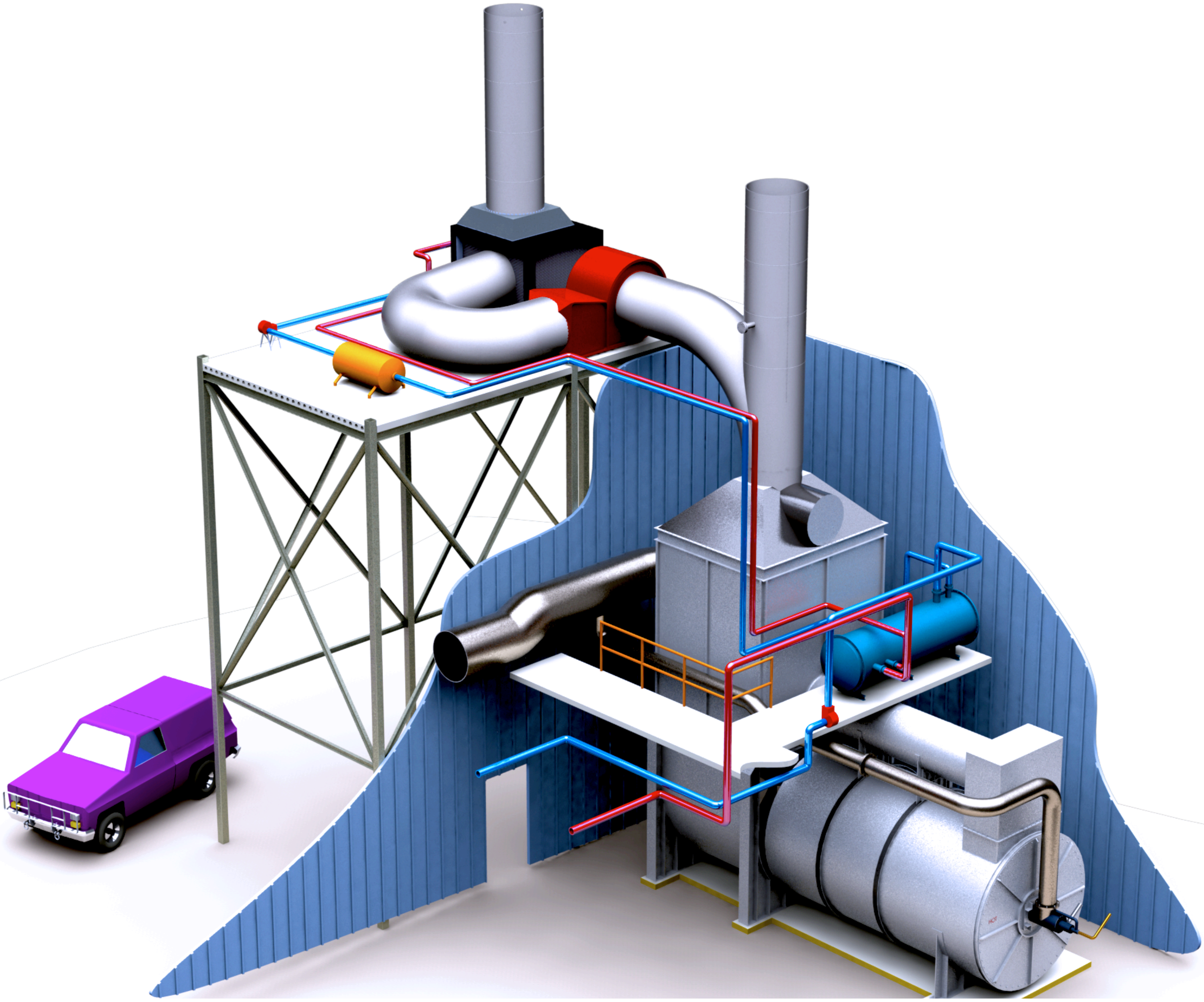
VALEANT™
Pharmaceuticals North America

THERMAL OXIDIZER HEAT RECOVERY SYSTEM
TEAM 17



Valeant Thermal Oxidizer Heat Recovery System

University of Manitoba
December 6th, 2010

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LETTER OF TRANSMITTAL

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December 6, 2010

Mark Lobe
Director of Engineering
Valeant Pharmaceuticals International
100 LifeSciences Parkway
Steinbach, Manitoba
R5G 1Z7

Dear Mr. M. Lobe:

Please accept the accompanying report, submitted on December 6, 2010, by Team 17 - SĀFF Engineering, entitled “Valeant Thermal Oxidizer Heat Recovery System”.

This report was written to explain and evaluate several heat recovery systems including waste heat boilers, direct-contact recuperators, and thermal fluid loops. The report includes background info on the project, the project definition, target specifications, a final design, and a final recommendation. The methods and processes undertaken by the team throughout the project are also outlined.

The team would like to thank the following people for their support and their time to help with this report: Robert Triebe – Chief Operating Officer, Americas and Asia, at Thermal Energy International; Trigg Turner – Industrial Sales Engineer at Midwest Engineering Limited; Jessica Perrault – Environmental Engineer at Valeant Pharmaceuticals International; Dale Robinson – Facilities Manager at Valeant Pharmaceuticals International; Kevin Gadient – Process Engineer at Valeant Pharmaceuticals International; Michael Ferley – Energy Advocate at the University of Manitoba; Dr. Tarek ElMekkawy – Associate Professor at the University of Manitoba, Dr. Paul Labossière – Assistant Professor at the University of Manitoba.

Sincerely,

Nathan Arnal Dean Ferley

Jordan Friesen Mitch Smith
Team 17 – SĀFF Engineering

Encl. 1 [“Valeant Thermal Oxidizer Heat Recovery System”]

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NOMENCLATURE

Direct-contact recuperator (DCR): Heat recovery system that recovers sensible and latent heat by condensing flue gas vapours using a direct spray of water.

Heat exchanger (HX-01): The air-to-oil heat exchanger that transfers the recovered heat from the TOX flue gases to the thermal oil loop.

Heat exchanger (HX-02): The oil-to-water heat exchanger that transfers the heat from the thermal oil loop to the building heating water.

Lower explosive limit (LEL): The volumetric percentage of a solvent required of a mixture with air to be ignitable.

Thermal oxidizer (TOX): Incinerator used to combust residual volatile organic compounds.

Volatile organic compound (VOC): Carbon-based molecule that has a low vapour pressure. Ethyl, methyl, and isopropyl alcohols are an example of VOCs.

Waste heat boiler (WHB): A non-fired water or steam boiler.

Totally enclosed fan cooled (TEFC) motor: Electrical motor were all the electrical components are sealed in the motor casing, and utilizes a fan to cool the electrical components.

1 ABSTRACT

SĀFF Engineering has been commissioned by Valeant Pharmaceuticals International to propose a suitable heat recovery system for their thermal oxidizer system. The following report presents the full design process undertaken including the final Gantt chart in Appendix E.

Three main design concepts were chosen as best suited for the project based on the concept screening process outlined in Appendix A. The first design, the waste heat boiler, was deemed infeasible as no suitable designs could be reached. The second concept, the direct-contact recuperator, was found to be ill-suited for Valeant's facility as the required outlet water temperatures were too high to capture the latent heat of the TOX flue gases. Finally, a suitable design was reached for the thermal fluid loop concept.

Thermal Energy International was responsible for the design and specification of the major equipment while SĀFF Engineering specified the minor equipment for the thermal fluid loop system. A thorough cost analysis was performed and the system was estimated to cost $673,672.89 with an annual maintenance cost of $6,740.00. The projected savings from the project were $257,332.54 per year, which translates into a payback period of approximately 2.65 years. Thus, SĀFF Engineering recommends implementing the thermal fluid loop design from Thermal Energy International.

2 INTRODUCTION

SĀFF Engineering has been commissioned by Valeant Pharmaceuticals International to determine a feasible heat recovery system for their thermal oxidizer (TOX). The purpose, problem, and scope of the project are defined below.

2.1 PURPOSE

The purpose of this project was to determine a suitable heat recovery system for Valeant's TOX. Any recovered heat would be used to reduce utility costs elsewhere within the Valeant facility.

2.2 PROBLEM

Valeant spends a considerable amount of money heating their facility, as all of their air is single-pass only. In addition, a TOX is used to remove volatile organic compounds from the air used for the various pharmaceutical processes that Valeant performs. The high temperature flue gases exhausted are then released into the atmosphere. If a portion of this heat could be recovered and reused within the facility, it would represent a significant cost saving.

2.3 SCOPE

The project scope includes the proposal of a heat recovery system for the TOX stack and the piping system to deliver the reclaimed energy back into Valeant's existing distribution systems. In addition, a control strategy, sequence of operations, and payback period estimate on the overall implementation of the design must also be specified. Any cost saving opportunities before or within the TOX are outside the scope of the project. Very important was the request that only commercially available equipment be used. Finally, the control systems that Valeant uses to manage and distribute the reclaimed heat will not be specified.

3 BACKGROUND

SĀFF Engineering was originally commissioned by Biovail Pharmaceuticals to perform an analysis of heat recovery options for their TOX. However, Biovail has since merged with Valeant Pharmaceuticals International and the combined company has retained the Valeant name. Valeant Pharmaceuticals International is an international specialty pharmaceutical company with manufacturing facilities in Canada, Poland, Brazil, and Mexico. Within Canada, Valeant is located in Montreal, Quebec, and Steinbach, Manitoba.

At Valeant's Steinbach facility, oral dose pharmaceutical products are manufactured. In particular, the facility specializes in extended release technology for prescription medicine. Some manufacturing processes involve the application of alcohol-based solutions to granulations or tablets. These solutions emit gaseous volatile organic compounds (VOC) into the process air as they evaporate. In order to adhere to environmental codes, the volatile organic compounds must to be removed before the process air can be released to the atmosphere.

A TOX is used to remove the solvents by combusting the air. However, the solvent vapors are often not at a high enough concentration to combust on their own. Even when the solvents reach the lower explosive limit, complete combustion of the solvents cannot be achieved without the use of natural gas. Immediately after combustion, the flue gases are directed through a primary heat exchanger that was originally packaged with the TOX from Bigelow-Liptak. The primary heat exchanger serves to increase the temperature of the incoming process air using the heat from the flue gases. However, the flue gases are still at an approximate temperature of 700°F as they exit the exhaust stack to atmosphere. The capture of the remaining thermal energy of the flue gas after the primary heat exchanger is the focus of the project.

4 DESIGN CRITERIA

Project objectives, target specifications, and project limitations were developed to provide clear and precise design criteria for the heat recovery project. These criteria are outlined in the following section.

4.1 PROJECT OBJECTIVES

The project objectives were developed through client input to meet Valeant's needs and expectations for the project. The following section outlines the project objectives in order of importance.

4.1.1 RECOVER HEAT FROM TOX EXHAUST STACK

The TOX emits a stream of extremely hot gases into the atmosphere. Recovering the thermal energy from these gases to use elsewhere in the facility has great potential to reduce the facility's natural gas costs. This is the main objective of the project

4.1.2 SAVE MONEY

It is very important that any heat recovery system saves Valeant money. An effective way of doing so is to reduce Valeant's natural gas consumption as it represents a significant cost to the company. Natural gas is key to heating operations within the facility heating and represents a major cost to the company.

4.1.3 ACCOMMODATE FULL RANGE OF TOX OPERATING CONDITIONS

The TOX operates under a broad range of conditions. The flue gas flow rate and temperature fluctuate based on product demand and manufacturing process types. Thus, a feasible heat recovery system must accommodate all foreseeable conditions imposed by the TOX. The design values used for the heat recovery project are a volumetric flow rate from 4,000-8,000 ACFM and an outlet stack temperature of 715°F.

4.1.4 LEAVE CURRENT TOX OPERATING CONDITIONS UNAFFECTED

The operation of the TOX must not be affected by the addition of the heat recovery system. This is important in order to maintain TOX productivity and ensure that existing equipment is not damaged.

4.1.5 ENSURE DESIGN RELIABILITY

Periodic maintenance is an inevitability of heat recovery systems. It is important that the frequency and amount of the preventative maintenance required is minimized. This is important to maximize the operation time of the system, which in turn maximizes the heat recovered and cost savings.

4.1.6 ENSURE ACCESSIBILITY FOR MAINTENANCE

Safety considerations, codes, and standards necessitate adequate accessibility to a piece of equipment. A feasible heat recovery system must provide sufficient access to its various components to facilitate maintenance operations.

4.2 TARGET SPECIFICATIONS

The following subsection outlines the target specifications for the heat recovery project. Each target specification corresponds to a project objective from the previous section.

4.2.1 HEAT RECOVERED FROM TOX STACK

With the large amount of heat emitted from the TOX stack, there is a large potential for heat recovery. The target specification for the amount of heat recovered by the proposed system is an ideal value of 2.0 MMBTU/hr with 1.1 MMBTU/hr being acceptable. These values were determined early in the project based on an erroneous flue gas flow rate. These target specifications are marginally and artificially low.

4.2.2 PAYBACK PERIOD

One of the most important target specifications is the payback period. Valeant has specified that a three-year payback period is acceptable with a two-year payback period being ideal. The final payback period will have a large impact on whether the proposed system is implemented or not.

4.2.3 AVERAGE EFFICIENCY OVER RANGE OF OPERATING CONDITIONS

The proposed heat recovery system must achieve an acceptable average efficiency measured in percentage of theoretically recoverable thermal energy. An acceptable value is 70% with 90% being ideal. Unfortunately, this data was not available for the proposed system. This criterion is further discussed in the conclusion.

