18.02} \right) \quad \text{Chem. exergy of water leaving converted to BTU/lb} \quad (19)$$

Total exergy of inlet and outlet streams

$$\dot{E}_1 = \dot{E}_{1,ph} + \dot{E}_{1,ch} \quad (20)$$

$$\dot{E}_2 = \dot{E}_{2,ph} + \dot{E}_{2,ch} \quad (21)$$

$$\dot{E}_3 = \dot{E}_{3,ph} + \dot{E}_{3,ch} \quad (22)$$

$$\dot{E}_{recirc} = (\dot{m}_4 - \dot{m}_3) \cdot E_4 \quad (23)$$

Second Law Balance for deaerator

$$\dot{E}_{d1} = \dot{E}_1 + \dot{E}_2 + \dot{E}_{recirc} - \dot{E}_3 + (1 - (537/600)) \cdot \dot{Q}_{DA} \quad (24)$$

$$\eta_{da,ii} = \frac{\dot{E}_3}{(\dot{E}_1 + \dot{E}_2)} \quad \text{Second Law Efficiency for Deaerator Tank} \quad (25)$$

Boiler Feed Pumps

First Law Energy Balance of Feed Pumps - kinetic or potential energy effects neglected

$$P_4 = 463.2 \text{ [psia]} \quad \text{Discharge pressure from boiler feed pumps} \quad (26)$$

$$\dot{m}_4 = 40000 \quad \text{Mass flow rate through pump. Rem. recirculated} \quad (27)$$

$$Hyd_{hp,pump} = (\dot{m}_4/60) \cdot (P_4 - P_3) \cdot 2.31/33000 \quad \text{Pump Hydraulic horsepower} \quad (28)$$

$$BHP_{pump} = Hyd_{hp,pump}/0.85 \quad \text{Pump Brake Horsepower - assume eff. of 0.85} \quad (29)$$

$$\dot{W}_{pump} = BHP_{pump} \cdot 2544.53/0.9 \quad \text{BTU/hr input to pumps} \quad (30)$$

$$h_4 = h_3 - \frac{W_{in} - \dot{Q}}{\dot{m}_4} \quad (31)$$

$$T_4 = T(\text{steam}, h = h_4, P = P_4) \quad (32)$$

$$W_{in} = -\dot{W}_{pump} \quad (33)$$

$$\dot{Q} = - \left(\dot{W}_{pump} - (BHP_{pump} \cdot 0.85) \cdot 2544.53 \right) \quad (34)$$

$$\eta_{pump,i} = 0.85 \cdot 0.9 \quad \text{Given mechanical efficiency of pump} \quad (35)$$

Second Law Balance of Feed Pumps

$$E_3 = E_{ph}(T_3, (P_3 - 14.5)) + \dot{E}_{3,ch}/\dot{m}_3 \quad (36)$$

$$E_4 = Eph(T_4, (P_4 - 14.5)) + \dot{E}_{3,ch}/\dot{m}_3 \quad (37)$$

$$\dot{E}_{d2} = \dot{m}_4 \cdot (E_3 - E_4) - W_{in} \quad (38)$$

$$\eta_{pump,ii} = \dot{m}_4 \cdot \frac{E_4 - E_3}{(-W_{in})} \quad \text{Second Law Efficiency for Feed Pumps} \quad (39)$$

Total Exergy destruction from DA and Feed Pumps

$$\dot{E}_d = \dot{E}_{d1} + \dot{E}_{d2} \quad (40)$$

Steam Turbine Calc

Equations

Recommendation #1 - Insertion of Steam Back-Pressure Turbine

Parametric Input Values

$P_{N,026}$ = Turbine Exhaust Pressure (psig)

SR_t = Theoretical steam rate (lb/hp-hr)

User created functions used:

E_{ph} - Calculation of physical exergy of water liquid or vapor (BTU/lb)

$$\dot{m}_{11} = 18100 \quad \text{Steam Mass Flow Rate Entering Turbine} \quad (1)$$

$$P_{N,025} = 349.3 \text{ [psig]} \quad \text{Steam Pressure Entering Turbine from Steam Piping Losses Calculation} \quad (2)$$

$$T_{025} = 497.1 \text{ [F]} \quad \text{Superheated Steam Temperature Entering Turbine from Steam Piping Losses Calculation} \quad (3)$$

$$h_{025} = h(\text{steam}, T = T_{025}, P = (14.7 + P_{N,025})) \quad (4)$$

$$s_{025} = s(\text{steam}, T = T_{025}, P = (14.7 + P_{N,025})) \quad (5)$$

$$E_{025} = E_{ph}(T_{025}, P_{N,025}) + 206.15 \quad \text{Exergy of Entering Steam - Physical + Chemical} \quad (6)$$

$$T_{026} = T_{\text{sat}}(\text{steam}, P = (14.7 + P_{N,026})) \quad (7)$$

$$h_{026} = h(\text{steam}, T = T_{026}, P = (14.6 + P_{N,026})) \quad \text{Actual Exhaust Enthalpy} \quad (8)$$

$$h_{026,s} = h(\text{steam}, P = (14.7 + P_{N,026}), s = s_{025}) \quad \text{Isentropic Enthalpy} \quad (9)$$

$$E_{026} = E_{ph}(T_{026}, P_{N,026}) + 206.15 \quad \text{Exergy of Exiting Steam} \quad (10)$$

$$\eta_s = \frac{h_{025} - h_{026}}{h_{025} - h_{026,s}} \quad (11)$$

$$SR_a = SR_t / \eta_s \quad \text{Actual Steam Rate} \quad (12)$$

$$\dot{W}_{hp} = (\dot{m}_{11} / SR_a) \quad \text{Power Generation in horsepower} \quad (13)$$

$$\dot{W} = (\dot{m}_{11} / SR_a) \cdot 2544 \text{ [BTU/h]} \quad \text{Power Generation} \quad (14)$$

$$\dot{E}_{d,turbine} = \dot{m}_{11} \cdot (E_{025} - E_{026}) - \dot{W} \quad \text{Total Exergy Destruction of Steam Turbine} \quad (15)$$

Steam_piping losses

Equations

Steam Piping Losses

Parametric Input Values

\dot{m}_1 = Steam generated by blr. #5 (lb/hr)

\dot{m}_2 = Steam generated by HRSG #1 (lb/hr)

\dot{m}_3 = Steam to campus loop #1 (lb/hr)

\dot{m}_4 = Steam to campus loop #1 (lb/hr)

\dot{m}_{5a} = Steam to absorption chiller #9 (lb/hr)

\dot{m}_{5b} = Steam to absorption chiller #10 (lb/hr)

$\dot{m}_5 = \dot{m}_{5a} + \dot{m}_{5b}$ Steam to absorption chillers (lb/hr) (1)

\dot{m}_6 = Steam to old deaerator (lb/hr)

$\dot{m}_7 = \dot{m}_{14} - \dot{m}_{12}$ Steam to basement tunnel (lb/hr) (2)

$\dot{m}_8 = \dot{m}_4 - (\dot{m}_2 - \dot{m}_3)$

\dot{m}_{11} = Steam generated by HRSG #2 (lb/hr)

\dot{m}_{13} = Flash steam from Condensate Blowdown Tank (lb/hr)

\dot{m}_{15} = Steam to mechanical engineering building at 125 psig (lb/hr)

\dot{m}_{16} = Steam generated by Blr. #6

\dot{m}_{17} = Steam to new deaerator (lb/hr)

\dot{m}_{19} = Steam to campus loop #2 (lb/hr)

PS₀₀₁

steam header pressure

$P_{N,002} = 60$ [psig] lower steam header pressure - recommendation #2 (3)

$T_{002} = T_{\text{sat}}(\text{steam}, P = (14.7 + P_{N,002}))$ saturated steam temperature (F) (4)

$h_{002} = h(\text{steam}, T = T_{002}, P = (14.6 + P_{N,002}))$ (5)

