# Attachment G- OSWI 60.2895 Air Pollution Control Alternatives

## RACT Analysis

**Purpose:**

This document serves as the RACT assessment per the requirements associated with 5 CCR 1001-5 (Regulation 3, III.D.2) as well as the requirements stated in 40 CFR 60.2895 EEEE (EEEE) siting analysis:

> *"….must consider air pollution control alternatives that minimize, on site-specific basis, to the maximum extent practicable, potential risks to public health or the environment. In considering such alternatives, you may consider costs, energy impacts, nonair environmental impacts, or any other factors related to the practicability of the alternatives."* (Government, 2014)

The information and items below were/are being used to determine appropriate technologies and processes to meet the new emission, operational, reporting, and other permitting requirements for Denver Zoo's waste to energy facility. This information will be modified as necessary based on development, testing and operation of proposed equipment.

**General Description:**

Denver Zoo's gasification system is a downdraft unit that utilizes a processed waste stream with the goal of producing a combustible "syngas" or (prior to clean-up) "producer gas". This gas contains primarily hydrogen and carbon monoxide deemed combustible and utilized downstream either through general combustion or in an internal combustion engine/ combustion turbine. With the use of air as an oxidizer for the reaction, the resulting gas produced will be have high levels of nitrogen but still have an energy value of approximately 120 Btu/scf of gas.

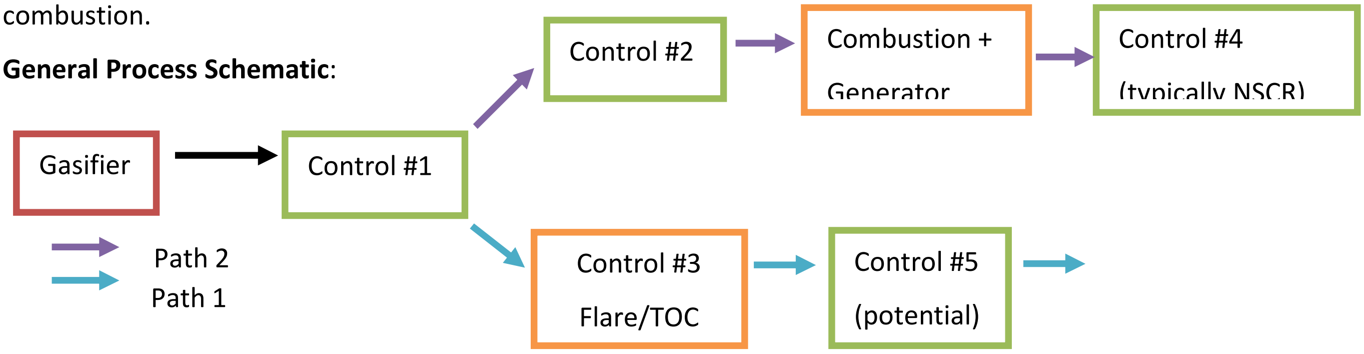
The primary goal is the combustion of the 120 Btu/scf "syngas" is for the production of energy. In order to achieve this, DZF will need to test the operation and production of gas to understand and collect data related to the constituents inherent in the gas that are considered problematic for controlled combustion in a generator/turbine. These include, but are not limited to: Particulate matter (PM), tars (organics produced under thermal or partial-oxidation regimes, generally assumed to be largely aromatic – sometimes simply stated as "hydrocarbons with a molecular weight higher than benzene" (Rabou, 2009), Hydrochloric Acid (HCl), Hydrogen Sulfide (H2S), and Nitrogen Oxides (NOx).

During start-up, shutdown, and upset conditions DZF requires the use of a robust combustion technology with the primary requirement to fully combust/destroy syngas and tars for clean-up. The challenge being that start up and shutdown is outside of the gasifier's optimal operating temperatures and thus the gas produced is heavily laden with tars and particulates due to incomplete conversion. The challenge is to design/develop a system that can handle a large range of conditions without being overloaded or affected in a way the warrants shutdown or emergency release of gas do to plugged or clogged lines. Initially and because sampling and testing must occur for to fully understand the gas produced from our scaled laboratory gasifer, we will need to collect samples, because of this DZF will be utilizing the flare/oxidizer for more than start-up and shut-down.