4.2.4 INCURRED PRESSURE DROP

It is important not to cause any unwanted changes to the existing TOX operating conditions for safety and reliability reasons. The proposed design must not cause any pressure drop to the system upon implementation to ensure seamless integration with the existing equipment.

4.2.5 PREVENTATIVE MAINTENANCE SCHEDULE

Maintenance is an essential part of the lifecycle of any heat recovery system. Reliability will be measured in terms of the preventative maintenance schedule required. The proposed design must allow for a quarterly preventative maintenance schedule or better to be deemed acceptable.

4.2.6 SPACE AROUND PROPOSED AND EXISTING EQUIPMENT

In order to install and maintain the proposed heat recovery system, adequate space must be provided around all major components. A minimum distance of two feet around major components is acceptable with three feet being desirable. This specification does not apply to the piping or ventilation networks required.

4.3 CONSTRAINTS

The proposed heat recovery system will be subject to several constraints and limitations. Spatial, time, and financial constraints are outlined in the following section.

4.3.1 SPATIAL CONSTRAINTS

The potential locations of the heat recovery system are restricted to two main regions. The first is inside the plant, beside the incinerator. The second is outside of the plant, where the flue gas is vented. Space is somewhat limited inside the plant, as adjacent equipment and maintenance access must be considered. Space outside is much more abundant around the TOX stack itself.

4.3.2 TIME CONSTRAINTS

The project began on September 13, 2010 and was completed on December 6, 2010, spanning 13 weeks. The Gantt chart included in Appendix E illustrates the individual tasks and deadlines that make up the overall timeline.

4.3.3 PROJECT BUDGET

Valeant defined the budget for the project in terms of payback period as opposed to a maximum capital expenditure value. The prescribed acceptable payback period is three years with two years being ideal.

5 FINAL DESIGNS

Three distinct types of heat recovery systems were carried past the conceptual screening phase of the project. The three designs were the waste heat boiler, direct-contact recuperator, and thermal fluid loop and are outlined in the following section.

5.1 INITIAL DATA

Valeant was able to supply initial design data for the project. This data consists of temperatures and flow rates relating to the TOX system and is presented in the following section.

5.1.1 INTRODUCTION

Valeant was able to provide TOX flow rate and temperature data on two different time intervals acquired from their TOX monitoring system. First, one year of data was given in eight-hour averages from 09/08/01 – 10/08/27. Second, two and a half months of data, recorded in one-hour averages, were also given from 10/07/01 – 10/09/30. By analyzing both data sets, it was possible to accurately predict the expected flow rates and temperatures needed to estimate the payback period of the project.

Below is an excerpt of the data received from Valeant in one-hour averages. The incinerator (TOX), primary heat exchanger, and exhaust stack temperatures are given in °F. The inlet air flow rate entering the TOX is also given in actual cubic feet per minute (ACFM) and the lower explosive limit (LEL) of the process air is given as a percent concentration required for explosion.

TABLE I: Data except from Valeant TOX data [1]

Date	Time	Incinerator Temp	Heat Exchanger Temp	Exhaust Stack Temp	Duct Flow	LEL.PointValue
10-08-27	3:00:00 PM	1,284.19	922.78	699.42	5,776.34	5.15
10-08-27	7:00:00 AM	1,285.02	930.7	687.82	5,169.28	7.02
10-08-26	11:00:00 PM	1,283.17	942.66	676.31	4,514.21	9.72
10-08-26	3:00:00 PM	1,284.28	933.84	688.44	5,074.12	8.15
10-08-26	7:00:00 AM	1,290.69	906.99	714.94	6,807.73	8.7
10-08-25	11:00:00 PM	1,286.23	905.95	711.36	6,689.51	9.51

It was predetermined by Valeant that no changes were to be made to the existing TOX system. Therefore, the incinerator and heat exchanger temperatures must remain unaffected and will not be carried further through the analysis. Likewise, the LEL value is measured before the TOX to determine the amount of natural gas used to fire the combustion chamber and must also remain unaffected.

After consulting with Dr. Tarek ElMekkawy, the data was organized into a histogram in order to gain a better understanding of its distribution and to quantify the number of outlying points [1].

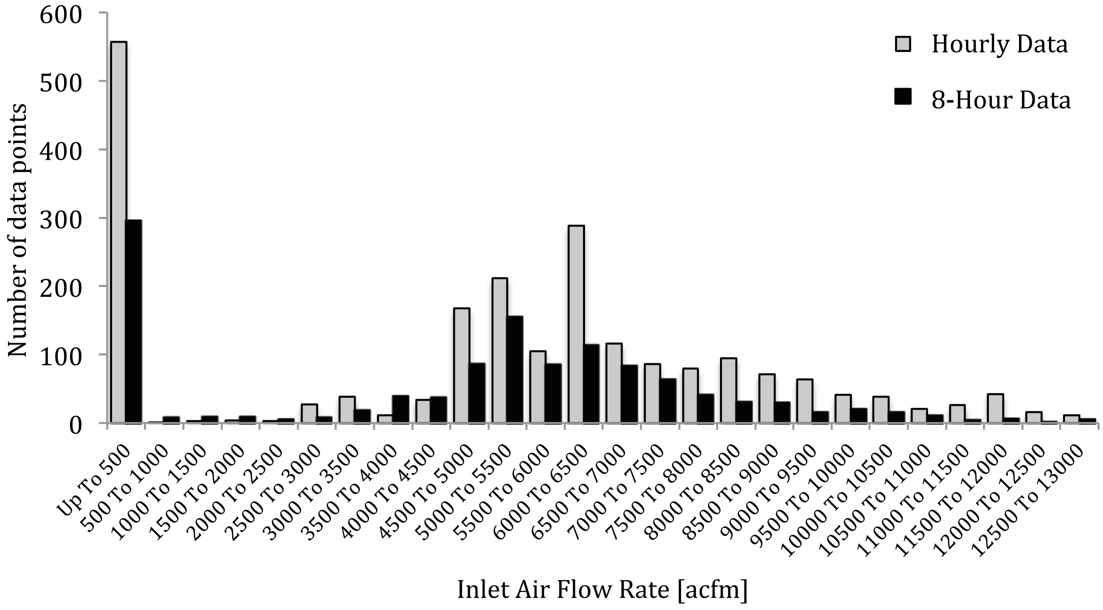

Figure 5.1: Histogram of exhaust gas flow rate

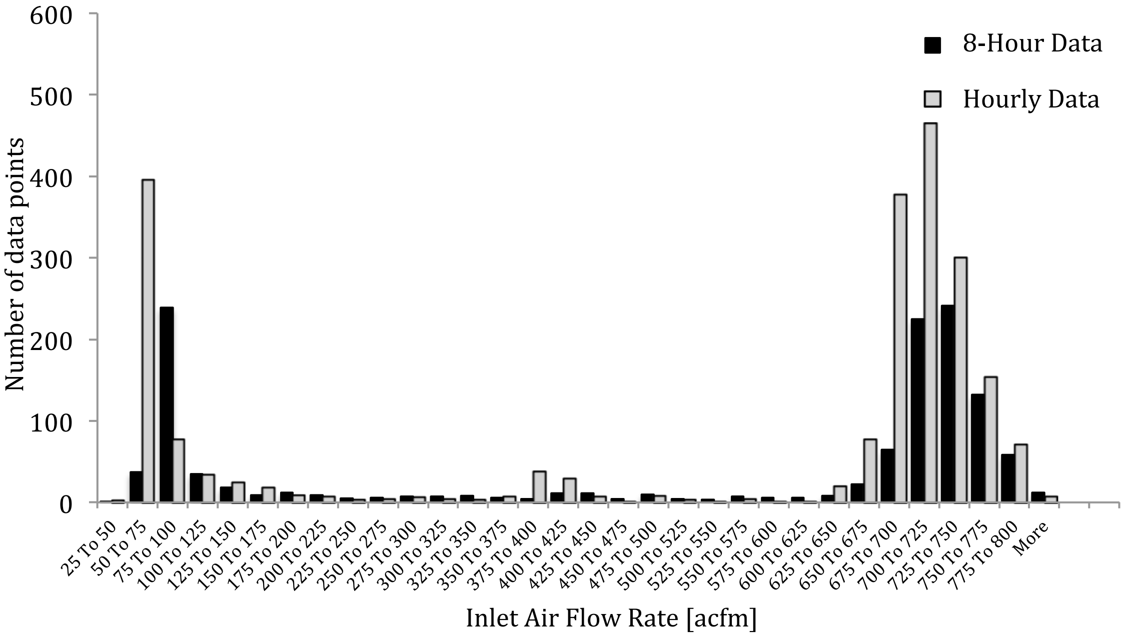

Figure 5.2: Histogram of exhaust flow temperature

Although the number of points varies, the general shape of both data sets is relatively the same. Three distinct operational conditions exist within the data sets:

On, Warm-up/Cool-down, and Off. Separating the data into time spent in each operational condition is crucial in calculating accurate heat recovery potential. Shown below is a plot of the exhaust temperature versus the flow rate with the three different operating conditions highlighted.

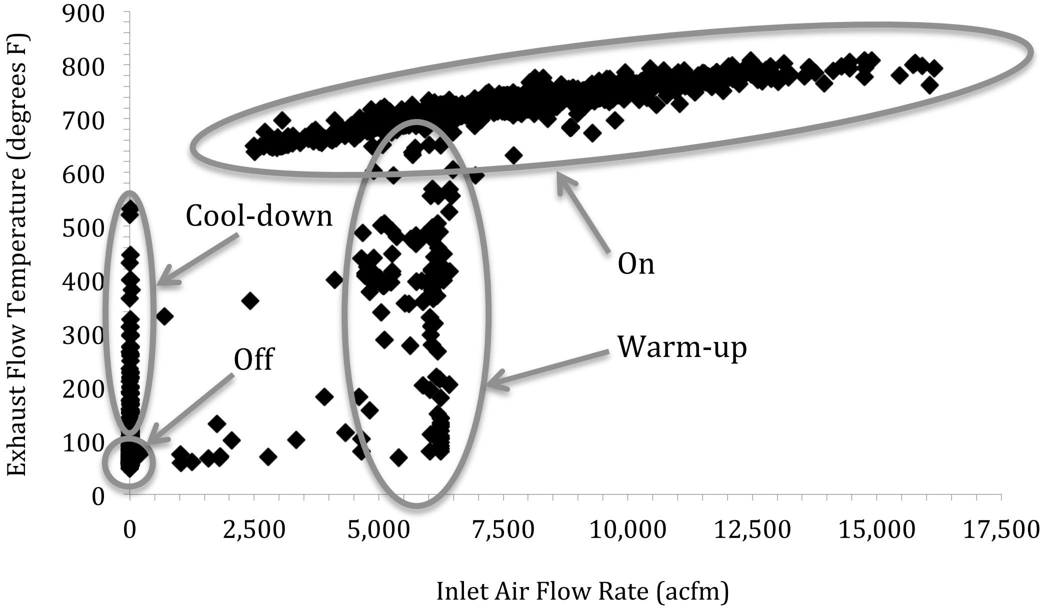

Figure 5.3: TOX flow rate vs. temperature in one-hour averages

The small circle located at the bottom left of the graph corresponds to the 'Off' condition while the left and right vertical ovals are the 'Cool-down' and 'Warm-up' conditions, respectively. Finally, the positively sloped oval corresponds to the 'On' condition. It should be noted that data analysis was only performed on the one-hour averaged data provided. The eight-hour averaged data offers too long of a period to resolve the trends accurately.

5.1.2 OFF CONDITION

The off condition is easily identified in the data as corresponding to zero flow rate and ambient temperature. However, programming a definite zero in data acquisition equipment is very difficult so non-zero values are prevalent. Consequently, 9.77 and 14.65 ACFM occur regularly, typically scheduled towards late Friday evening and continuing through the late Sunday night or early Monday morning. The average temperature corresponding to all flow rates in the range between 0 and 15 ACFM is 86^{o}F, which is a reasonable value as the measuring thermocouple is located within the insulated TOX. As these values represent one-hour increments, the percentage of time spent turned 'Off' can be determined. Taking a weekly average as a representative TOX operational cycle, a fraction of 23.75% of the time, or roughly 1.66 days, is spent 'Off'. The weekly data is summarized in the table below.

TABLE II: Weekly averages of TOX data in 'Off' operating condition

Week	Avg. Temperature (^{o}F)	Avg. Flow Rate (ACFM)	Hours in 'Off' (hr/week)	Time in 'Off' (% of week)
30	111.36	0.00	20.00	11.90
31	74.64	11.27	39.00	23.21
32	72.64	14.65	74.00	44.05
33	79.64	10.04	18.00	10.71
34	69.05	0.00	7.00	4.17
35	72.38	14.65	45.00	26.79
36	77.18	14.65	47.00	27.98
37	71.75	11.67	59.00	35.12
38	68.32	9.79	58.00	34.52
39	83.93	9.77	32.00	19.05
Average	*78.09*	*9.65*	*39.90*	*23.75*

The above range of data was selected as representative of regular operation conditions. While data was available for week 27 and 28, a plant shut down affected portions of the data and these weeks were omitted for this reason. This data was used in Appendix D to help determine the average downtime of the system throughout the year.