$K_{001} = 0.17 \cdot 4 + 0.84 \cdot 1 + 0.11 \cdot 3$ K_{tot} of pipe PS₀₀₁ (6)

$P_{N,001} = P_{N,002} + HL_{\text{steam}}(\dot{m}_1, T_{001}, P_{N,001}, 28, K_{001}, ff_{\text{steam}}(\dot{m}_1, T_{001}, 8), 8)$ steam outlet pressure from Boiler #5 (7)

$T_{001} = T_{\text{sat}}(\text{steam}, P = (P_{N,001} + 14.7))$ (8)

$h_{001} = h(\text{steam}, T = T_{001}, P = (P_{N,001} + 14.6))$ (9)

$\dot{Q}_{001} = \dot{m}_1 \cdot (h_{002} - h_{001})$ (10)

$E_{001} = Eph(T_{001}, P_{N,001}) + 206.15$ physical + chemical exergy in BTU/lb (11)

$$E_{002} = Eph(T_{002}, P_{N,002}) + 206.15 \quad (12)$$

$$Eq_{001} = \dot{E}q(8, 28, T_{001}, \dot{Q}_{001}) \quad (13)$$

$$\dot{E}_{d,001} = \dot{m}_1 \cdot (E_{001} - E_{002}) - Eq_{001} \quad \text{Exergy destruction due to pressure drop in BTU/hr. No } E_{ch} \text{ change, with heat transfer(14)}$$

PS₀₀₂

$$P_{N,003} = 240 \text{ [psig]} \quad \text{steam outlet pressure from HRSG \#1} \quad (15)$$

$$T_{003} = T_{\text{sat}}(\text{water}, P = (14.7 + P_{N,003})) \quad (16)$$

$$h_{003} = h(\text{steam}, T = T_{003}, P = (14.6 + P_{N,003})) \quad (17)$$

$$K_{002} = 0.18 \cdot 4 + 0.3 \cdot 1 + 0.9 \cdot 2 + 0.12 \cdot 5 \quad K_{tot} \text{ of pipe PS}_{002} \quad (18)$$

$$P_{N,003a} = P_{N,003} - HL_{\text{steam}}(\dot{m}_2, T_{003}, P_{N,003}, 17, K_{002}, ff_{\text{steam}}(\dot{m}_2, T_{003}, 6), 6) \quad (19)$$

$$T_{003a} = T_{\text{sat}}(\text{water}, P = (14.7 + P_{N,003a})) \quad (20)$$

$$h_{003a} = h(\text{steam}, T = T_{003a}, P = (14.6 + P_{N,003a})) \quad (21)$$

$$\dot{Q}_{002} = \dot{m}_2 \cdot (h_{003} - h_{003a}) \quad (22)$$

$$E_{003} = Eph(T_{003}, P_{N,003}) + 206.15 \quad \text{physical + chemical exergy in BTU/lb} \quad (23)$$

$$E_{003a} = Eph(T_{003a}, P_{N,003a}) + 206.15 \quad (24)$$

$$Eq_{002} = \dot{E}q(6, 17, T_{003}, \dot{Q}_{002}) \quad (25)$$

$$\dot{E}_{d,002} = \dot{m}_2 \cdot (E_{003} - E_{003a}) - Eq_{002} \quad \text{Exergy destruction due to pressure drop in BTU/hr. No } E_{ch} \text{ change, with heat transfer(26)}$$

PRV-1

$$P_{N,004} = 125 \text{ [psig]}$$

$$P_{N,004} = 60 \text{ [psig]} \quad \text{Recommendation \#2 - lower steam header pressure} \quad (27)$$

$$h_{004} = h_{003a} \quad (28)$$

$$T_{004} = T(\text{steam}, h = h_{004}, P = (P_{N,004} + 14.7)) \quad (29)$$

$$E_{004} = Eph(T_{004}, P_{N,004}) + 206.15 \quad (30)$$

$$\dot{E}_{d,PRV1} = \dot{m}_2 \cdot (E_{003a} - E_{004}) \quad \text{Exergy destruction from PRV1} \quad (31)$$

Steam Header Piping is PS₀₀₃ to PS₀₀₉. Constant pressure assumed for header

PS₀₀₃

$$P_{N,005} = P_{N,004} \quad (32)$$

$$T_{005} = T_{\text{sat}}(\text{steam}, P = (P_{N,005} + 14.7)) \quad (33)$$

$$h_{005} = h(\text{steam}, T = T_{005}, P = (P_{N,005} + 14.6)) \quad (34)$$

$$E_{005} = Eph(T_{005}, P_{N,005}) + 206.15 \quad (35)$$

$$\dot{Q}_{003} = \dot{Q}(8, 6, T_{005}) \quad \mathbf{m}_{dot,2}^*(\mathbf{h}_{004}-\mathbf{h}_{005}) \quad (36)$$

$$Eq_{003} = \dot{E}q(8, 6, T_{005}, \dot{Q}_{003}) \quad (37)$$

$$\dot{E}_{d,003} = \dot{m}_2 \cdot (E_{004} - E_{005}) - Eq_{003} \quad (38)$$

PS₀₀₄

$$P_{N,006} = P_{N,005} \quad (39)$$

$$T_{006} = T_{005} \quad (40)$$

$$h_{006} = h_{005} \quad (41)$$

$$\dot{Q}_{004} = \dot{Q}(8, 1, T_{005}) \quad \mathbf{m}_{dot,3}^*(\mathbf{h}_{006}-\mathbf{h}_{005}) \quad (42)$$

$$E_{006} = Eph(T_{006}, P_{N,006}) + 206.15 \quad (43)$$

$$Eq_{004} = \dot{E}q(8, 1, T_{006}, \dot{Q}_{004}) \quad (44)$$

$$\dot{E}_{d,004} = \dot{m}_3 \cdot (E_{006} - E_{005}) - Eq_{004} \quad (45)$$

PS₀₀₅

$$P_{N,007} = P_{N,006} \quad (46)$$

$$T_{007} = T_{006} \quad (47)$$

$$h_{007} = h_{006} \quad (48)$$

$$\dot{Q}_{005} = \dot{Q}(8, 4, T_{005}) \quad \mathbf{m}_{dot,9}^*(\mathbf{h}_{007}-\mathbf{h}_{006}) \quad (49)$$

$$E_{007} = Eph(T_{007}, P_{N,007}) + 206.15 \quad (50)$$

$$Eq_{005} = \dot{E}q(8, 4, T_{007}, \dot{Q}_{005}) \quad (51)$$

$$\dot{E}_{d,005} = \dot{m}_9 \cdot (E_{007} - E_{006}) - Eq_{005} \quad (52)$$

PS₀₀₆

$$P_{N,008} = P_{N,007} \quad (53)$$

$$T_{008} = T_{007} \quad (54)$$

$$h_{008} = h_{007} \quad (55)$$

$$\dot{Q}_{006} = \dot{Q}(8, 1, T_{005}) \quad \mathbf{m}_{dot,9}^*(\mathbf{h}_{008}-\mathbf{h}_{007}) \quad (56)$$

$$E_{008} = Eph(T_{008}, P_{N,008}) + 206.15 \quad (57)$$

$$Eq_{006} = \dot{E}q(8, 1, T_{008}, \dot{Q}_{006}) \quad (58)$$

$$\dot{E}_{d,006} = \dot{m}_9 \cdot (E_{008} - E_{007}) - Eq_{006} \quad (59)$$

PS₀₀₇

$$\dot{Q}_{007} = \dot{Q}(8, 1, T_{005}) \quad \mathbf{m}_{dot,9}^*(\mathbf{h}_{002}-\mathbf{h}_{008}) \quad (60)$$

$$Eq_{007} = \dot{E}q(8, 1, T_{008}, \dot{Q}_{007}) \quad (61)$$

$$\dot{E}_{d,007} = \dot{m}_9 \cdot (E_{002} - E_{008}) - Eq_{007} \quad (62)$$

PS₀₀₈

$$P_{N,009} = P_{N,002} \quad (63)$$

$$T_{009} = T_{002} \quad (64)$$

$$h_{009} = h_{002} \quad (65)$$

$$\dot{Q}_{008} = \dot{Q}(8, 3, T_{005}) \quad \mathbf{m}_{dot,10} * (\mathbf{h}_{009} - \mathbf{h}_{002}) \quad (66)$$

$$E_{009} = Eph(T_{009}, P_{N,009}) + 206.15 \quad (67)$$

$$Eq_{008} = \dot{E}q(8, 3, T_{009}, \dot{Q}_{008}) \quad (68)$$

$$\dot{E}_{d,008} = \dot{m}_{10} \cdot (E_{009} - E_{002}) - Eq_{008} \quad (69)$$