Gas clean-up technologies (additional control devices beyond the flare/thermal oxidizer) vary and much work has been performed to identify the best means to clean-up the producer gas and keep the valuable gases unchanged or positively altered. The options and technologies available to address these concerns are defined within this document.

In order to operate successfully, the use of multiple control devices are necessary. It is generally more cost effective due to scale to approach as much clean-up as possible prior to the last control mechanism: combustion.

**General Process Schematic**:



**Previous Design:**

Denver Zoo's previous design for destroying and/or limiting emissions related to start-up, shut-down, and general operation were primarily controlled by a forced draft flare engineered and designed by System Analysis and Solutions (SAS). This flare/control device included monitoring, and mixing air with natural gas to attain high and controlled temperatures with the product gas from the gasifier at an estimated destruction efficiency of around 98.9%.

Prior to reaching the flare DZF and SAS were working on a rudimentary means of removing additional particulates and tars through the use of a striker plate/pressure drop/ and potential heated oil misting system (control #1). The purpose of this system was to keep temperatures above the saturation temperature of most of the problematic tars contained in the gases to specifically remove those that will condense between 850°C (exit temperature of gasifier) and 500°C in a controlled manner. (Basu, 2010)

Prior to these design adjustments were considered, the design, engineer, fabrication, and installation had the following approximate elements:

**Costs (est)**

The budgeted cost and estimated budget to complete work associated (capital and installation) with this flare came to around $120,000 - $140,000. This cost did not included continuous emission monitoring and initially a btu monitoring systems was included, but consideration of maintenance and concerns about the accuracy related to maintenance caused it to be removed.

**Energy Impacts**

In order to achieve higher destruction efficiency and control, natural gas is blended with the “syngas” created from the gasifier to raise the inherent BTU value of these gas and also develop more complete combustion and destruction. This was designed to be between 10-12% by volume to achieve a higher energy content overall of around 200-250 btu/scf when the gasifier is operating at ideal operating conditions. The design included a forced draft blower for controlled air introduction and mixing. The associated rudimentary clean-up system could cause a pressure drop that may require additional support to move gas and thus the addition of an in-line blower/gas mover was considered a potential and room was left for it in the initial design.

**Practicability**

This approach was the most practical approach for the gasifier when considering costs, maintenance, and future usage. The operation of the flare will be decreasing as the gasifier and downstream combustion for energy production was implemented further.

**Non-air environmental impacts**

After reviewing and determining OSWI (40 CFR 60 Table 1) requirements applicability to existing design conditions, it was discovered that alternations to the design must occur. The focus of these adjustments will be around further removal of: Carbon Monoxide (CO), Hydrogen Chloride (HCl), and Sulfur oxides (SOx) as required after performing calculations. Of these particular constituents, SOx and HCL became the focus for controlling as they can’t be controlled with just the Flare alone. Carbon Monoxide is a gas that can be more controlled with the use of residence time and temperatures during combustion. Some of the combustion alternatives are described below.

**Control #3 - Combustion Alternatives (Flare/TOC)**

There are alternatives that could be used to improve and further control destruction efficiency to meet the new EEEE requirements. (Government, 2014) The locations of the control technologies are critical to the successful use and operation of them, they are covered briefly in this document currently because they are still being identified and evaluated. This document will be updated and submitted as more information and data as more data and information becomes available. The Technologies that have been evaluated and have estimated costs from associated vendors and/or costs provide from articles and journals are as follows:

**Direct Fired Thermal Oxidizer (no heat recovery)**

Thermal oxidative controls (TOCs) are used to degrade and breakdown volatile organic compounds (VOCs) to carbon dioxide and water vapor with high temperatures (~1500°F) to perform complete oxidation of chemical compounds. However, considerable energy/fuel must be supplied to the device to achieve these temperatures with the associated energy content of the fuel. Direct fired TOC is relatively simple but requires a high temperature chemical reaction and supplemental fuel to maintain these operational temperatures at 1500°F. Not only would this technique breakdown VOC, but it would thermally degrade and breakdown associated tars. The inclusion of tars would also assist in driving the thermal process and fuel portions of the reaction.