5.1.3 ON CONDITION

The time spend 'On' is the most substantial portion of the data. Initial estimates assumed five out of seven days of the week were operational while the other two were off. The third operating condition, 'Warm-up/Cool-down', was neglected in these estimates. A further consideration, obtained from talks with Valeant, is that the TOX idles at 4,000 ACFM. This value was used to define the lower flow rate, with a corresponding temperature of 651^{o}F. These values are in good agreement with the operational range defined in Figure 5.1.3. As the data shows an approximately linear trend with respect to flow rate and temperature, plotting a line of best-fit approximates the system curve of the TOX.

The table below shows the number of hours, average flow rate, and average temperatures the TOX spent in the 'On' operating condition.

TABLE III: Weekly averages of TOX data in 'On' operating condition

Week	Avg. Temperature (^oF)	Avg. Flow Rate (ACFM)	Hours in 'On' (hr/week)	Time in 'On' (% of week)
29	694.24	5478.77	145.00	86.31
30	669.74	4931.03	95.00	56.55
31	718.27	8115.04	88.00	52.38
32	740.81	9367.59	134.00	79.76
33	725.28	7491.43	140.00	83.33
34	711.45	6761.71	118.00	70.24
35	711.91	6575.53	113.00	67.26
36	724.67	7481.47	96.00	57.14
37	740.21	8484.50	103.00	61.31
38	732.60	8070.97	127.00	75.60
Average	*716.92*	*7275.80*	*115.90*	*68.99*

As was expected, the operation of the TOX represents the majority of the available weekly time, averaging 68.99% of a week, or roughly 4.83 days. However, the operational time has a much higher flow rate and slightly higher temperature than first estimated. This increases the theoretical estimate of total recoverable heat.

5.1.4 WARM-UP/COOL-DOWN CONDITION

The remaining data falls in the 'Warm-up/Cool-down' condition, which occurs as the TOX turns on and off. This transient region typically occurs on weekends with the TOX turning off late Friday nights and back on late Sunday nights. Operating temperature varies depending on the flow rate through the machine, but roughly 5-6 hours are required to fully heat-up the TOX. Weekly averaged data is shown below.

TABLE IV: Weekly averages in Warm-up/Cool-down condition

Week	Avg. Temperature (°F)	Avg. Flow Rate (ACFM)	Hours in 'WU/CD' (hr/week)	Time in 'WU/CD' (% of week)
30	560.35	4099.91	3.00	1.79
31	468.11	3913.15	34.00	20.24
32	317.08	4826.08	6.00	3.57
33	394.54	6026.65	16.00	9.52
34	193.60	5777.02	21.00	12.50
35	428.68	5834.38	5.00	2.98
36	367.09	4594.01	8.00	4.76
37	389.21	5378.84	13.00	7.74
38	369.18	5194.17	7.00	4.17
39	329.23	5073.37	9.00	5.36
Average	381.71	5071.76	12.20	7.26

There is far more variability in the temperature averages of this operating condition than the previous two. It is difficult to predict plausible heat recovery in this condition, as the data is sporadic. This information is presented for completeness but will not be used in the final performance prediction calculations.

5.1.5 FINAL DESIGN DATA

Based on the previous sections, the following data was computed.

TABLE V: Final design data

Average Exhaust Stack Temperature	717°F
Average Exhaust Flow Rate	7,275 [ACFM]
Percentage of Time Active	69%

This data will be used to predict the performance of the proposed heat recovery systems.

5.2 CODES AND STANDARDS

The final design concept was reviewed for code compliance as well as department of labor standards for fuel fired boilers and furnaces. There are several standards that are applicable to the design of the heat recovery system. The applicable standards and codes are CSA B51 – Boiler and Pressure Vessel code, CSA C22 – Canadian

Electrical code, NFPA 85 – Boiler and Combustion System Hazards, NFPA 86 – Standards for Ovens and Furnaces and Department of Labour Mechanical Division.

5.2.1 CSA B51 – BOILER AND PRESSURE VESSEL CODE

The Canadian Standards Association (CSA) provides codes and standards for most electrical, and hazardous mechanical equipment in Canada. The Boiler and Pressure Vessel code, CSA B51, provides requirements for boiler and pressure vessel construction and installation for safe and effective operation. The construction of boilers and pressure vessels need to be considered when selecting the equipment as the equipment manufacturer must comply with this standard and provide the required certification. The installation portion of B51 is the portion that must be adhered to in the design of the heat recovery system. The installation considerations in B51 are listed in section 6.3.4. The heat recovery system must provide [2]:

- Adequate clearance for operation, inspection and maintenance,
- Walkways around the equipment of at least 2 feet,
- Clearance under a boiler of at least 12 inches,
- Clearance for cleaning and replacing tubing, fuel-burning and related equipment,
- And access to important part of the equipment via platforms, ladders and safety rails.

These safety and access requirements will be addressed in the design and installation of the system.

5.2.2 CSA C22 – CANADIAN ELECTRICAL CODE

The Canadian Electrical Code, CSA C22, applies to the manufacturing and installation of all the electrical devices and equipment in the proposed design. One major requirement is that all electrical equipment in the proposal must bare the CSA or equivalent approval sticker. Another consideration for this installation is the requirement for hazardous rated electrical devices since there is solvent vapors in the process air that goes to the TOX. The TOX is rated at 98% efficiency in terms of removing solvent vapors from the air stream, so under normal operating conditions, there should be no requirement for hazardous ratings. This does not consider failure conditions where the TOX does not remove the solvents from the air stream. This would be considered a Class I Division II type hazardous rating within the ductwork [3]. The TOX has interlocks that prevent it from starting if there is a buildup of solvent vapors, or if the furnace is not up to the required temperature to combust the solvent vapors. The TOX will only give permission to the process equipment when it is up to temperature and in operating condition. In light of the interlocks on the TOX, there should never be solvent vapors in the stack of the TOX. In discussions with Valeant, it was decided that the sensing equipment in the ductwork does not require hazardous rating. However, the additional fan does require type B spark proof construction [4], as it is the most likely source of ignition if the interlocks of the TOX were to fail [5].

5.2.3 NFPA CODES

The National Fire Protection Agency provides codes and guidelines for fire suppression and prevention systems. The authority having jurisdiction in each area usually adopts these codes and standards. In general, the authority having jurisdiction is the fire commissioner in the area and they must be contacted before the proposed design can be implemented.

The applicable NFPA codes are NFPA 85 – Boiler and Combustion System Hazards and NFPA 86 – Standards for Ovens and Furnaces. These standards provide classification guidance for boilers and furnaces and requirements for each classification [6] [7]. These classifications will depend on the implemented system and will be considered in design section.

5.2.4 DEPARTMENT OF LABOR FLUE STACK REQUIREMENTS

The mechanical engineering group within the Manitoba Department of Labor has requirements for the installation of restrictive devices in fuel fired flue stacks. The requirements are based on ensuring that there cannot be a restriction in the flue stack. This is to ensure that the fuel-fired equipment cannot be over pressurized or leak flue gas into any portion of the building. For the design of the heat recovery system, a normally open, spring return damper will be located in the TOX flue stack. This provides a fail-safe position if the damper does not operate properly. Also, an interlock between the system and the pressure transducer in the exhaust stack will open the damper fully if an excess of static pressure is built up in the flue stack.

5.3 WASTE HEAT BOILER

A waste heat boiler is an indirectly fired boiler, relying on the exhaust gases of the TOX to transfer heat to a working fluid inside the boiler. Assuming physical isolation from the effluent flue gases, this boiler can directly couple to existing heating loops, providing either hot water or steam.

There are numerous designs for waste heat boilers, many of them variations of typical boiler designs where the combustion gases are replaced with the TOX flue gases. Fire tube boilers consist of a series of parallel tubes running through a larger tank. The tubes carry the hot exhaust gases and are submersed in water in the tank. This setup is meant for lower pressure applications and is seen as best suited for the TOX flue gases. The large pressure vessel required for this application would need to be mounted externally to the TOX. Ideally, the boiler tank would be mounted around the exhaust stack. A schematic of a typical waste heat boiler configuration integrated into the TOX system can be seen below.

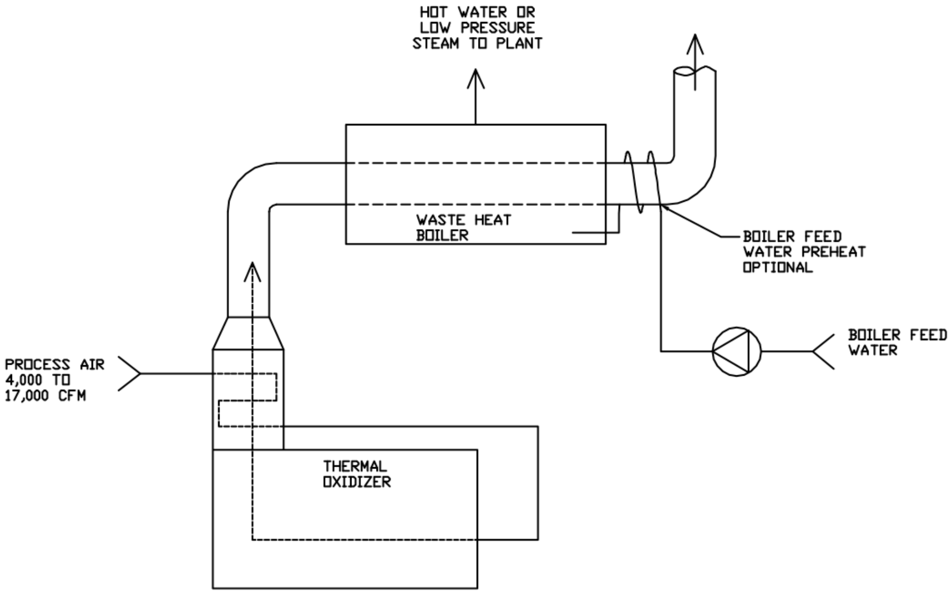

Figure 5.4: Typical waste heat boiler integrated with the TOX system

A second type of waste heat boiler, the water tube boiler, functions under the same geometric setup but with the fluids in opposite locations. In this case, the tank is not placed around the tubes but small diameter tubes are routed through the stack instead. This water tube boiler design is much simpler as the combustion air is already supplied and the water tubes can easily be placed in the flow of the gas. However, at such high temperatures, this system is best suited to produce high-pressure steam as opposed to hot water. This is less attractive for the current project due to the added complexities of using a steam system.

A number of boiler companies were contacted to inquire about suitable waste heat boilers for the project. Numerous companies were contacted regarding waste heat boiler designs, including: Rentech, Clayton Industries, and R.G. Sales (representing Cleaver Brooks). Unfortunately, even after repeated attempts, only Rentech responded. Upon submission of operational data, Rentech responded that the TOX temperature was too low and that they would not be able to suggest a waste heat boiler design to meet the minimum output requirements [8].

Due to the lack of responses and any suitable designs, the waste heat boiler concept was not carried through the design process.

5.4 Direct-Contact Waste Heat Recuperator

A direct-contact waste heat recuperator (DCR) is a heat recovery device that uses a fine spray of water to capture both sensible and latent heat of the flue gas. Figure 5.4.1 illustrates the DCR system. The flue gases are first diverted from the TOX stack using a valve (not pictured) to the recuperator. A fan ensures that no pressure drop is incurred. Once the flue gases reach the recuperator chamber, they are met with a spray of water. The water effectively captures both sensible and latent heat from the gases by condensing them and forming a pool of liquid at the bottom of the chamber. The top half of the recuperator chamber is packed with proprietary stainless steel coils to augment the heat transfer area.

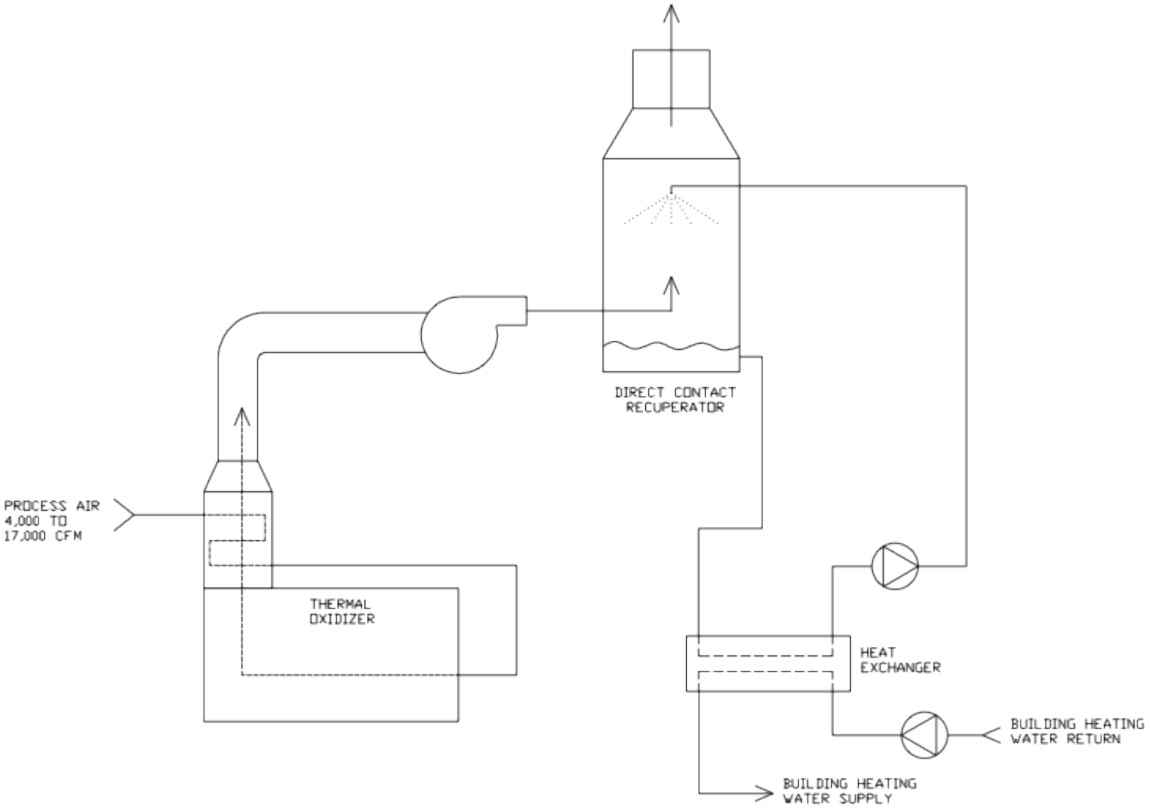

Figure 5.5: Direct-contact waste heat recuperator

The gases that are not condensed escape out the top of the recuperator to the atmosphere. The hot liquid at the bottom of the chamber is pumped through a heat exchanger where the recovered heat is transferred to the building heating water. Both sides of the heat exchanger operate in isolation from each other so contamination does not occur. A water line is also attached to the liquid loop on the recuperator side to regulate the amount of water in the system.