PS₀₀₉

$$P_{N,010} = P_{N,009} \quad (70)$$

$$T_{010} = T_{009} \quad (71)$$

$$h_{010} = h_{009} \quad (72)$$

$$\dot{Q}_{009} = \dot{Q}(8, 6, T_{005}) \quad \mathbf{m}_{dot,7} * (\mathbf{h}_{010} - \mathbf{h}_{009}) \quad (73)$$

$$E_{010} = Eph(T_{010}, P_{N,010}) + 206.15 \quad (74)$$

$$Eq_{009} = \dot{E}q(8, 6, T_{010}, \dot{Q}_{009}) \quad (75)$$

$$\dot{E}_{d,009} = \dot{m}_7 \cdot (E_{010} - E_{009}) - Eq_{009} \quad (76)$$

PS₀₁₀

$$K_{010} = 0 \quad (77)$$

$$P_{N,011} = P_{N,010} \quad + \mathbf{HL}_{steam}(\mathbf{m}_{dot,7}, \mathbf{T}_{010}, \mathbf{P}_{N,010}, 20, \mathbf{K}_{010}, \mathbf{ff}_{steam}(\mathbf{m}_{dot,7}, \mathbf{T}_{010}, 8), 8) \quad (78)$$

$$T_{011} = T_{sat}(steam, \mathbf{P} = (14.7 + P_{N,011})) \quad (79)$$

$$h_{011} = h(steam, \mathbf{T} = T_{011}, \mathbf{P} = (14.6 + P_{N,011})) \quad (80)$$

$$\dot{Q}_{010} = \dot{m}_7 \cdot (h_{011} - h_{010}) \quad (81)$$

$$E_{011} = Eph(T_{011}, P_{N,011}) + 206.15 \quad (82)$$

$$Eq_{010} = \dot{E}q(8, 20, T_{010}, \dot{Q}_{010}) \quad (83)$$

$$\dot{E}_{d,010} = \dot{m}_7 \cdot (E_{011} - E_{010}) - Eq_{010} \quad (84)$$

PS₀₁₁

$$K_{011} = 1 \cdot 0.26 + 3 \cdot 0.16 \quad (85)$$

$$\dot{m}_{12} = \dot{m}_{19} + \mathbf{m}_{dot,8} \quad (86)$$

$$P_{N,012} = P_{N,011} - HL_{steam}(\dot{m}_{12}, T_{011}, P_{N,011}, 125, K_{011}, ff_{steam}(\dot{m}_{12}, T_{011}, 12), 12) \quad (87)$$

$$T_{012} = T_{sat}(steam, \mathbf{P} = (14.7 + P_{N,012})) \quad (88)$$

$$h_{012} = h(steam, \mathbf{T} = T_{012}, \mathbf{P} = (14.6 + P_{N,012})) \quad (89)$$

$$\dot{Q}_{011} = \dot{m}_{12} \cdot (h_{012} - h_{011}) \quad (90)$$

$$Eq_{011} = \dot{E}q(12, 125, T_{011}, \dot{Q}_{011}) \quad (91)$$

$$E_{012} = Eph(T_{012}, P_{N,012}) + 206.15 \quad (92)$$

$$\dot{E}_{d,011} = \dot{m}_{12} \cdot (E_{011} - E_{012}) - Eq_{011} \quad (93)$$

PS₀₁₂

$$K_{012} = 1 \cdot 0.36 + 2 \cdot 0.14 \quad (94)$$

$$P_{N,013} = P_{N,005} - HL_{steam}(\dot{m}_3, T_{005}, P_{N,005}, 1, K_{012}, ff_{steam}(\dot{m}_3, T_{005}, 3), 3) \quad (95)$$

$$T_{013} = T_{sat}(steam, \mathbf{P} = (14.7 + P_{N,013})) \quad (96)$$

$$h_{013} = h(steam, \mathbf{T} = T_{013}, \mathbf{P} = (14.6 + P_{N,013})) \quad (97)$$

$$\dot{Q}_{012} = \dot{m}_3 \cdot (h_{013} - h_{005}) \quad (98)$$

$$Eq_{012} = \dot{E}q(3, 1, T_{005}, \dot{Q}_{012}) \quad (99)$$

$$E_{013} = Eph(T_{013}, P_{N,013}) + 206.15 \quad (100)$$

$$\dot{E}_{d,012} = \dot{m}_3 \cdot (E_{005} - E_{013}) - Eq_{012} \quad (101)$$

PS₀₁₃

$$K_{013} = 1 \cdot 0.18 + 1 \cdot 0.30 + 2 \cdot 0.12 \quad (102)$$

$$P_{N,014} = P_{N,006} - HL_{steam}(\dot{m}_4, T_{006}, P_{N,006}, 2, K_{013}, ff_{steam}(\dot{m}_4, T_{006}, 6), 6) \quad (103)$$

$$T_{014} = T_{sat}(steam, \mathbf{P} = (14.7 + P_{N,014})) \quad (104)$$

$$h_{014} = h(steam, \mathbf{T} = T_{014}, \mathbf{P} = (14.6 + P_{N,014})) \quad (105)$$

$$\dot{Q}_{013} = \dot{m}_4 \cdot (h_{014} - h_{006}) \quad (106)$$

$$Eq_{013} = \dot{E}q(6, 2, T_{006}, \dot{Q}_{013}) \quad (107)$$

$$E_{014} = Eph(T_{014}, P_{N,014}) + 206.15 \quad (108)$$

$$\dot{E}_{d,013} = \dot{m}_4 \cdot (E_{006} - E_{014}) - Eq_{013} \quad (109)$$

PRV-2

$$P_{N,015} = 60 \text{ [psig]}$$

$$P_{N,015} = P_{N,013} \quad \text{Recommendation \#2 - no reduction in pressure to campus loop \#1} \quad (110)$$

$$h_{015} = h_{013} \quad \text{enthalpy(steam, T = } T_{\text{sat}}(\text{steam, P = (14.7+P}_{N,015}), \text{ P = (14.6+P}_{N,015})) \quad (111)$$

$$T_{015} = \text{temperature(steam, h = } h_{015}, \text{ P = (P}_{N,015}+14.7))$$

$$T_{015} = T_{013} \quad \text{Recommendation \#2 - no reduction in temperature across PRV to campus loop \#1} \quad (112)$$

$$E_{015} = \text{Eph}(T_{015}, P_{N,015}) + 206.15 \quad (113)$$

$$\dot{E}_{d,PRV2} = \dot{m}_3 \cdot (E_{013} - E_{015}) \quad \text{Exergy destruction from PRV2} \quad (114)$$

PRV-3

$$\dot{E}_{d,PRV3} = \dot{m}_4 \cdot (E_{014} - E_{015}) \quad \text{Exergy destruction from PRV3} \quad (115)$$