**Practicability**

Maintain such high temperature and require supplementation of fuel to maintain operational temperatures of the device. Despite regenerative methods, operation must be sustained and supported with external natural gas sources (preferably higher than 25% LEL (Explosive Level)). Fouling is always a concern when introducing tar into a process stream. Condensation of tar within piping and stream transitions can lead to clogging, increased maintenance, operation inefficiencies, and overall cost increase.

**Costs (est)**

Capital costs have been calculated from 18,000 scf/hr (300 scfm) resulting in \$8 – 32K (~25% less than regenerative methods). Previous calculation have generalized all items associated with device implementation, including installation, auxiliary equipment, operation, maintenance. This factor is 2.0768 of capital cost and results in a range of $17 - 66K to implement the technology. Natural gas consumption was estimated at 10-12% of overall TOC flow rate, and electricity usage at approximately 28,000 kWh, resulting in an annual cost from $60,200 -66,400. A complete description of line items and calculations can be found in Appendix G.1 Direct Fired Thermal Oxidizer.

**Energy impacts**

No regenerative techniques to reduce the energy impact. Without energy recovery, incineration is a high cost for supplementation of natural gas fuel. This unit would operate similarly to the original flare design but with better control of combustion that would reduce the CO emissions. Testing will have to occur with the introduction of natural gas to determine the minimum usage of gas to still achieve necessary emission standards under OSWI (EEEE). Energy consumption will support electrical blowers and utilize natural gas to supplement operational temperatures.

**Non-Air Environmental Impacts**

Soot and particulates will build up over time and require maintenance within the TOC. Heat will be generated and released as well as combustion of natural gas with no heat recovery. The use of the heat possible and tying back into the system (collecting waste heat for use in external heating or energy production) or reusing the heat to improve combustion efficiency is important.

**Regenerative Thermal Oxidizer (RTO).**

To improve upon the high thermal energy losses, regenerative methods are employed to maintain operating temperatures and ensure complete oxidation and improve overall efficiency of the process. Regularly used to control solvent fumes, odors, and VOC's these are standard and used in many industries. RTO's commonly use ceramic beds to capture waste heat from the incinerator**.** The RTO process is driven by a high temperature chemical reaction. One energy recovery technique includes recuperation of thermal energy emitted by the chemical reaction to maintain these operational temperatures at 1500°F. Efficient recovery is in the range of 90-97% of energy recaptured.

**Practicability**

It will be a challenge to maintain such high temperature and require supplementation of fuel to maintain operational temperatures of the device. Despite regenerative methods, operation must be sustained and supported with external natural gas sources. Not only would this technique breakdown VOC, but it would thermally degrade and breakdown associated tars. The inclusion of tars would also assist in driving the thermal process and fuel portions of the reaction. Fouling is always a concern when introducing tar into a process stream. Condensation of tar within piping and stream transitions can lead to clogging, increased maintenance, operation inefficiencies, and overall cost increase. The use of ceramic/catalyst beds may be possible in this process and their use could improve the performance and reduce the necessary thermal ignition temperature of carbon monoxide to improve destruction efficiencies.

**Costs (est)**

Capital costs have been calculated from 18,000 scf/hr (300 scfm) resulting in $11 – 43K. Previous calculation have generalized all items associated with device implementation, including installation, auxiliary equipment, operation, maintenance. This factor is 2.0768 of capital cost and results in a range of $22 – 88K to implement the technology. Natural gas consumption was estimated at 8% of overall TOC flow rate, and electricity usage at approximately 28,000 kWh, resulting in an annual cost from $53,800 - 62,000. A complete description of line items and calculations can be found in Appendix G.2 Regenerative Thermal Oxidizer.

**Energy impacts**.

Regenerative techniques reduce the energy impact compared to methods without recovery where 90-97% of energy recaptured. Energy consumption will support electrical blowers and utilize natural gas to supplement operational temperatures.