Finally, the option exists to place a scrubbing device on the liquid loop of the recuperator. This is done to filter out the condensed chemicals and any newly formed substances from the water.

Several companies were found to offer DCR systems, including: Thermal Energy International, Sofame Technologies, Bionomic, and Kemco Systems. Upon detailed analysis, it was determined that a hot liquid temperature above 160°F was required for the recovered heat to be useful within the Valeant facility. Only Thermal Energy International (TEI) stated that they could meet the required leaving water temperature, achieving a temperature of 180°F with a proprietary "alternate design" [9].

The reason most systems are unable to meet such a high hot liquid temperature requirement is due to the adiabatic saturation temperature of the flue gases. The saturation temperature, or dew point, of a gas corresponds to the temperature at which the gas-to-liquid phase transformation (condensation) occurs. The heat released during this phase transformation is called the latent heat. The recovery of the latent heat of the flue gases is the main advantage of the DCR system. Unfortunately, to do so, it must operate at a hot liquid temperature that does not exceed the saturation temperature of the flue gases.

As TEI was the only company to offer a DCR system that was able to achieve an adequate hot liquid temperature, they were contacted for a suitable design. However, after performing a detailed analysis, TEI determined that it was more economically feasible to implement a thermal fluid loop. Their proposed design is outlined in next section.

DCR systems operate best with low temperature water sprayed onto the flue gas. To implement a DCR system within this constraint, the water temperature entering the DCR would be around 140°F. This high of an entering water temperature results in more of the water evaporating because there is less energy required to raise the water temperature to the adiabatic saturation temperature of the flue gas and spray mixture.

The adiabatic saturation temperature can be increased, to some degree, by saturating the process air before it enters the TOX. Also, the saturation temperature is related directly to gas composition and pressure. An increase in pressure causes an increase in the saturation temperature for a given substance whereas the gas composition determines the saturation temperature at a given pressure. Therefore, in theory, it would be possible to increase the saturation temperature of the flue gases by modifying composition or increasing the internal pressure in the DCR system. However, the design of such a system is well beyond the scope of the current project.

5.5 THERMAL FLUID LOOP

The following section outlines the proposed system design to recover heat from the TOX located at Valeant. The major system components have been proposed by Thermal Energy International with the auxiliary equipment such as piping, wiring, pumps, etc. specified by SĀFF Engineering.

5.5.1 DESIGN FEATURES

Upon contacting Thermal Energy International for a quote on their FLU-ACE direct-contact recuperator system, a thermal fluid loop design was recommended instead. Due to high water temperatures, the FLU-ACE system would require extensive re-configuring, additional equipment, and an increased capital expenditure to realize similar heat recovery as the proposed thermal fluid loop [10].

The thermal fluid loop uses two heat exchangers to extract heat out of the TOX exhaust air. The first heat exchanger is an air-to-liquid heat exchanger that transfers heat from the flue gas to a thermal oil. The thermal oil carries the heat to the second heat exchanger, which is a liquid-to-liquid shell-and-tube heat exchanger. The second heat exchanger transfers the heat from the thermal oil to the building heating water system. The building heating water system is used all year to meet building and process heating loads. The thermal oil system is shown in the figure below with a full piping and instrumentation diagram (P&ID) shown in Appendix F. Also shown in the appendices are tables of the system operating parameters for the oil and water loops. The following arrangement of components was determined to maximize accessibility to maintenance without sacrificing performance.

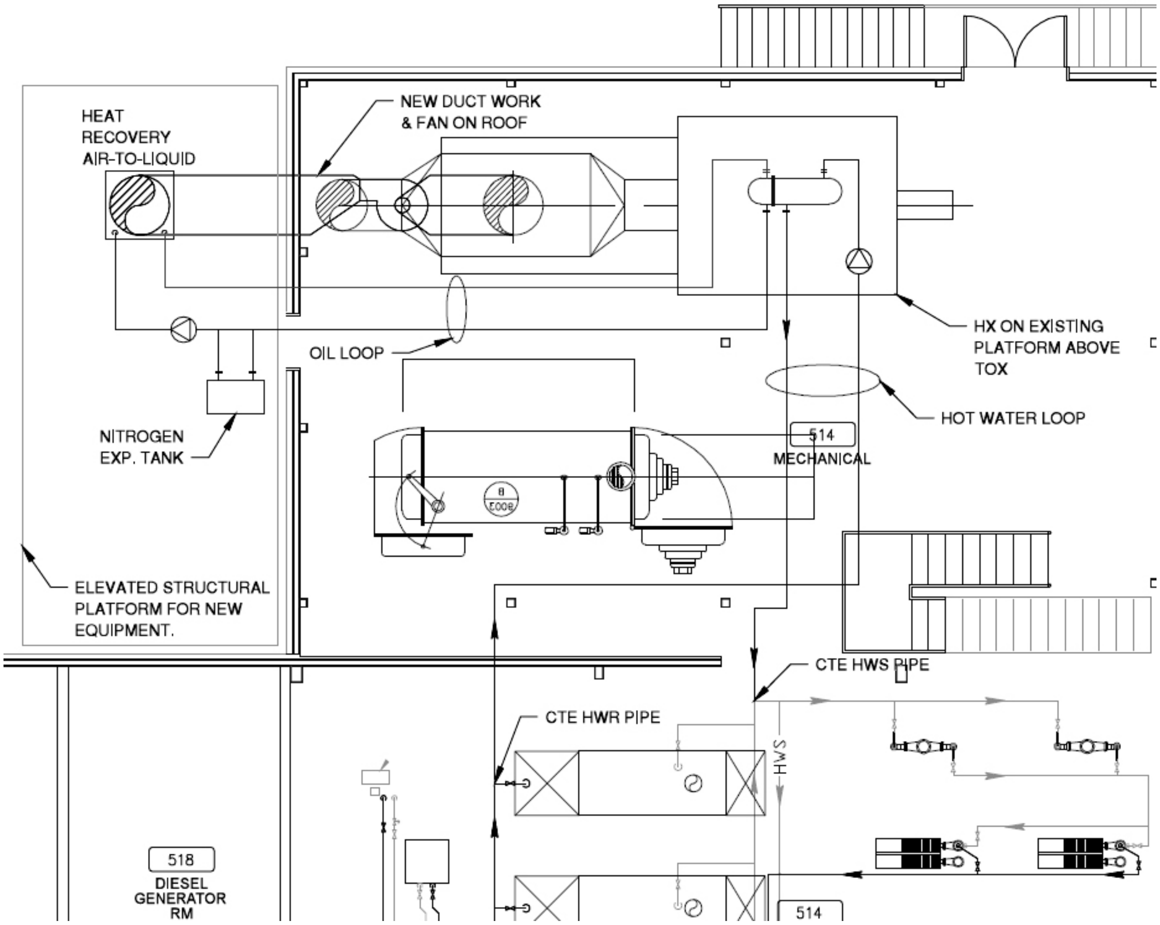

Figure 5.6: Thermal fluid loop system implementation

The thermal fluid system requires the operation of two circulation pumps and a fan. One of the circulation pumps is used to pump the thermal oil between the two heat exchangers. The second pump is used as a booster pump to pump the building heating water through the shell and tube heat exchanger. The fan is used to overcome the additional pressure loss caused by the air-to-liquid heat exchanger in the flue gas exhaust stack. The fan must be rated for high temperatures and spark proof applications. Pipe loss calculations were performed to determine the required pump characteristics. Pipe loss calculations can be found in Appendix C.

The design requires one of the pumps and the fan to be located outside as well half the oil fluid loop. The oil fluid loop is ok to be outside because the oil will not freeze outside and the change in density will be accounted for with the nitrogen expansion tank. The motors for the outside pump and the fan need to be totally enclosed fan cooled (TEFC) motors. TEFC motors are sealed and reduce the risk of water entering the motor. The fan and pump should also have a weather cover to ensure snow does not accumulate on the motors.

The thermal fluid loop system is designed for a maximum flow rate of 8,000 ACFM entering the TOX to capture all of the heat for most of the year. The heat recovered at 8,000 ACFM is approximately 5 MMBTU/hr. This amount of heat is very significant, and may exceed the needs of the facility at times.

Finally, preventative maintenance for the system will be required every 3 to 6 months. The components selected in the design are standard components that are similar to equipment Valeant already uses within their facility. The heat exchangers will require cleaning every 3 to 6 months depending on the fouling of the coils. The pumps and fans will require maintenance every 6 months to 1 year to check seals, balancing and belt tension.

5.5.2 SYSTEM OPERATION

The heat recovery system has to account for two different operating conditions from the TOX. The first condition is the TOX system warm-up and cool-down and the second condition is the when the system is in normal operation.

The TOX is normally shut down every weekend, so the cool-down and warm-up sequences must be considered as an important aspect of the heat recovery system design. When the TOX is off, the damper at the outlet of the flue stack will be fully open and the heat recovery system will be off. When the TOX starts and is warming-up, there is a period of time before any process air can be treated because the TOX must first reach its operating temperature. During the transient TOX warm-up process, the heat recovery system will not operate and the flue stack damper will remain fully open.

Once the TOX has reached its 'On' operating condition and is stable, it will output a permission signal for the heat recovery system to start. When the heat recovery system receives a permission signal, the fan and pumps will ramp up. For nominal TOX flows up to 8,000 ACFM, the heat recovery fan will modulate. Once the nominal flow rate exceeds 8,000 ACFM, the heat recovery system will operate at maximum capacity and allow the remaining flue gases to escape through the original TOX stack. The system operation is depicted in drawing PID-001 in Appendix F.

5.5.3 CONTROL STRATEGY

The control system for the thermal fluid loop consists of three separate control loops. The first control loop is for the fan to draw the hot flue gas from the TOX stack and the other two are to control the temperature of the oil and water loops.

The control loop for the fan consists of a dynamic pressure sensor in the flue stack positioned before the takeoff branch in the proposed design. The pressure element will generate a signal used to adjust the fan speed to match the flow through the TOX. The maximum capacity of the fan is 8,000 ACFM of air. When the TOX operates above the 8,000 ACFM limit, the fan will operate at maximum capacity and the excess flue gas will leave the existing flue stack. Thus, the heat from the excess flue gas will not be recovered.

The goal of the heat recovery system is to produce 165°F water at the outlet of the oil-to-water heat exchanger. To achieve this temperature, the temperature of the oil entering and the water leaving the heat exchanger must be controlled. A separate three-way control valve is required to control each of the supply temperatures of the oil and the water. For either fluid, to control the temperature of the leaving fluid, a three-way control valve is placed before the pump on the return side of the loop. Here, the control valve is modulated and used to control the temperature of the fluid leaving the control loop. If the temperature is below the set point, the fluid will flow through the three-way valve and back through the heat exchanger until the desired outlet temperature is achieved. If the temperature leaving the control loop is above the set point, the three-way valve will open to allow more return fluid to enter the control loop. This description of the control loop applies to both the oil and water loops and can be seen in Appendix F.

Using this control strategy, the flow through the heat exchanger is constant and consistently turbulent. The amount of fluid that enters and leaves the control loop is variable but the temperature at the outlet of the control loop is kept constant. The control loop is shown in Figure 5.5.2.