PS014

$$K_{014} = 1 \cdot 0.17 \quad (116)$$

$$P_{N,016} = P_{N,015} - \text{HL}_{\text{steam}}(\dot{m}_9, T_{015}, P_{N,015}, 1, K_{014}, \text{ff}_{\text{steam}}((\dot{m}_3 + \dot{m}_4), T_{015}, 8), 8) \quad (117)$$

$$\dot{Q}_{014} = \dot{Q}(8,1,T_{015})$$

$$h_{016} = h_{015} + \dot{Q}_{014}/\dot{m}_9$$

$$T_{016} = \text{Temperature(steam, h = } h_{016}, \text{ P = (14.7+P}_{N,016}))$$

$$T_{016} = T_{\text{sat}}(\text{steam, P = (14.7 + P}_{N,016})) \quad (118)$$

$$h_{016} = \text{h(steam, T = } T_{016}, \text{ P = (14.6 + P}_{N,016})) \quad (119)$$

$$\dot{Q}_{014} = \dot{m}_9 \cdot (h_{016} - h_{015}) \quad (120)$$

$$Eq_{014} = \dot{E}q(8, 1, T_{015}, \dot{Q}_{014}) \quad (121)$$

$$E_{016} = \text{Eph}(T_{016}, P_{N,016}) + 206.15 \quad (122)$$

$$\dot{E}_{d,014} = \dot{m}_9 \cdot (E_{015} - E_{016}) - Eq_{014} \quad (123)$$

PS015

$$K_{015} = 2 \cdot 0.18 + 2 \cdot 0.12 \quad (124)$$

$$P_{N,017} = P_{N,007} - \text{HL}_{\text{steam}}(\dot{m}_5, T_{007}, P_{N,007}, 4, K_{015}, \text{ff}_{\text{steam}}(\dot{m}_5, T_{007}, 6), 6) \quad (125)$$

$$T_{017} = T_{\text{sat}}(\text{steam, P = (14.7 + P}_{N,017})) \quad (126)$$

$$h_{017} = \text{h(steam, T = } T_{017}, \text{ P = (14.6 + P}_{N,017})) \quad (127)$$

$$\dot{Q}_{015} = \dot{Q}(6, 4, T_{008}) \quad \mathbf{m}_{\text{dot},5} \cdot (h_{007} - h_{017}) \quad (128)$$

$$Eq_{015} = \dot{E}q(6, 4, T_{007}, \dot{Q}_{015}) \quad (129)$$

$$E_{017} = \text{Eph}(T_{017}, P_{N,017}) + 206.15 \quad (130)$$

$$\dot{E}_{d,015} = \dot{m}_5 \cdot (E_{008} - E_{017}) - Eq_{015} \quad (131)$$

PS016

$$K_{016} = 10 \cdot 0.20 + 2 \cdot 0.14 + 1 \cdot 0.34 \quad (132)$$

$$P_{N,018} = P_{N,009} - HL_{steam}(\dot{m}_6, T_{009}, P_{N,009}, 75, K_{016}, ff_{steam}(\dot{m}_6, T_{009}, 4), 4) \quad (133)$$

$$T_{018} = T_{\text{sat}}(steam, \mathbf{P} = (14.7 + P_{N,018})) \quad (134)$$

$$h_{018} = h(steam, \mathbf{T} = T_{018}, \mathbf{P} = (14.6 + P_{N,018})) \quad (135)$$

$$\dot{Q}_{016} = \dot{m}_6 \cdot (h_{018} - h_{009}) \quad (136)$$

$$Eq_{016} = \dot{E}q(4, 75, T_{009}, \dot{Q}_{016}) \quad (137)$$

$$E_{018} = Eph(T_{018}, P_{N,018}) + 206.15 \quad (138)$$

$$\dot{E}_{d,016} = \dot{m}_6 \cdot (E_{009} - E_{018}) - Eq_{016} \quad (139)$$

PRV-4

$$P_{N,019} = 7 \text{ [psig]} \quad (140)$$

$$T_{019} = T_{\text{sat}}(steam, \mathbf{P} = (P_{N,019} + 14.7)) \quad (141)$$

$$h_{019} = h(steam, \mathbf{T} = T_{019}, \mathbf{P} = (14.6 + P_{N,019})) \quad (142)$$

$$E_{019} = Eph(T_{019}, P_{N,019}) + 206.15 \quad (143)$$

$$\dot{E}_{d,PRV4} = \dot{m}_6 \cdot (E_{018} - E_{019}) \quad \text{Exergy destruction from PRV4} \quad (144)$$

PS017

$$K_{017} = 1 \cdot 0.18 + 1 \cdot 0.12 \quad (145)$$

$$P_{N,020} = P_{N,019} - HL_{steam}(\dot{m}_6, T_{019}, P_{N,019}, 20, K_{017}, ff_{steam}(\dot{m}_6, T_{019}, 6), 6) \quad (146)$$

$$T_{020} = T_{\text{sat}}(steam, \mathbf{P} = (14.7 + P_{N,020})) \quad (147)$$

$$h_{020} = h(steam, \mathbf{T} = T_{020}, \mathbf{P} = (14.6 + P_{N,020})) \quad (148)$$

$$\dot{Q}_{017} = \dot{m}_6 \cdot (h_{020} - h_{019}) \quad (149)$$

$$Eq_{017} = \dot{E}q(6, 20, T_{019}, \dot{Q}_{017}) \quad (150)$$

$$E_{020} = Eph(T_{020}, P_{N,020}) + 206.15 \quad (151)$$

$$\dot{E}_{d,017} = \dot{m}_6 \cdot (E_{019} - E_{020}) - Eq_{017} \quad (152)$$

PS018

$$K_{018} = 0 \quad (153)$$

$$P_{N,021} = P_{N,020} - HL_{steam}((\dot{m}_6 + \dot{m}_{13}), T_{020}, P_{N,020}, 1, K_{018}, ff_{steam}((\dot{m}_6 + \dot{m}_{13}), T_{020}, 6), 6) \quad (154)$$

$$T_{021} = T_{\text{sat}}(steam, \mathbf{P} = (14.7 + P_{N,021})) \quad (155)$$

$$h_{021} = h(steam, \mathbf{T} = T_{021}, \mathbf{P} = (14.6 + P_{N,021})) \quad (156)$$

$$\dot{Q}_{018} = (\dot{m}_6 + \dot{m}_{13}) \cdot (h_{021} - h_{020}) \quad (157)$$

$$Eq_{018} = \dot{E}q(6, 1, T_{020}, \dot{Q}_{018}) \quad (158)$$

$$E_{021} = Eph(T_{021}, P_{N,021}) + 206.15 \quad (159)$$

$$\dot{E}_{d,018} = (\dot{m}_6 + \dot{m}_{13}) \cdot (E_{020} - E_{021}) - Eq_{018} \quad (160)$$

PS019

$$P_{N,022} = 350 \text{ [psig]} \quad \text{steam outlet pressure from HRSG \#2 - Fired (psig)} \quad (161)$$

$$T_{022} = 500 \text{ [F]} \quad \text{Duct Burner unfired temp at outlet of HRSG \#2} \quad (162)$$

$$h_{022} = h(\text{steam}, T = T_{022}, P = (14.7 + P_{N,022})) \quad (163)$$

$$K_{019} = 11 \cdot 0.18 + 2 \cdot 0.9 + 2 \cdot 0.12 \quad K_{tot} \text{ of pipe PS019} \quad (164)$$

$$P_{N,023} = P_{N,022} - HL_{steam}(\dot{m}_{11}, T_{022}, P_{N,022}, 157, K_{019}, ff_{steam}(\dot{m}_{11}, T_{022}, 6), 6) \quad (165)$$

$$\dot{Q}_{019} = \dot{Q}(6, 157, T_{022}) \quad (166)$$

$$h_{023} = h_{022} + \dot{Q}_{019}/\dot{m}_{11} \quad (167)$$

$$T_{023} = T(\text{steam}, h = h_{023}, P = (14.7 + P_{N,023})) \quad (168)$$

$$E_{022} = Eph(T_{022}, P_{N,022}) + 206.15 \quad \text{physical + chemical exergy in BTU/lb} \quad (169)$$

$$Eq_{019} = \dot{E}q(6, 157, T_{022}, \dot{Q}_{019}) \quad (170)$$

$$E_{023} = Eph(T_{023}, P_{N,023}) + 206.15 \quad (171)$$

$$\dot{E}_{d,019} = \dot{m}_{11} \cdot (E_{022} - E_{023}) - Eq_{019} \quad (172)$$