**Recuperative Thermal Oxidizer.**

Similar in cost to the regenerative TOC, this techniques uses a heat exchanger to capture the waste heat from the incinerator and transfer of heat to the incoming airstream. However, initial costs will be less and operating costs will be slightly more. As a result of lower energy recaptured (50-70%), the energy impact is more significant and maintaining high incineration temperature (1500°F) will require more natural gas fuel resulting is high operational costs for this method. With preferably higher than 15% LEL (Explosive Level), this method can run with particulate present. Natural gas consumption was estimated at 20% more than regenerative TOC resulting in 9.6% of overall TOC flow rate, and electricity usage at approximately 28,000 kWh, resulting in an annual cost from $57,600 -65,800. A complete description of line items and calculations can be found in Appendix G.3 Recuperative Thermal Oxidizer.

**Catalytic Oxidizer:**

A catalytic thermal oxidizer uses catalyst bed to complete the chemical process of oxidation. It uses a catalyst reaction to scrub off VOM. As an effect, the operational temperature is considerably lower at 800°F. Lower than 15% LEL is ideal, no Halogens or heavy metals in mixture, and needs small amount of particulate present. This device would be most effective at breakdown VOC and would not be effective at reducing overall tar content.

**Practicability**

Tar will be a considerable concern to foul streamlines and poison the expensive catalytic bed. . Maintenance cost for RCO will be double that of RTO. Tar will be a considerable concern to foul streamlines and poison the expensive catalytic bed.

**Costs (est)**

Capital costs will be higher than RTO and calculated from 18,000 scf/hr (300 scfm) resulting in $15 – 61K. Previous calculation have generalized all items associated with device implementation, including installation, auxiliary equipment, operation, maintenance. This factor is 2.0768 of capital cost and results in a range of $30 – 126K to implement the technology. Natural gas consumption was estimated at 15% of overall TOC flow rate, and electricity usage at approximately 28,000 kWh However, maintenance, associated labor and overhead will be double (associated with an additional 50% compared to RTO) resulting in an annual cost from $75,800 – 87,600. A complete description of line items and calculations can be found in Appendix G.4 Catalytic Oxidizer.

**Energy impacts**.

Regenerative techniques reduce the energy impact compared to methods without recovery. Energy consumption will support electrical blowers and utilize natural gas to supplement operational temperatures.

**Control #1 and #2 - Gas Clean-up Alternatives**

There are few alternative methods to remove tars/acids/particulates prior to downstream combustion. We are classifying them as basically as **wet, dry, and thermal (usually catalytic).** Additionally, they can be further classified by the temperatures at which they can be utilized: hot gas cleanup (HGC), cold gas cleanup (CGC) (usually wet), or warm gas cleanup (WGC). There is a little ambiguity in these definitions and overlaps in temperature and operational parameters; however, usually most of the “hot” systems operate between 400°C (752°F) to upwards of 1000°C (1832°F), with the majority in the 600°C (1112°F) range and the warm gas cleanup operate between 300°C (572°F) and 100°C (212°F). Cold gas cleanup is usually at or around ambient temperatures to 100°C (212°F).

**Wet Scrubbing.**

Wet scrubbers employ liquids to interact and effectively capture target materials, such as tars and particulate matter. In addition, acids can be captured and neutralized by tuning the chemical properties of the scrubbing solution. Liquid scrubbing works due to various ways of manipulating the scrubbing solution while utilizing the physical properties of the liquid to enhance target material capture.

**Single Stage Venturi / Ejector Venturi scrubbers:**

Venturi scrubbers have been applied to control Particulate Matter (PM) emission and acids in the gas stream. For PM efficiencies have been as high as 99% for aerodynamic diameters between .5 and 5um. The focus on PM will reduce the need for further residence and destruction from combustion. For Denver Zoo, a Venturi unit would also assist in the removal of tars in the gas line that are condensable. Venturi scrubbers direct an atomized mist of scrubbing fluid in the same direction as the gas flow and then the mist and gases converge in an orifice for physical separation through impaction and impingement. Venturi scrubbers are good at collecting tars and particulates above 1 micron, but drop sharply thereafter. (Basu, 2010) This liquid scrubbing technique could multiplex three major target materials: acids, particulate matter, and tars. The technique is very effective at tar removal and is reasonable as a primary control. With chemical tuning of the solution, it will quench acids (HCl and $H_2S$) that could be harmful to secondary controls downstream.