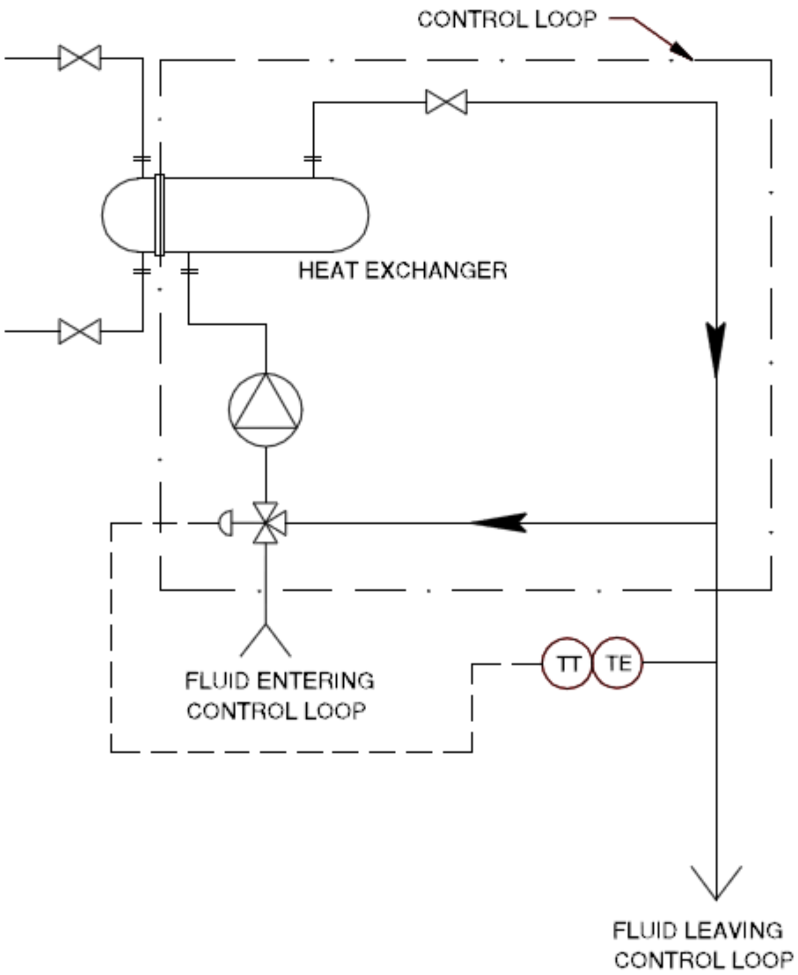

Figure 5.7: Thermal fluid control loop schematic

Safety interlocks are a key consideration whenever equipment failure can result in personal injury or property damage. This is certainly the case for both the TOX and the proposed thermal fluid loop. To determine the various interlocks required, failure modes were considered and mitigation strategies were determined to ensure safe operation. As a result, temperature elements were added in the new flue stack and in the shell of the oil-to-water heat exchanger.

The temperature element in the exhaust stack will monitor the outlet temperature. If the temperature in the stack starts to rise above the 200°F design temperature, the oil loop is malfunctioning. This could be caused by a pump or three-way control valve failure. Extreme oil temperatures are a safety hazard as the oil could overheat and break down or the water in the heat exchanger may boil. For these reasons, if the stack temperature reaches temperatures greater than 250°F, the system should generate an alarm and shutdown immediately.

The temperature element in oil-to-water shell-and-tube heat exchanger will measure the water temperature in the shell. Since the oil enters the heat exchanger at 250°F, it has the potential to boil the water in the heat exchanger if the water flow rate was too low. The water pump or the three-way control valve could affect the water flow rate if either is malfunctioning. Thus, if the water temperature in the oil-to-water heat exchanger exceeds 200°F, the system should generate an alarm and shutdown immediately.

Implementing these controls and interlocks in conjunction with the existing TOX controls should provide safe and effective operation of the heat recovery system. The control values may need to be adjusted to actual operating conditions during the commissioning of the system.

5.5.4 OVERALL COST

The implementation costs of this project can be separated into four major categories: equipment, materials, installation, and commissioning of the system. An itemized cost list can be found in Appendix B.

Thermal Energy International supplies all major equipment for this system. This includes the exhaust stack heat exchanger (HX-01), the oil-to-water heat exchanger (HX-02), and the nitrogen blanketing system. A quote of $427,200 was given for all of this equipment and some of the minor equipment including valves, thermal oil pump, and an exhaust fan to compensate for the induced pressure drop of the stack heat exchanger. Also included is the preliminary control system of the supplied design that will monitor the temperature elements and provide signaling to all pumps, fans and actuated valves.

Minor equipment required includes the pumps, sensing devices, pipefittings, valves, and other equipment needed to supplement the major equipment. The subtotal for the proposed minor equipment is estimated at $33,118.50.

Materials required for this installation are pipes of various diameters, electrical wire and conduit to connect sensing and control devices, and structural steel for the proposed platform and additional structural bracing. Material costs have been estimated at $85,302.00.

Installation costs reflect the time required for professionals to install the proposed equipment. Among the professionals required are pipefitters, electricians, welders, and rented-equipment operators. Using estimates from previous jobs performed, a value of $58,680.00 was found for installation.

As this is a proprietary design, verification of correct installation and initial start-up of the system must be performed by the designer. Thus, funding must be set aside for site visits by Thermal Energy International and the possibility of mid construction consulting and design modifications. $4,500 has been allocated for this aspect of the project.

Finally, a contingency fund should be set aside in the event that there is a mistake in the design, installation, start-up of the system, or if there are any extra required services or supplies needed. This value has been set at 10% of the total expenditure, which works out to $64,872.39.

TABLE VI: Heat recovery project cost outline

Category	Cost
Major Equipment	$427,200.00
Minor Equipment	$33,118.50
Material	$85,302.00
Installation	$58,680.00
Commissioning	$4,500.00
Contingency Funding	$64,872.39
Total	$673,872.89

The cost outline for the heat recovery project is outlined above. The total estimated cost for the project is $673,872.39.

The overall system cost is a considerable capital cost. We started analyzing the system provided by Thermal Energy International, to breakdown the cost for each component. The basic system from Thermal Energy provides one air-to-liquid economizer, a liquid-to-liquid heat exchanger, an oil pump, and a control system. With the design data specified in this report, a request for quotation could be sent out to different suppliers for each required component. Due to time constraints this exercise was not completed within this report. A sampling of costs for various components was received to show that this approach could reduce the capital cost significantly. Midwest Engineering quoted an oil-to-liquid heat exchanger at a cost of $20,762.00 [11]. The oil pump is very similar in size to the pump boost pump specified for the water, and thus the price can be estimated at $3,000 to $4,000. Finally, Heat Sponge, a manufacture of air-to-liquid economizers provides approximate sizing an pricing on their website, and provided an estimated cost for the economizer $90,866.00 USD [12]. With these prices, the overall system cost could be significantly reduced, and the payback could be reduced significantly as well.

5.5.5 BILL OF MATERIALS

See Appendix D for Bill of Materials.

6 CONCLUSIONS

Final designs for the waste heat boiler, direct-contact recuperator, and thermal fluid loop concepts were pursued past the concept-screening phase of the heat recovery project. Unfortunately, no suitable waste heat boiler or direct-contact recuperator designs were reached. However, Thermal Energy International proposed a suitable thermal fluid loop system design.
The projected amount of heat recovered from the TOX system is 4.6 MMBTU/hr. This is a conservative estimate and a more in-depth analysis expects even greater amounts of recovered heat. This value easily exceeds the desirable amount of 2.0 MMBTU/hr specified at the beginning of the project.

The cost of the thermal fluid loop system is estimated at $673,672.89 with an annual maintenance cost of $6,740.00. At a projected annual savings of $257,332.54, the payback period for the system is less than three years. This is within the desired target of a two to three year payback period.

Another concern for the heat recovery system was the average efficiency of the system over the range of TOX operating conditions. Unfortunately, it was not possible to obtain this data for the proposed thermal fluid loop system. However, the estimates for recoverable heat are significant and will likely exceed the facility capacity at times. Therefore, the exact efficiency of the system is of reduced importance.

Next, there was no incurred pressure drop on the system as an auxiliary fan was used to divert the flue gas flow. This was done in accordance with the target specification of not imposing a pressure drop on the TOX system.

Finally, preventative maintenance for the system was determined to be required every 3 to 6 months at most. The target quarterly schedule translates to maintenance operations being required every 3 months. Thus, the specification was met.

7 RECOMMENDATION

SĀFF Engineering recommends the thermal fluid loop be implemented for the Valeant TOX system. It is also recommended that the design specifications contained herein be used to obtain equipment pricing.

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APPENDIX A – CONCEPT SELECTION AND ANALYSIS

Concepts were generated through extensive external research as well as internal brainstorming sessions. The team then evaluated how the different heat recovery systems could meet the previously developed project objectives and target specifications. A screening matrix was used to rate the various heat recovery systems. This appendix presents an overview of the screening process, metrics, and scoring justification. A conclusion section is also presented at the end.

A.1 SCREENING PROCESS

A total of nine designs were assigned a score from -2 to +2 across eight different design criteria based on their relative strength in each. The scores were then weighted based on which criteria were of greater importance to the overall project. Once each of the designs had been assigned a weighted score for each criterion, these were summed to determine an overall rank.

A.2 DESIGN CRITERIA

Several design criteria were developed to evaluate the heat recovery system concepts. They are discussed in the following section.

A.2.1 COST

The cost of each design was one of the most important aspects of a given heat recovery system concept. The commercial availability of the required parts, complexity of the design, cost of installation, and cost of auxiliary equipment were all factors that were considered.

A.2.2 RECOVERABLE HEAT (BTU/HR)

The potential amount of energy that could be captured per hour by each design was also very important. Research was conducted to estimate the amount of energy that could be recovered by each design.

A.2.3 RANGE SUITABILITY

The range of TOX flow rates that the heat transfer system could accommodate was also evaluated. Again, external research was needed to determine the approximate operational ranges for each concept.

A.2.4 PRESSURE DROP

The pressure drop incurred by the heat recovery system on the TOX was evaluated. Any auxiliary equipment such as heat exchangers, tubes, etc. that comes in direct contact with the flue gas flow cause a loss in pressure. This is an important consideration as too large of a pressure drop could severely impact the operation and efficiency of the TOX system.

A.2.5 RELIABILITY

The reliability of a given concept was evaluated based on expected preventative maintenance schedules, design complexity, and technological maturity. A final consideration was if components of the system needed to be placed outdoors where thermal stress could have a negative impact on the life expectancy of the system.

A.2.6 ACCESSIBILITY

The accessibility of the given systems in regards to maintenance operations was also considered. The size and location of the systems were taken into account to determine a score.

A.2.7 AVERAGE EFFICIENCY

The average efficiency of each concept was another factor considered. External research was required in certain instances and coupled with expected values based on the previous experience of certain team members to determine a proper score.

A.2.8 FEASIBILITY

The feasibility of each concept was of great importance and evaluated using two main factors. The primary factor considered was the commercial availability of the system components. The secondary factor were the physical size requirements of the system.

A.3 RESULTS AND DISCUSSION

The completed screening matrix is presented below.

TABLE VII: Concept screening matrix

	Scaling Factor	Air-Air Heat Exchanger	Air-Air to Air-Liquid Heat Exchanger	Air-Liquid Heat Exchanger	Waste Heat Boiler	Heat Wheel	WHB with Preheat	Direct-Contact Recuperator	TOX Encompassing Boiler	WHB with DCR
Cost	2	-2	0	2	-2	-4	-2	-4	-4	-4
BTU/hr	3	0	-3	0	3	6	3	6	0	6
Range Suitability	3	-3	-3	0	3	3	3	3	0	3
Pressure Drop	2	2	2	0	2	-2	-2	4	0	2
Reliability	2	4	0	2	2	2	2	-2	-4	-4
Accessibility	1	0	-1	0	-1	-1	-1	-1	-1	-1
Avg. Efficiency	2	0	-2	-2	2	0	0	4	-2	2
Feasibility	3	-6	-3	-6	6	-6	-6	6	-6	-3
Sum		-5	-10	-4	15	-2	-3	16	-17	1
Rank		7	8	6	2	4	5	1	8	3

The scores for various design criteria are discussed in the following subsections.

A.3.1 COST

The designs that scored low in the cost category included the heat wheel, direct-contact recuperator, TOX encompassing boiler, and waste heat boiler with direct-contact recuperator. These designs all had similar flaws in that they were relatively new concepts that required custom parts instead of off-the-shelf components. The air-to-liquid heat exchanger was the only design that received a positive score in this category.

A.3.2 BTU/HR

The designs that scored highly in the amount of energy recovered per hour were the heat wheel, direct-contact recuperator, and the waste heat boiler with direct-contact recuperator. Research performed by the team showed that these designs offered a higher heat recovery capacity relative to the others.

A.3.3 RANGE SUITABILITY

The waste heat boiler, heat wheel, waste heat boiler with reheat, direct-contact recuperator, and waste heat boiler with direct-contact recuperator all scored well in terms of accommodating the flow range of the current operating system. These designs are all scale well to accommodate a wide range of flow conditions. The heat exchangers scored lower because they are not found to be as flexible with regards to the flow rate.

A.3.4 PRESSURE DROP

The direct-contact recuperator scored highest in terms of incurred pressure drop on the TOX system because the designs that are available come with a pre-specified fan. The fan serves to eliminate any potential pressure drop in the system. The heat wheel scored poorly because its design directly impedes the flow. The waste heat boiler also scored poorly because it generally places tubes inside the stack that also impede the flow.

A.3.5 RELIABILITY

The air-to-air heat exchanger scored well in regards to the reliability of the system. Its simple design, proven technology, and commercially available components make it attractive. However, the TOX encompassing boiler and the waste heat boiler with direct-contact recuperator did not score well because of their increased complexity.

A.3.6 ACCESSIBILITY

Accessibility was a category where none of the design concepts received a high score. This is because of the lack of available space within the plant where they would ideally be located. Complexity was also a factor that made some of the designs score poorly with regards to accessibility, as added components require added space.

A.3.7 AVERAGE EFFICIENCY

The average efficiencies for each design were estimated through research. The direct-contact recuperator had the highest efficiency when compared to the other designs because it has the unique ability to recover latent heat.

A.3.8 FEASIBILITY

The waste heat boiler and direct-contact recuperator scored highest in terms of feasibility because they require few modifications to the current TOX system. The air-to-air heat exchanger, air-to-air and air-to-liquid heat exchanger, heat wheel, waste heat boiler with reheat, and TOX encompassing boiler all scored poorly in this category. This is either due to their large physical size or dependence on several modifications to the existing system.