PRV-5

Exergy destruction from PRV5

PS020

$$K_{020} = 3 \cdot 0.17 \quad (173)$$

$$P_{N,025} = P_{N,023} - HL_{steam}(\dot{m}_{11}, T_{023}, P_{N,023}, 20, K_{020}, ff_{steam}(\dot{m}_{11}, T_{023}, 8), 8) \quad (174)$$

$$\dot{Q}_{020} = \dot{Q}(8, 20, T_{023}) \quad (175)$$

$$Eq_{020} = \dot{E}q(8, 20, T_{023}, \dot{Q}_{020}) \quad (176)$$

$$h_{025} = h_{023} + \dot{Q}_{020}/\dot{m}_{11} \quad \text{enthalpy at node 21 after heat transfer} \quad (177)$$

$$T_{025} = T(\text{steam}, h = h_{025}, P = (P_{N,025} + 14.7)) \quad (178)$$

$$E_{025} = Eph(T_{025}, P_{N,025}) + 206.15 \quad (179)$$

$$\dot{E}_{d,020} = \dot{m}_{11} \cdot (E_{023} - E_{025}) - Eq_{020} \quad (180)$$

PS021

$$h_{027} = 196 \quad \text{enthalpy of water entering desuperheater at 227 F (BTU/lb)} \quad (181)$$

$$T_{026} = T_{sat}(\text{steam}, P = (P_{N,026} + 14.7)) \quad (182)$$

$$h_{026} = h(\text{steam}, T = T_{026}, P = (P_{N,026} + 14.6)) \quad (183)$$

mass and energy balance - existing

$$\dot{m}_{14} = \dot{m}_{11} \quad \text{mass balance - steam turbine option} \quad (184)$$

$$K_{021} = 2 \cdot 0.17 + 1 \cdot 0.09 + 1 \cdot 0.11 \quad (185)$$

$$P_{N,026} = P_{N,011} + HL_{\text{steam}}(\dot{m}_{14}, T_{011}, P_{N,026}, 85, K_{021}, ff_{\text{steam}}(\dot{m}_{14}, T_{011}, 8), 8) \quad (186)$$

$$\dot{Q}_{021} = \dot{m}_{14} \cdot (h_{011} - h_{026}) \quad (187)$$

$$Eq_{021} = \dot{E}q(8, 85, T_{026}, \dot{Q}_{021}) \quad (188)$$

$$E_{026} = Eph(T_{026}, P_{N,026}) + 206.15 \quad (189)$$

$$\dot{E}_{d,021} = \dot{m}_{14} \cdot (E_{026} - E_{011}) - Eq_{021} \quad \text{Pipe terminates at node 11, end of PS}_{010} \quad (190)$$

Desuperheater Valve

Exergy destruction from desuperheater

PS022

$$K_{022} = 1 \cdot 0.18 \quad (191)$$

$$P_{N,028} = P_{N,017} - HL_{\text{steam}}(\dot{m}_5, T_{017}, P_{N,017}, 40, K_{022}, ff_{\text{steam}}(\dot{m}_5, T_{017}, 6), 6) \quad (192)$$

$$T_{028} = T_{\text{sat}}(\text{steam}, P = (14.7 + P_{N,028})) \quad (193)$$

$$h_{028} = h(\text{steam}, T = T_{028}, P = (14.6 + P_{N,028})) \quad (194)$$

$$\dot{Q}_{022} = \dot{Q}(6, 40, T_{017}) \quad \dot{m}_{dot,5} \cdot (h_{017} - h_{028}) \quad (195)$$

$$Eq_{022} = \dot{E}q(6, 40, T_{017}, \dot{Q}_{022}) \quad (196)$$

$$E_{028} = Eph(T_{028}, P_{N,028}) + 206.15 \quad (197)$$

$$\dot{E}_{d,022} = \dot{m}_5 \cdot (E_{017} - E_{028}) - Eq_{022} \quad (198)$$

PS023

$$K_{023} = 6 \cdot 0.18 + 1 \cdot 0.90 + 2 \cdot 0.12 \quad (199)$$

$$P_{N,029} = P_{N,028} - HL_{\text{steam}}(\dot{m}_{5a}, T_{028}, P_{N,028}, 33, K_{023}, ff_{\text{steam}}(\dot{m}_{5a}, T_{028}, 6), 6) \quad (200)$$

$$T_{029} = T_{\text{sat}}(\text{steam}, P = (14.7 + P_{N,029})) \quad (201)$$

$$h_{029} = h(\text{steam}, T = T_{029}, P = (14.6 + P_{N,029})) \quad (202)$$

$$\dot{Q}_{023} = \dot{Q}(6, 33, T_{028}) \quad \dot{m}_{dot,5a} \cdot (h_{028} - h_{029}) \quad (203)$$

$$Eq_{023} = \dot{E}q(6, 33, T_{028}, \dot{Q}_{023}) \quad (204)$$

$$E_{029} = Eph(T_{029}, P_{N,029}) + 206.15 \quad (205)$$

$$\dot{E}_{d,023} = \dot{m}_{5a} \cdot (E_{028} - E_{029}) - Eq_{023} \quad (206)$$

PS024

$$K_{024} = 5 \cdot 0.18 + 2 \cdot 0.09 + 3 \cdot 0.12 \quad (207)$$

$$P_{N,030} = P_{N,028} - HL_{steam}(\dot{m}_{5b}, T_{028}, P_{N,028}, 72, K_{024}, ff_{steam}(\dot{m}_{5b}, T_{028}, 6), 6) \quad (208)$$

$$T_{030} = T_{sat}(steam, P = (14.7 + P_{N,030})) \quad (209)$$

$$h_{030} = h(steam, T = T_{030}, P = (14.6 + P_{N,030})) \quad (210)$$

$$\dot{Q}_{024} = \dot{Q}(6, 72, T_{028}) \quad \dot{m}_{dot,5b} \cdot (h_{028} - h_{030}) \quad (211)$$

$$Eq_{024} = \dot{E}q(6, 72, T_{028}, \dot{Q}_{024}) \quad (212)$$

$$E_{030} = Eph(T_{030}, P_{N,030}) + 206.15 \quad (213)$$

$$\dot{E}_{d,024} = \dot{m}_{5b} \cdot (E_{028} - E_{030}) - Eq_{024} \quad (214)$$

PS025

$$K_{025} = 7 \cdot 0.18 + 2 \cdot 0.09 + 1 \cdot 0.12 \quad (215)$$

$$P_{N,031} = P_{N,020} + HL_{steam}(\dot{m}_{13}, T_{020}, P_{N,020}, 100, K_{025}, ff_{steam}(\dot{m}_{13}, T_{020}, 6), 6) \quad (216)$$

$$T_{031} = T_{sat}(steam, P = (14.7 + P_{N,031})) \quad (217)$$

$$h_{031} = h(steam, T = T_{031}, P = (14.6 + P_{N,031})) \quad \text{enthalpy at node 31} \quad (218)$$

$$\dot{Q}_{025} = \dot{m}_{13} \cdot (h_{020} - h_{031}) \quad (219)$$

$$Eq_{025} = \dot{E}q(6, 100, T_{020}, \dot{Q}_{025}) \quad (220)$$

$$E_{031} = Eph(T_{031}, P_{N,031}) + 206.15 \quad (221)$$

$$\dot{E}_{d,025} = \dot{m}_{13} \cdot (E_{031} - E_{020}) - Eq_{025} \quad (222)$$

PS026

$$\dot{m}_{18} = \dot{m}_{16} - \dot{m}_{17} \quad (223)$$

$$K_{026} = 5 \cdot 0.17 + 2 \cdot 0.09 + 1 \cdot 0.11 \quad (224)$$

$$P_{N,032} = P_{N,012} + HL_{steam}(\dot{m}_{18}, T_{012}, P_{N,012}, 43, K_{026}, ff_{steam}(\dot{m}_{18}, T_{012}, 8), 8) \quad (225)$$

$$T_{032} = T_{sat}(steam, P = (14.7 + P_{N,032})) \quad (226)$$

$$h_{032} = h(steam, T = T_{032}, P = (14.6 + P_{N,032})) \quad (227)$$

$$\dot{Q}_{026} = \dot{m}_{18} \cdot (h_{032} - h_{012}) \quad (228)$$

$$Eq_{026} = \dot{E}q(8, 43, T_{032}, \dot{Q}_{026}) \quad (229)$$

$$E_{032} = Eph(T_{032}, P_{N,032}) + 206.15 \quad (230)$$

$$\dot{E}_{d,026} = \dot{m}_{18} \cdot (E_{032} - E_{012}) - Eq_{026} \quad (231)$$

PS027

$$K_{027} = 3 \cdot 0.2 + 2 \cdot 0.14 \quad (232)$$

$$P_{N,033} = P_{N,032} - HL_{steam}(\dot{m}_{17}, T_{032}, P_{N,032}, 22, K_{027}, ff_{steam}(\dot{m}_{17}, T_{032}, 4), 4) \quad (233)$$

$$T_{033} = T_{sat}(steam, P = (14.7 + P_{N,033})) \quad (234)$$

$$h_{033} = h(steam, T = T_{033}, P = (14.6 + P_{N,033})) \quad (235)$$

$$\dot{Q}_{027} = \dot{m}_{17} \cdot (h_{032} - h_{033}) \quad (236)$$

$$Eq_{027} = \dot{E}q(4, 22, T_{033}, \dot{Q}_{027}) \quad (237)$$

$$E_{033} = Eph(T_{033}, P_{N,033}) + 206.15 \quad (238)$$

$$\dot{E}_{d,027} = \dot{m}_{17} \cdot (E_{032} - E_{033}) - Eq_{027} \quad (239)$$

PRV-6

$$P_{N,034} = 7 \text{ [psig]} \quad (240)$$

$$h_{034} = h_{033} \quad (241)$$

$$T_{034} = T(steam, h = h_{034}, P = (P_{N,034} + 14.7)) \quad (242)$$

$$E_{034} = Eph(T_{034}, P_{N,034}) + 206.15 \quad (243)$$

$$\dot{E}_{d,PRV6} = \dot{m}_{17} \cdot (E_{033} - E_{034}) \quad \text{Exergy destruction from PRV6} \quad (244)$$

PS028

$$K_{028} = 3 \cdot 0.18 + 1 \cdot 0.90 + 1 \cdot 0.12 \quad (245)$$

$$P_{N,035} = P_{N,034} - HL_{steam}(\dot{m}_{17}, T_{034}, P_{N,034}, 10, K_{028}, ff_{steam}(\dot{m}_{17}, T_{034}, 6), 6) \quad (246)$$

$$\dot{Q}_{028} = 0 \quad Q_{dot}(6, 10, T_{034}) \quad (247)$$

$$h_{035} = h_{034} + \frac{\dot{Q}_{028}}{(\dot{m}_{17} + 0.0001)} \quad (248)$$

$$T_{035} = T(steam, h = h_{035}, P = (P_{N,035} + 14.7)) \quad (249)$$

$$Eq_{028} = \dot{E}q(6, 10, T_{034}, \dot{Q}_{028}) \quad (250)$$

$$E_{035} = Eph(T_{035}, P_{N,035}) + 206.15 \quad (251)$$

$$\dot{E}_{d,028} = \dot{m}_{17} \cdot (E_{034} - E_{035}) - Eq_{028} \quad (252)$$

PS029

$$K_{029} = 3 \cdot 0.17 + 1 \cdot 2.1 + 2 \cdot 0.11 \quad (253)$$

$$P_{N,036} = P_{N,032} + HL_{steam}(\dot{m}_{16}, T_{032}, P_{N,032}, 35, K_{029}, ff_{steam}(\dot{m}_{16}, T_{032}, 8), 8) \quad \text{Pressure Leaving Blr. #6(254)}$$

$$T_{036} = T_{sat}(steam, P = (P_{N,036} + 14.7)) \quad (255)$$

$$h_{036} = h(steam, T = T_{036}, P = (14.6 + P_{N,036})) \quad (256)$$

$$\dot{Q}_{029} = \dot{m}_{16} \cdot (h_{036} - h_{032}) \quad (257)$$

$$Eq_{029} = \dot{E}q(8, 35, T_{032}, \dot{Q}_{029}) \quad (258)$$

$$E_{036} = Eph(T_{036}, P_{N,036}) + 206.15 \quad (259)$$

$$\dot{E}_{d,029} = \dot{m}_{16} \cdot (E_{036} - E_{032}) - Eq_{029} \quad (260)$$

PS030

$$K_{030} = 2 \cdot 0.10 \quad (261)$$

$$P_{N,037} = P_{N,012} - HL_{steam}(\dot{m}_{19}, T_{012}, P_{N,012}, 18, K_{030}, ff_{steam}(\dot{m}_{19}, T_{012}, 8), 8) \quad (262)$$

$$T_{037} = T_{sat}(steam, P = (14.7 + P_{N,037})) \quad (263)$$

$$h_{037} = h(steam, T = T_{037}, P = (14.6 + P_{N,037})) \quad (264)$$

$$\dot{Q}_{030} = \dot{m}_{19} \cdot (h_{037} - h_{012}) \quad (265)$$

$$Eq_{030} = \dot{E}q(8, 18, T_{037}, \dot{Q}_{030}) \quad (266)$$

$$E_{037} = Eph(T_{037}, P_{N,037}) + 206.15 \quad (267)$$

$$\dot{E}_{d,030} = \dot{m}_{19} \cdot (E_{012} - E_{037}) - Eq_{030} \quad (268)$$

PRV-7

$$P_{N,038} = 60 \text{ [psig]}$$

$$P_{N,038} = P_{N,037} \quad \text{Recommendation \#2 - no pressure reduction prior to being sent out to campus loop \#2} \quad (269)$$

$$h_{038} = h_{037} \quad (270)$$

$$T_{038} = \text{temperature}(steam, h = h_{038}, P = (P_{N,038} + 14.7))$$

$$T_{038} = T_{037} \quad \text{Recommendation \#2 - no temperature reduction across PRV to campus loop \#2} \quad (271)$$

$$E_{038} = Eph(T_{038}, P_{N,038}) + 206.15 \quad (272)$$

$$\dot{E}_{d,PRV7} = \dot{m}_{19} \cdot (E_{037} - E_{038}) \quad \text{Exergy destruction from PRV7} \quad (273)$$

PS031

$$K_{031} = 2 \cdot 0.17 + 3 \cdot 0.11 \quad (274)$$

$$P_{N,039} = P_{N,038} - HL_{steam}(\dot{m}_{19}, T_{038}, P_{N,038}, 119, K_{031}, ff_{steam}(\dot{m}_{19}, T_{038}, 8), 8) \quad (275)$$

$$\dot{Q}_{031} = \dot{Q}(8, 119, T_{038})$$

$$h_{039} = h_{038} + \dot{Q}_{031}/\dot{m}_{19}$$

$$T_{039} = \text{Temperature}(steam, h = h_{039}, P = (14.7 + P_{N,039}))$$

$$T_{039} = T_{sat}(steam, P = (P_{N,039} + 14.7)) \quad (276)$$

$$h_{039} = h(steam, T = T_{039}, P = (14.6 + P_{N,039})) \quad (277)$$

$$\dot{Q}_{031} = \dot{m}_{19} \cdot (h_{039} - h_{038}) \quad (278)$$

$$Eq_{031} = \dot{E}q(8, 119, T_{038}, \dot{Q}_{031}) \quad (279)$$

$$E_{039} = Eph(T_{039}, P_{N,039}) + 206.15 \quad (280)$$

$$\dot{E}_{d,031} = \dot{m}_{19} \cdot (E_{038} - E_{039}) - Eq_{031} \quad (281)$$