A.4 CONCLUSION

The top two designs as per the screening matrix are the direct-contact recuperator and the waste heat boiler. These concepts were the first to be investigated in further detail for the project. Further into the project, the air-liquid to liquid-liquid heat exchanger concept was also considered.

APPENDIX B – DETAILED DESIGN ANALYSIS

B.1 EXHAUST FLOW ANALYSIS

To determine the mass flow rate of the TOX's flue gases, the incineration process was analyzed. All known process parameters are indicated in the figure below.

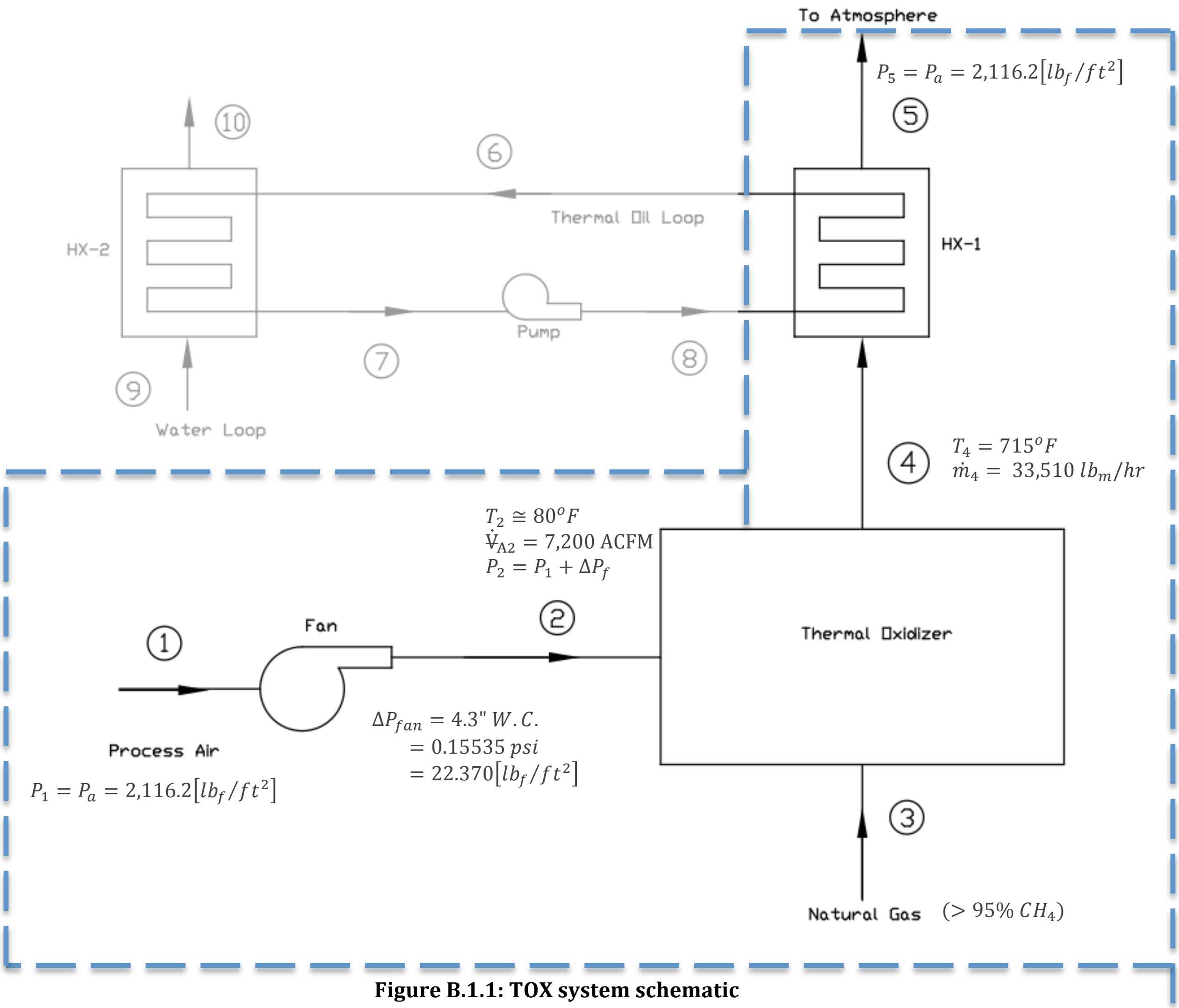


Figure B.1.1: TOX system schematic

The process air contains trace amounts of ethyl, methyl and isopropyl alcohols. Because their concentration is so small, their thermodynamic effects are minimal and they are neglected in the analysis. Thus, the process air to be incinerated was assumed to be standard air with a dew point (saturation temperature) of $8°C$. The assumed composition of the dry standard air is outlined below.

Composition of dry standard air [1]:

$$21\%\ O_2$$

$$79\%\ N_2,\ \therefore 3.76\ mol\ N_2\ per\ 1\ mol\ O_2$$

To determine the amount of water vapour in the air, the humidity ratio corresponding to the saturation temperature was found from the psychrometric chart [1].

$$\omega = m_{water\ vapour}/m_{dry\ air},\ \omega|_{T_{sat}=8℃} = 0.007\left[lb_{h_2o}/lb_{air}\right]$$

The number of moles of water vapour per mole of O_2 in the air is x.

$$x = 7.655\omega = 0.053585$$

The natural gas from Manitoba Hydro was found to be more than 95% methane [2]. Therefore, it was assumed to be 100% methane to ease calculations. Through talks with Valeant, it was determined that approximately 110% of theoretical air was required for the combustion process. Thus, the combustion reaction can be written as follows,

$$CH_4 + 1.1(2)(O_2 + 3.76N_2 + 0.053585H_2O) \rightarrow CO_2 + 2.1179H_2O + 8.272N_2 + 0.2O_2$$

To determine the mass flow rate of the flue gases, first, the air-to-fuel molar ratio was found.

$$AF_{mole} = \frac{mole\ air}{mole\ fuel} = \frac{(1.1)(2)(1+3.76+0.053585)}{1} = 10.560\left[\frac{kmol\ air}{kmol\ fuel}\right]$$

Next, the air-to-fuel mass ratio was found by first calculating the molecular mass of the air. Here, n_i and M_i are the number of moles and molecular masses of each component of the air, respectively.

$$\bar{M}_{O_2} = 31.999 \qquad [1]$$

$$\bar{M}_{N_2} = 28.013 \qquad [1]$$

$$\bar{M}_{H_2O} = 18.015 \qquad [1]$$

$$\bar{M}_2 = \frac{\sum n_i M_i}{\sum n_i} = \frac{1(31.999)+3.76(28.013)+0.053585(18.015)}{1+3.76+0.053585} = 28.720$$

$$\bar{M}_{CH4} = 16.043 \quad [1]$$

$$AF_{mass} = \frac{10.56(28.72)}{1(16.043)} = 18.904\left[\frac{kg\ air}{kg\ fuel}\right]$$

Finally, the air was analyzed to determine the density, ρ_{a2}, as it was needed to calculate the mass flow rate of the air, $\dot{m}_a$.

$$\dot{m}_2 = \rho_2 \dot{\cancel{V}}_2,\ \dot{\cancel{V}}_2 = 7{,}200\ [acfm]$$

The density, ρ_{A2}, can be found using the ideal gas law.

$$P_2 = \rho_2 R_2 T_2 \rightarrow \rho_2 = \frac{P_2}{R_2 T_2}$$

However, first R_A must be calculated using the molecular weight of the humid air, $\bar{M}_2$, from before and the ideal gas constant, $\bar{R}$.

$$\bar{M}_2 = 28.72$$

$$\bar{R} = 8.3145\left[\frac{kJ}{kmol\cdot K}\right] \quad [1]$$

$$R_2 = \frac{\bar{R}}{\bar{M}_2} = \frac{8.3145}{28.730} = 0.28940\left[\frac{kJ}{kmol\cdot K}\right] = 53.789\left[\frac{ft\cdot lb_f}{lb_m\cdot {}^{\circ}R}\right]$$

The temperature of the air was approximated at 80°F.

$$T_2 \cong 80°\text{F} = 539.67°R$$

Pressure was then calculated, taking the pressure rise from the fan into account.

$$P_2 = P_1 + \Delta P_{fan} = 2116.2 + 22.3704 = 2{,}138.6\ \left[\frac{lb_f}{ft^3}\right]$$

Thus,

$$\rho_2 = \frac{P_2}{R_2 T_2} = \frac{2{,}138.6}{53.789(539.67)} = 0.073673\left[\frac{lb_m}{ft^3}\right]$$

$$\dot{m}_2 = \rho_2 \dot{V}_2 = 0.073673(7{,}200(60)) = 31{,}827 \left[\frac{lb_m}{hr}\right]$$

$$\dot{m}_4 = \dot{m}_2 + \dot{m}_F = \dot{m}_2 + \dot{m}_2\left(\frac{1}{\dot{m}_2/\dot{m}_F}\right) = \dot{m}_2 + \frac{\dot{m}_2}{AF} = \dot{m}_2\left(1 + \frac{1}{AF}\right)$$

$$= 31{,}827\left(1 + \frac{1}{18.904}\right) = 33{,}510 \left[\frac{lb_m}{hr}\right]$$

With the mass flow rate of the flue gases known, the last step is to calculate the volumetric flow rate of the flue gases as it was required by the suppliers. The density, ρ_4, is found in similar fashion as ρ_2. Again, the ideal gas law applies.

$$P_4 = \rho_4 R_4 T_4 \rightarrow \rho_4 = \frac{P_4}{R_4 T_4}$$

R_4 is calculated using the molecular weight of the combustion products, $\bar{M}_4$, and the ideal gas constant, $\bar{R}$.

$\bar{M}_{CO_2} = 44.01$ [1]

$\bar{M}_{O_2} = 31.999$ [1]

$\bar{M}_{N_2} = 28.013$ [1]

$\bar{M}_{H_2O} = 18.015$ [1]

$$\bar{M}_4 = \frac{\sum n_i M_i}{\sum n_i} = \frac{1(44.01)+2.117887(18.015)+8.272(28.013)+0.2(31.999)}{1+2.117887+8.272+0.2} = 27.635 \left[\frac{kg}{kmol}\right]$$

$\bar{R} = 8.3145 \left[\frac{kJ}{kmol\cdot K}\right]$ [1]

$$R_4 = \frac{\bar{R}}{\bar{M}_4} = \frac{8.3145}{27.635} = 0.30087 \left[\frac{kJ}{kmol\cdot K}\right] = 55.920 \left[\frac{ft\cdot lb_f}{lb_m\cdot{}^\circ R}\right]$$

The average temperature of the flue gases was calculated to be 715°F.

$$T_4 = 715^\circ\mathrm{F} = 1{,}174.7^\circ R$$

Pressure was taken as atmospheric, neglecting the pressure drop from the heat exchanger. Thus,

$$\rho_4 = \frac{P_a}{R_4 T_4} = \frac{2138.6}{55.920(1174.7)} = 0.032215 \left[\frac{lb_m}{ft^3}\right]$$

$$\dot{m}_4 = \rho_4 \dot{V}_4 \ \rightarrow \ \dot{V}_4 = \frac{\dot{m}_4}{\rho_4}$$

Finally,

$$\dot{V}_4 = \frac{33{,}510}{0.032215^2} = 1{,}040{,}182 \left[\frac{ft^3}{hr}\right] = 17{,}336 \ [acfm]$$

B.2 HEAT EXCHANGER ANALYSES

The proposed thermal fluid loop heat recovery system is pictured in the figure below. A thermodynamic analysis of the system was performed to verify the values supplied by Thermal Energy International. The theoretical potential heat recovery from the two heat exchangers is calculated in this section.