Solution

$Eq_{001} = -9999$	$Eq_{002} = -9999$
$Eq_{003} = -9999$	$Eq_{004} = -9999$
$Eq_{005} = -9999$	$Eq_{006} = -9999$
$Eq_{007} = -9999$	$Eq_{008} = -9999$
$Eq_{009} = -9999$	$Eq_{010} = -9999$
$Eq_{011} = -9999$	$Eq_{012} = -9999$
$Eq_{013} = -9999$	$Eq_{014} = -9999$
$Eq_{015} = -9999$	$Eq_{016} = -9999$
$Eq_{017} = -9999$	$Eq_{018} = -9999$
$Eq_{019} = -9999$	$Eq_{020} = -9999$
$Eq_{021} = -9999$	$Eq_{022} = -9999$
$Eq_{023} = -9999$	$Eq_{024} = -9999$
$Eq_{025} = -9999$	$Eq_{026} = -9999$
$Eq_{027} = -9999$	$Eq_{028} = -9999$
$Eq_{029} = -9999$	$Eq_{030} = -9999$
$Eq_{031} = -9999$	$E_{001} = -9999$
$E_{002} = -9999$	$E_{003} = -9999$
$E_{003a} = -9999$	$E_{004} = -9999$
$E_{005} = -9999$	$E_{006} = -9999$
$E_{007} = -9999$	$E_{008} = -9999$
$E_{009} = -9999$	$E_{010} = -9999$
$E_{011} = -9999$	$E_{012} = -9999$
$E_{013} = -9999$	$E_{014} = -9999$
$E_{015} = -9999$	$E_{016} = -9999$
$E_{017} = -9999$	$E_{018} = -9999$
$E_{019} = -9999$	$E_{020} = -9999$
$E_{021} = -9999$	$E_{022} = -9999$
$E_{023} = -9999$	$E_{025} = -9999$
$E_{026} = -9999$	$E_{028} = -9999$
$E_{029} = -9999$	$E_{030} = -9999$
$E_{031} = -9999$	$E_{032} = -9999$
$E_{033} = -9999$	$E_{034} = -9999$
$E_{035} = -9999$	$E_{036} = -9999$
$E_{037} = -9999$	$E_{038} = -9999$
$\dot{E}_{039} = -9999$	$\dot{E}_{d,001} = -9999$
$\dot{E}_{d,002} = -9999$	$\dot{E}_{d,003} = -9999$
$\dot{E}_{d,004} = -9999$	$\dot{E}_{d,005} = -9999$
$\dot{E}_{d,006} = -9999$	$\dot{E}_{d,007} = -9999$
$\dot{E}_{d,008} = -9999$	$\dot{E}_{d,009} = -9999$
$\dot{E}_{d,010} = -9999$	$\dot{E}_{d,011} = -9999$
$\dot{E}_{d,012} = -9999$	$\dot{E}_{d,013} = -9999$
$\dot{E}_{d,014} = -9999$	$\dot{E}_{d,015} = -9999$
$\dot{E}_{d,016} = -9999$	$\dot{E}_{d,017} = -9999$
$\dot{E}_{d,018} = -9999$	$\dot{E}_{d,019} = -9999$
$\dot{E}_{d,020} = -9999$	$\dot{E}_{d,021} = -9999$
$\dot{E}_{d,022} = -9999$	$\dot{E}_{d,023} = -9999$
$\dot{E}_{d,024} = -9999$	$\dot{E}_{d,025} = -9999$
$\dot{E}_{d,026} = -9999$	$\dot{E}_{d,027} = -9999$
$\dot{E}_{d,028} = -9999$	$\dot{E}_{d,029} = -9999$
$\dot{E}_{d,030} = -9999$	$\dot{E}_{d,031} = -9999$
$\dot{E}_{d,PRV1} = -9999$	$\dot{E}_{d,PRV2} = -9999$
$\dot{E}_{d,PRV3} = -9999$	$\dot{E}_{d,PRV4} = -9999$
$\dot{E}_{d,PRV6} = -9999$	$\dot{E}_{d,PRV7} = -9999$

$h_{001} = -9999$	$h_{002} = 1182$
$h_{003} = 1202$	$h_{003a} = -9999$
$h_{004} = -9999$	$h_{005} = 1182$
$h_{006} = 1182$	$h_{007} = 1182$
$h_{008} = 1182$	$h_{009} = 1182$
$h_{010} = 1182$	$h_{011} = 1182$
$h_{012} = -9999$	$h_{013} = -9999$
$h_{014} = -9999$	$h_{015} = -9999$
$h_{016} = -9999$	$h_{017} = -9999$
$h_{018} = -9999$	$h_{019} = 1158$
$h_{020} = -9999$	$h_{021} = -9999$
$h_{022} = 1249$	$h_{023} = -9999$
$h_{025} = -9999$	$h_{026} = -9999$
$h_{027} = 196$	$h_{028} = -9999$
$h_{029} = -9999$	$h_{030} = -9999$
$h_{031} = -9999$	$h_{032} = -9999$
$h_{033} = -9999$	$h_{034} = -9999$
$h_{035} = -9999$	$h_{036} = -9999$
$h_{037} = -9999$	$h_{038} = -9999$
$h_{039} = -9999$	$K_{001} = 1.85$
$K_{002} = 3.42$	$K_{010} = 0$
$K_{011} = 0.74$	$K_{012} = 0.64$
$K_{013} = 0.72$	$K_{014} = 0.17$
$K_{015} = 0.6$	$K_{016} = 2.62$
$K_{017} = 0.3$	$K_{018} = 0$
$K_{019} = 4.02$	$K_{020} = 0.51$
$K_{021} = 0.54$	$K_{022} = 0.18$
$K_{023} = 2.22$	$K_{024} = 1.44$
$K_{025} = 1.56$	$K_{026} = 1.14$
$K_{027} = 0.88$	$K_{028} = 1.56$
$K_{029} = 2.83$	$K_{030} = 0.2$
$K_{031} = 0.67$	$\dot{m}_1 = -9999$
$\dot{m}_{10} = -9999$	$\dot{m}_{11} = -9999$
$\dot{m}_{12} = -9999$	$\dot{m}_{13} = -9999$
$\dot{m}_{14} = -9999$	$\dot{m}_{16} = -9999$
$\dot{m}_{17} = -9999$	$\dot{m}_{18} = -9999$
$\dot{m}_{19} = -9999$	$\dot{m}_2 = -9999$
$\dot{m}_3 = -9999$	$\dot{m}_4 = -9999$
$\dot{m}_5 = -9999$	$\dot{m}_{5a} = -9999$
$\dot{m}_{5b} = -9999$	$\dot{m}_6 = -9999$
$\dot{m}_7 = -9999$	$\dot{m}_9 = -9999$
$P_{N,001} = -9999$ [psig]	$P_{N,002} = 60$ [psig]
$P_{N,003} = 240$ [psig]	$P_{N,003a} = -9999$
$P_{N,004} = 60$ [psig]	$P_{N,005} = 60$
$P_{N,006} = 60$	$P_{N,007} = 60$
$P_{N,008} = 60$	$P_{N,009} = 60$
$P_{N,010} = 60$	$P_{N,011} = 60$
$P_{N,012} = -9999$	$P_{N,013} = -9999$
$P_{N,014} = -9999$	$P_{N,015} = -9999$ [psig]
$P_{N,016} = -9999$	$P_{N,017} = -9999$
$P_{N,018} = -9999$	$P_{N,019} = 7$ [psig]
$P_{N,020} = -9999$	$P_{N,021} = -9999$
$P_{N,022} = 350$ [psig]	$P_{N,023} = -9999$
$P_{N,025} = -9999$	$P_{N,026} = -9999$