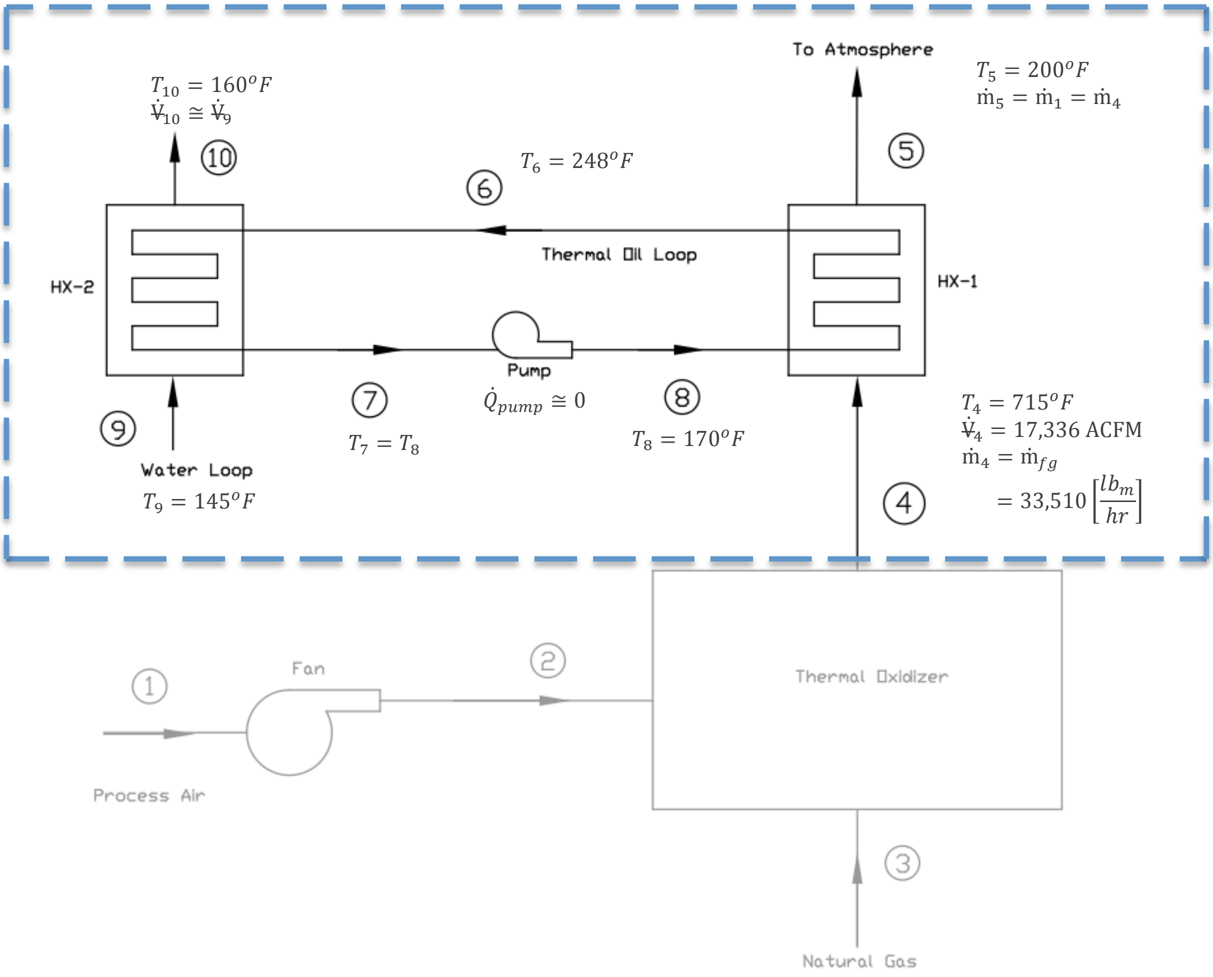


Figure B.2.1: Thermal fluid loop schematic

The heat flux from the flue gas can be calculated by the formula below.

$$\dot{Q}_4 = \dot{m}_4\left(C_{p_4}T_4 - C_{p_4}T_5\right) \qquad where \qquad \dot{m}_4 = \rho_4\dot{V}_4 = \rho_5\dot{V}_5$$

The only unknowns are C_{p_4} and C_{p_5}. Both values can be found using the C_{p_i} values of each flue gas component with the following formula.

$$C_{p_{4,5}} = \sum c_i C_{p_i} = \sum \frac{\dot{m}_i}{\dot{m}_{fg}} = \sum \frac{\left(\frac{n_i}{n_{fg}}\right)M_i}{M_{fg}} C_{p_i}$$

The individual C_{p_i} are found with the following cubic approximation.

$$C_{p_i} = C_0 + C_1\theta + C_2\theta^2 + C_3\theta^3$$

The following table summarizes the cited and calculated data for each flue gas component.

TABLE VIII: Cp data for flue gas components

	C_0[1]	C_1[1]	C_2[1]	C_3[1]	$C_{p_{i1}}$	$C_{p_{i2}}$	n_i	M_i[1]	c_i
CO_2	0.45	1.67	-1.27	0.39	1.1074	0.91065	1	44.01	0.13741
H_2O	1.79	0.107	0.586	-0.2	2.0538	1.8981	2.117887	18.015	0.11912
N_2	1.11	-0.48	0.96	-0.42	1.0889	1.0424	8.272	28.013	0.72349
O_2	0.88	-1e-4	0.54	-0.33	1.0182	0.93625	0.2	31.999	0.019981

Using the above data, the $C_{p_{fg}}$ can be calculated.

$$C_{p_4} = 0.13741(1.1074) + 0.11912(2.0538) + 0.72349(1.0889)$$

$$+0.019981(1.0182) = 1.2050\left[\frac{kJ}{kg\cdot K}\right]$$

$$C_{p_5} = 0.13741(0.91065) + 0.11912(1.8981) + 0.72349(1.0424)$$

$$+0.019981(0.93625) = 1.1241\left[\frac{kJ}{kg\cdot K}\right]$$

With these values, the heat flux can be determined.

$$\dot{Q}_4 = \dot{m}_4\left(C_{p_4}T_4 - C_{p_5}T_5\right)$$

$$= 33{,}510\left(1.2050(1174.7) - 1.1241(659.67)\right)$$

$$= 5.3943\left[\frac{MMBtu}{hr}\right]$$

This value for heat flux is higher than the predicted value from Thermal Energy International. The reason for this is likely because TEI assumed dry standard air as the working fluid whereas the above analysis considers the combustion of humid air. Throughout the rest of the analysis, the heat flux from TEI was used as a conservative estimate.

The thermal oil loop is analyzed next. The thermal oil is assumed to be incompressible ($\therefore \rho_6 = \rho_7 = \rho_8 = constant$).

$$\dot{m}_6 = \rho_6 \dot{V}_6$$

With the design heat flux of 4.6 $\left[\frac{MMBtu}{hr}\right]$ and the assumed values of $c_{p_6} = 0.6\ \left[\frac{Btu}{lb_m{\cdot}°\mathrm{F}}\right]$ and $\rho_6 = 7\ \left[\frac{lb_m}{gal}\right]$ from TEI, the heat flux equation becomes:

$$\dot{Q}_6 = \dot{Q}_{HX1} = \dot{V}_6 \rho_6 c_{p_6}(T_6 - T_7) = 4.6\left[\frac{MMBtu}{hr}\right]$$

Rearranging for $\dot{V}_{TO}$

$$\dot{V}_6 = \frac{\dot{Q}_6}{\rho_6 c_{p_6}(T_6 - T_7)} = \frac{4{,}600{,}000\left[\frac{Btu}{hr}\right]\cdot\left[\frac{1\,hr}{60\,min}\right]}{\left(7\left[\frac{lb_m}{gal}\right]\right)0.6\left[\frac{Btu}{lb_m{\cdot}°\mathrm{F}}\right](248°F - 170°F)} = 234.0[gpm]$$

Moving on to the oil-to-water heat exchanger, water is assumed incompressible ($\therefore\ \rho_9 = \rho_{10} = constant$). Therefore, the heat flux formula can be written:

$$\dot{Q}_{HX1} = \dot{Q}_{HX2} = \dot{V}_W \rho_W c_{p_W}(T_{10} - T_9)$$

Rearranging for $\dot{V}_W$,

$$\dot{V}_W = \frac{\dot{Q}_{HX2}}{\rho_w c_{p_w}(T_7 - T_6)}$$

where,

$$c_{p_w} = 1.00\left[\frac{Btu}{lb_m{\cdot}°R}\right]\ [1]$$

$$\rho_W = \rho_6 = ({v_6}^{-1}) = 61.293\ \left[\frac{lbm}{ft^3}\right]\ [1]$$

Thus, the volumetric flow rate can be calculated as follows:

$$\dot{V}_W = \frac{4{,}600{,}000\ \left[\frac{Btu}{hr}\right]\cdot\left[\frac{1\ hr}{60\ min}\right]}{\left(61.293\ \left[\frac{lb_m}{ft^3}\right]\cdot\left[\frac{ft^3}{7.8405\ gal}\right]\right)1\left[\frac{Btu}{lb_m \cdot °F}\right](165°F - 145°F)}$$

$$= 467.8\ gpm$$

References:

[1] R.E. Sonntag, C. Borgnakke, and G.J. Van Wylen, *Fundamentals of Thermodynamics*, 6th ed. Hoboken, NJ: John Wiley & Sons, 2003.

[2] Manitoba Hydro. (2010). *Manitoba Hydro Odorized Natural Gas MSDS* [Online]. Available: http://www.hydro.mb.ca/safety_and_education/home/natural_gas_odorized.pdf [Nov. 22, 2010].

APPENDIX C – PIPE LOSS CALCULATIONS

Volumetric flow rates $\dot{V}_W$ and $\dot{V}_{TO}$ were calculated in Appendix B at the average system flow rate. However, to determine piping and pump sizes, the maximum volumetric flow rates must be used. The maximum flow rates were calculated using the method shown in Appendix B, yielding:

$$\dot{V}_{T_o} = 250\ [gmp], \dot{V}_w = 500\ [gpm]$$

Both the oil and water loops are closed systems. Therefore, only the length of the pipe will be considered and not the change in elevation for the head loss calculations.

C.1 OIL LOOP PIPE LOSSES

Piping losses are based on the frictional losses in the main pipes, fitting losses, and pressure drop across the heat exchangers. Assume that the system will contain 12 - 90° elbows and 7 gate valves.

Use ø4" schedule 40 piping.

$$\Delta P = \Delta P_{pipe} + \Delta P_{fittings} + \ \Delta P_{HX}$$

Where,

$$\Delta P_{pipe} = \frac{Loss}{100ft} \cdot L$$

$$\frac{Loss}{100ft} = 3.75 \left[\frac{ft}{100\ ft}\right] \quad [1]$$

$$L = 125\ [ft]$$

$$\Delta P_{fittings} = L_e \cdot \#_{fittings} + K_v \left(\frac{V^2}{2g}\right)$$

$$L_e = 11.6\ [ft] \qquad [1]$$

$$K_v = 0.16 \qquad [1]$$

$$V = 5 \left[\frac{ft}{s}\right] \qquad [1]$$

$$\Delta P_{HX} = 5\ [psi] = 11.53\ [ft]$$

$$\Delta P = \frac{3.75[ft]}{100\ [ft]} \cdot (125\ [ft] + 11.6\ [ft] \cdot 12) + 0.16 \cdot \frac{\left(5\left[\frac{ft}{s}\right]\right)^2}{2g} + 2 \cdot 11.53\ [ft]$$

$$\Delta P = 33.0\ [ft]$$

Applying a safety factor of 10% to account for differences in the construction of the system and piping yields:

$$\Delta P = 36.3\ [ft]$$

Thus, a pump rated at 250 [gpm] @ 36.3 [ft] of head is required for the oil circulation pump.

C.2 WATER LOOP PIPE LOSSES

Use ø5" schedule 40 piping. Assume 12 - 90° elbows and 7 gate valves.

$$\Delta P = \Delta P_{pipe} + \Delta P_{fittings} + \Delta P_{HX}$$

Where,

$$\Delta P_{pipe} = \frac{Loss}{100ft} \cdot L$$

$$\frac{Loss}{100ft} = 4.5\left[\frac{ft}{100\ ft}\right] \qquad [1]$$

$$L = 115\ [ft]$$

$$\Delta P_{fittings} = L_e \cdot \#_{fittings} + K_v\left(\frac{V^2}{2g}\right)$$

$$L_e = 19.8\ [ft] \qquad [1]$$

$$K_v = 0.13 \text{ Gate Valves} \qquad [1]$$

$$V = 8\left[\frac{ft}{s}\right] \qquad [1]$$

$$\Delta P_{HX} = 5\ [psi] = 11.53\ [ft]$$

$$\Delta P = \frac{4.5\ [ft]}{100\ [ft]} \cdot (115\ [ft] + 19.8[ft] \cdot 12) + 0.13 \cdot \frac{\left(8\left[\frac{ft}{s}\right]\right)^2}{2g} + 11.53\ [ft]$$

$$\Delta P = 27.6\ [ft]$$

Applying a safety factor of 10% to account for differences in the construction of the system and piping yields:

$$\Delta P = 30.4\ [ft]$$

Thus, a pump rated at 500 [gpm] @ 30.4 [ft] of head is required for the water booster pump.

References:

[1] ASHRAE – Handbook, *Fundamentals (*I-P edition), American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 2005.

APPENDIX D – DETAILED COST ANALYSIS WITH BILL OF MATERIALS

Cost components for this project can be separated into five major sections:

Major Equipment: Critical functional components of the system. E.g. heat exchangers and expansion tanks.

Minor Equipment: Auxiliary equipment required allowing major equipment to function, e.g. pumps, valves, fittings, and sensing devices.

Material: Raw material required to connect major and minor equipment, also used for support structuring, e.g. pipe, electrical wire & conduit, ducting.

Installation: Required professionals to install above equipment, e.g. electricians, pipe fitters, welders.

Commissioning: Budgeting of site visits and technical support from major equipment suppliers.