$P_{N,028} = -9999$	$P_{N,029} = -9999$
$P_{N,030} = -9999$	$P_{N,031} = -9999$
$P_{N,032} = -9999$	$P_{N,033} = -9999$
$P_{N,034} = 7$ [psig]	$P_{N,035} = -9999$
$P_{N,036} = -9999$	$P_{N,037} = -9999$
$P_{N,038} = -9999$ [psig]	$P_{N,039} = -9999$
$\dot{Q}_{001} = -9999$	$\dot{Q}_{002} = -9999$
$\dot{Q}_{003} = -9999$	$\dot{Q}_{004} = -9999$
$\dot{Q}_{005} = -9999$	$\dot{Q}_{006} = -9999$
$\dot{Q}_{007} = -9999$	$\dot{Q}_{008} = -9999$
$\dot{Q}_{009} = -9999$	$\dot{Q}_{010} = -9999$
$\dot{Q}_{011} = -9999$	$\dot{Q}_{012} = -9999$
$\dot{Q}_{013} = -9999$	$\dot{Q}_{014} = -9999$
$\dot{Q}_{015} = -9999$	$\dot{Q}_{016} = -9999$
$\dot{Q}_{017} = -9999$	$\dot{Q}_{018} = -9999$
$\dot{Q}_{019} = -9999$	$\dot{Q}_{020} = -9999$
$\dot{Q}_{021} = -9999$	$\dot{Q}_{022} = -9999$
$\dot{Q}_{023} = -9999$	$\dot{Q}_{024} = -9999$
$\dot{Q}_{025} = -9999$	$\dot{Q}_{026} = -9999$
$\dot{Q}_{027} = -9999$	$\dot{Q}_{028} = 0$
$\dot{Q}_{029} = -9999$	$\dot{Q}_{030} = -9999$
$\dot{Q}_{031} = -9999$	$T_{001} = -9999$
$T_{002} = 307.3$	$T_{003} = 402.7$
$T_{003a} = -9999$	$T_{004} = -9999$
$T_{005} = 307.3$	$T_{006} = 307.3$
$T_{007} = 307.3$	$T_{008} = 307.3$
$T_{009} = 307.3$	$T_{010} = 307.3$
$T_{011} = 307.3$	$T_{012} = -9999$
$T_{013} = -9999$	$T_{014} = -9999$
$T_{015} = -9999$	$T_{016} = -9999$
$T_{017} = -9999$	$T_{018} = -9999$
$T_{019} = 232.3$	$T_{020} = -9999$
$T_{021} = -9999$	$T_{022} = 500$ [F]
$T_{023} = -9999$	$T_{025} = -9999$
$T_{026} = -9999$	$T_{028} = -9999$
$T_{029} = -9999$	$T_{030} = -9999$
$T_{031} = -9999$	$T_{032} = -9999$
$T_{033} = -9999$	$T_{034} = -9999$
$T_{035} = -9999$	$T_{036} = -9999$
$T_{037} = -9999$	$T_{038} = -9999$
$T_{039} = -9999$	

NOMENCLATURE

Aux.	auxiliary
Blr.	boiler
CHP	combined heat and power
e	specific exergy
\dot{E}	exergy flow rate
h	specific enthalpy
HRSG	heat recovery steam generator
LHV	lower heating value
M	molecular weight
\dot{m}	mass flow rate
P	pressure
PRV	pressure reducing valve
\dot{Q}	rate of heat transfer
s	specific entropy
T	temperature
\dot{W}	Work
x	molecular fraction
η	efficiency

Subscripts and superscripts

–	molar
c	cold
CH	chemical
CV	control volume
D	destruction
e	exit
f	fuel
h	hot

<i>hyd</i>	hydraulic
<i>i</i>	inlet
<i>in</i>	input
<i>I</i>	first law
<i>II</i>	second law
<i>j</i>	control volume boundary
<i>k</i>	mixture component
<i>o</i>	reference condition
<i>out</i>	output
<i>PH</i>	physical
<i>s</i>	isentropic

REFERENCES

1. "The Greenhouse Effect." *Global Climate Change: NASA's Eyes on the Earth*. National Aeronautics and Space Administration. <<http://climate.nasa.gov/causes/>>.
2. "International Energy Statistics." *U.S. Energy Information Administration, Independent Statistics and Analysis*. U.S. Energy Information Administration. <<http://tonto.eia.doe.gov/cfapps/ipdbproject/IEDIndex3.cfm>>.
3. Bejan, A., Moran, M., Tsatsaronis, G., *Thermal Design and Optimization*, Wiley & Sons, 1996.
4. Gaggioli, R. *Efficiency and Costing. Ch. 1: Second Law Analysis for Process and Energy Engineering*. American Chemical Society, 1983. 3-50.
5. Habib, M.A. "First- and Second-Law Analysis of Steam-Turbine Cogeneration Systems." *Journal of Engineering for Gas Turbines and Power*, 116.1 (1994): 15-19.
6. Dincer, I, *et al.* "Exergetic analysis of cogeneration-based district energy systems." *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, 218.6 (2004): 369-375.
7. Ahmadi, P., *et al.*, "Exergy Analysis of a 420 MW combined cycle power plant," *International Journal of Energy Research*, 32 (2008): 175-183.
8. Butcher, C., Reddy, B., "Second Law analysis of a natural gas-fired gas turbine cogeneration system," *International Journal of Energy Research*, 33 (2009): 728-736.
9. Butcher, C., Reddy, B., "Second Law analysis of a waste heat recovery based power generation system," *International Journal of Heat and Mass Transfer*, 50 (2007): 2355-2363.
10. Ahmadi, P., *et al.*, "Energy, exergy and exergoeconomic analysis of a steam power plant: A case study," *International Journal of Energy Research*, 33 (2009): 499-512.
11. Kim, S.-M., *et al.* "Exergy Analysis for a Gas Turbine Cogeneration System." *Journal of Engineering for Gas Turbines and Power*, 118.4 (1996): 782-791.
12. Law, B. and Reddy, B. "Energy and Exergy Analyses of a Natural Gas Fired Combined Cycle Cogeneration System." *ASME 2007 Energy Sustainability Conference*, Long Beach, CA, 2007. 179-186.

13. Chuang, C. and Sue, D. "Engineering design and exergy analyses for combustion gas turbine based power generation system." *Journal of Engineering for Gas Turbines and Power*, 29.8 (2004): 1183-1205.
14. Jeon, J.-S., *et al.* "Exergetic and thermoeconomic analyses of power plants." *Energy*, 28.4 (2003): 343-360.
15. Dincer, I., *et al.* "Exergy analysis of a thermal power plant with measured boiler and turbine losses." *Applied Thermal Engineering*, 30.8-9 (2010): 970-976.
16. Oman, J. *et al.* "Efficiency of a combined gas-steam process." *Energy Conversion and Management*, 40.11 (1999): 1163-1175.
17. Aljundi, I. "Energy and exergy analysis of a steam power plant in Jordan." *Applied Thermal Engineering*, 29.2-3 (2009): 324-328.
18. Casarosa, C. and Franco, A. "On some perspectives for increasing the efficiency of combined cycle power plants." *Applied Thermal Engineering*, 22.13 (2002): 1501-1518.
19. Pirone, A., *et al.* "Thermodynamic evaluation of combined cycle plants." *Energy Conversion and Management*, 51.5 (2010): 1099-1110.
20. EES, F-Chart Software, 2010, <http://www.fchart.com>
21. Moran, M., Shapiro, H. *Fundamentals of Engineering Thermodynamics*, 5th ed., Wiley & Sons, 2004.
22. Heald, C., *Cameron Hydraulic Data*, Nineteenth Edition, Flowserve Corporation, 2002.
23. Churchill, S. W., "Frictional-factor equation spans all fluid-flow regimes." *Chemical Science and Engineering*, 7 (1977): 91-92.