Major Equipment

No.	Type	Supplier	Quantity	Cost/ Unit	Total Cost	Note
1	Indirect Heat Recovery Unit	TEI	1	--		
2	Shell and Tube Water Heater	TEI	1	--		
3	Expansion Tank	TEI	1	--		
4	Control System	TEI	1	--		
5	Nitrogen Blanket System	TEI	1	--	$427,200.00	Total of above items [1]
				Subtotal	$427,200.00	

Minor Equipment

No.	Type	Supplier for Pricing	Quantity	Cost/ Unit	Total Cost	Note
1	Water Side Pump	Midwest Engineering	1	2912	$2,912.00	
2	4.0" Globe Valve	Online	8	556	$4,448.00	Online [2]
3	5.0" Glove Valve	Online	3	717.5	$2,152.50	Online [2]
4	3-way valve	TBD	1	2140	$2,140.00	Online [2]
5	4" Elbow	Victaulic	24	110	$2,640.00	
6	5" Elbow	Victaulic	24	263.5	$6,324.00	
7	4" Coupling	Victaulic	86	89	$7,654.00	
8	5" Coupling	Victaulic	16	115.5	$1,848.00	
9	Other Piping Components		1	3000	$3,000.00	
				Subtotal	$33,118.50	

Material

No.	Type	Supplier	Quantity	Cost/ Unit	Total Cost	Note
1	5.0" C/W Blk Steel Pipe	Wolseley	120	36.85	$4,422.00	Estimated [3]
2	4.0" C/W Blk Steel Pipe	Wolseley	150	22.36	$3,354.00	Estimated [3]
3	Structural Steel	Brunswick	8250	3	$24,750.00	$3/lb installed [4]
4	Electrical Supplies	??	1	15000	$15,000.00	Estimate
5	Pipe Insulation	??			$7,776.00	Estimate
6	Duct	Basar	--		$30,000.00	Estimate
				Subtotal	$85,302.00	

Installation

No.	Type	Supplier	Quantity (day)	Cost/ Unit	Total Cost	Note
1	Pipe Fitter		10	1040	$10,400.00	2 fitters over 10 days [5]
2	Electrician - High Voltage	Tri-Star	15	1000	$15,000.00	
3	Electrician - Electronics	Honeywell	3	800	$2,400.00	
4	Craning		1	800	$800.00	
5	Welding		8	560	$4,480.00	3 days labour
6	Ductwork	Basar	5	1040	$5,200.00	
7	Pipe Insulation				$10,400.00	
8	Structural Engineering		1	10000	$10,000.00	
				Subtotal	$58,680.00	

Commissioning

No.	Type	Supplier	Quantity	Cost/ Unit	Total Cost	Note
1	Commissioning Site visit	TEI		1500	$4,500.00	3 day site visit at $1500/day
				Subtotal	$4,500.00	

Contingency

Subtotal	$64,872.39	10% of total cost

Total	$673,672.89

The following parameters were omitted as they were outside the scope of the project [6]:

-Time-value of money

-Tax adjustments

-Inflation

The cost breakdown and bill of materials can be seen in the following table. Subtotals for each cost section are found at the end of the section. A total cost of \$673,672.89 for the implementation of this system was estimated.

Return on investment can be calculated in quantity time, using the simple formula,

$$ROI = \frac{Yearly\ Savings - Yearly\ Operational\ Cost}{Total\ Capital\ Investment}$$

Yearly cost savings are dependent on energy saved, and its equivalent cost in terms of natural gas. Manitoba Hydro rates for Valeant place the facility in the 'High Volume Firm' service line and a report submitted to Valeant in 2009 stated the cost of natural gas at \$0.3451/m^3 of natural gas [7].

At an average of 4.6 MMBtu/hr savings from the existing system, using a value of 36,285.5 BTU/m^3 of natural gas, an equivalent 126.77 m^3/hr of natural gas is saved using this system. At the Valeant price rate of \$0.3451/m^3, a total saving of \$43.7492/hr is realized. Using the 69% 'On' time and estimating 10 days of downtime for the system, a total of 5,882 hrs. of operational time is found. This translates to \$257,332.54 annually.

Knowing the total capital investment, and yearly savings, the yearly operational costs must be approximated. A percentage of the system capital cost is used for this, in the area of 1%. Therefore a total value of \$6,740 per year is required to operate this system. From this, the overall return on investment is 37.8%, which translates to an approximate 2.65-year payback.

References:

[1] R. Triebe (private communication), Nov. 16, 2010.

[2] The Valve Shop. (2010). *Smith Gate Valve* [Online]. Available: http://www.thevalveshop.com/menu/manual/smith/gate.html [Nov. 28, 2010].

[3] State Supply. (2010). *Standard Black Iron Pipe* [Online]. Available: http://www.statesupply.com/displayCategory.do?cuid=PF2042A [Nov. 28, 2010].

[4] K. Sim (private communication). Nov. 15, 2010.

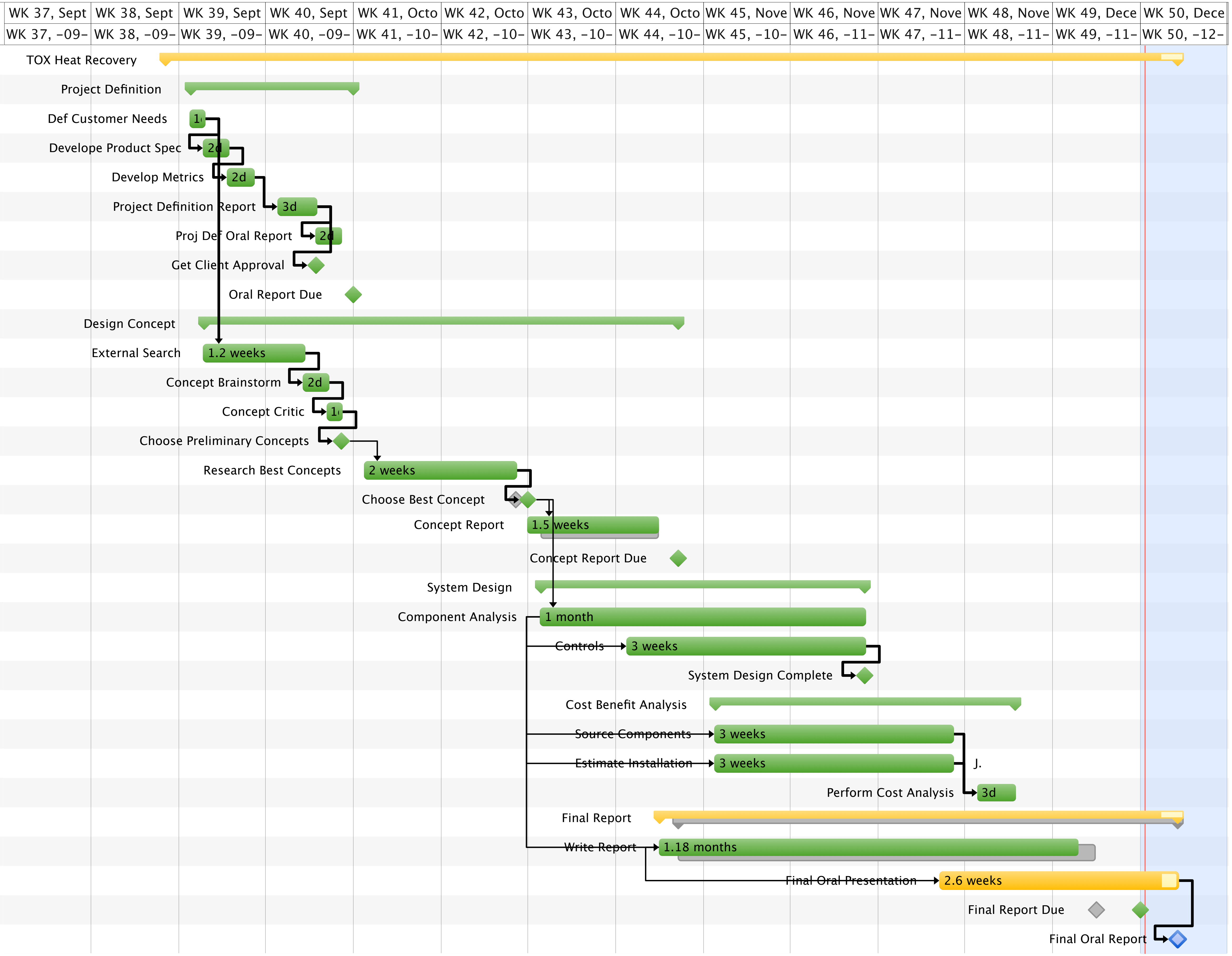
[5] A. Berg (private communication). Nov. 24, 2010.

[6] D. Dowle (private communication), Nov. 28, 2010.

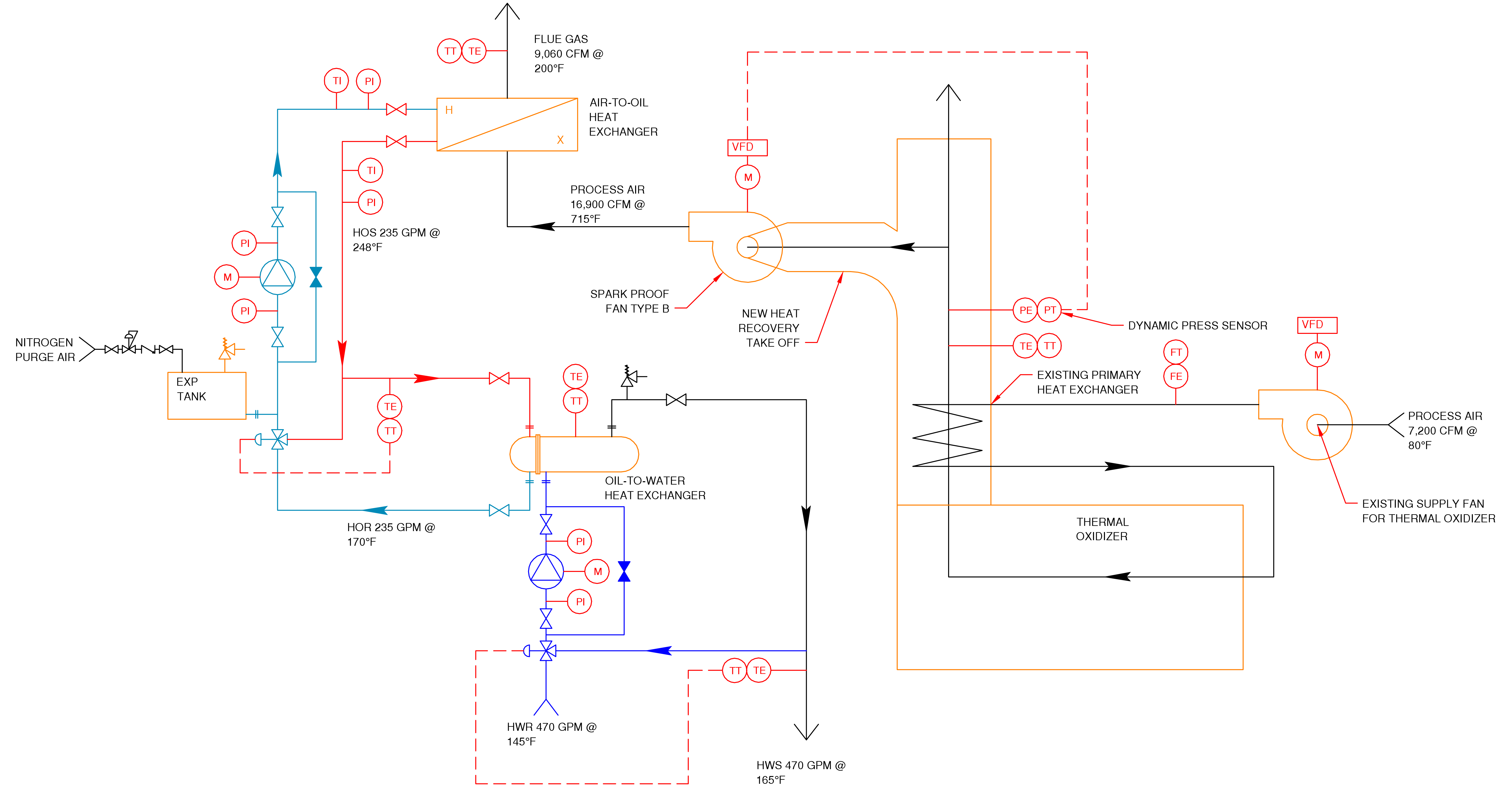
[7] D. Robinson (private communication), Oct. 21, 2010.

APPENDIX E – GANTT CHART

#	Title	Planned End
0	**TOX Heat Recovery**	10-12-07
1	**Project Definition**	10-10-03
2	Def Customer Needs	10-09-20
3	Develope Product Spec	10-09-22
4	Develop Metrics	10-09-24
5	Project Definition Report	10-09-29
6	Proj Def Oral Report	10-10-01
7	Get Client Approval	10-09-29
8	Oral Report Due	10-10-03
9	**Design Concept**	10-10-29
10	External Search	10-09-28
11	Concept Brainstorm	10-09-30
12	Concept Critic	10-10-01
13	Choose Preliminary Concepts	10-10-01
14	Research Best Concepts	10-10-15
15	Choose Best Concept	10-10-15
16	Concept Report	10-10-27
17	Concept Report Due	10-10-29
18	**System Design**	10-11-12
19	Component Analysis	10-11-12
20	Controls	10-11-12
21	System Design Complete	10-11-12
22	**Cost Benefit Analysis**	10-11-24
23	Source Components	10-11-19
24	Estimate Installation	10-11-19
26	Perform Cost Analysis	10-11-24
27	**Final Report**	10-12-07
28	Write Report	10-12-01
29	Final Oral Presentation	10-12-07
30	Final Report Due	10-12-01
31	Final Oral Report	10-12-07



APPENDIX F – PIPING & INSTRUMENTATION DIAGRAM (PID-001)



SĀFF
ENGIEERING
UNIVERSITY OF MANITOBA
DEPARTMENT OF MECHANICAL AND
MANUFACTURING ENGINEERING

CLIENT
VALEANT PHARMACEUTICALS

TOX HEAT RECOVERY
P&ID LOOP

DESIGNED	JSF	APPROVED	
DRAWN	JSF	SCALE	NTS
CHECKED		DATE (MMM/DD/YY)	NOV 29/30
PROJECT NO.		DRAWING NO.	REV
4680		PID-001	00