**Practicability**

Denver Zoo currently believes that the handling of tars and particulates from the unit could be captured and collected in organic filters that could be reintroduced into the waste stream. The design parameters to assist in making this happen are still under development and will require specific handling procedures as tars for safety measures.

The use of venturi scrubbers has been effective in gas clean-up for gasifier since the mid 80’s. Reed described the use of this technology and the effectiveness of it in Reed’s Downdraft biomass gasification handbook as being a good means to remove “very dirty, corrosive, or abrasive materials that might otherwise damage…..” (Das, 1988). The main challenge is the removal of “tar balls” which are long-chained hydrocarbons that have a tendency to agglomerate and stick together, fouling equipment in the tar collecting areas. (Basu, 2010). The general design and implementation of a venturi scrubber is rather simple and can be designed and installed by DZF. DZF has already constructed and tested a small prototype unit that was used with the laboratory scale gasifier to test effectiveness. Unfortunately, the testing was limited and the laboratory unit (because it was made of thin gauge carbon steel) failed to retain seals and quickly became a safety issue that could no longer be tested. Further testing and development will be required for the larger unit.

The most likely scrubbing liquid to be used will be an organic solvent/oil as water does not have the collection efficiency for class 3 and 4 tars. (Niessen, 2010) The capacity of tar removal is determined by the liquid to gas ratio (L/V) and by the solubility of the tar in the liquid. The selection of usage of an oil that can be entrained in the gas and/or easily condensed is preferred, currently this appears to be rapeseed oil, other lipophilic solvents, etc. Water may be used initially to determine effectiveness and to keep costs down.

The scrubbing liquid eventually will require replacement and the consideration currently is that this replacement will occur quarterly in quantities of approximately 5000 lb or about 600-650 gallons of scrubbing liquid.

**Costs (est.)**

Because the materials used and the custom engineering design required to handle the particulates/tars/acids inherent in the gas the capital cost is higher than even most posted cost per standard cubic foot estimates of $2.5 - $21 per scfm. (Agency, 2002) Using stainless steel for protection against corrosion associated with acids and hydrogen penetration the costs would nearly double just for materials. Add in the higher custom engineering costs associated and the Denver Zoo estimates the cost to be upwards of $100,000 with controls etc. The operation and maintenance costs (O & M) associated are higher than the purchase costs according to the EPA, which can be as high as $120 per scfm (Agency, 2002). This is very understandable as the filtration of the scrubbing fluid, clean-out, and continued maintenance of these units are known drawbacks to their use.

Capital costs will be higher than RTO and calculated from 18,000 scf/hr (300 scfm) resulting in $19 – 58K. Previous calculation have generalized all items associated with device implementation, including installation, auxiliary equipment, operation, maintenance. This factor is 2.2538 of capital cost and results in a range of $43 – 130K to implement the technology. A complete description of line items and calculations can be found in Appendix G.5 Single Stage Venturi / Ejector Venturi scrubbers.

**Energy Impacts**

The largest energy impact from the use of these units comes from the heat transfer associated with the process to remove tars, particulates, and acids. Typically this means dropping the temperature from an incoming value (sustained to mitigate condensing in the line) of 500°C and exiting in the 65-70°C range. This heat removal typically is not reused or considered to be necessary or valuable for heat recovery. Therefore, this can be a significant energy loss in the process (upwards of 1 MMbtu/hr). Evaluations for reuse of heat or recapture of heat have occurred, but the incoming energy value will have a loss of 60-70% even with means to capture available energy. The consumption of energy will be in the pumps in recirculation of the scrubbing fluid. If pressure drop is significant enough in-line compressors will have to be installed to boost the pressure for downstream equipment and processing.

**Non-air environmental impacts**

In condensing out the acids, tars, and particulates collection, management and disposal become the new areas that have to be assessed. Even with the best organic collection and reintroduction methods waste water will have to be dealt with. The estimates for tars/particulate collection are as high as 30-40 lb/hr after the scrubbing liquid is removed to 95%. The capability of collecting these tars using organic media such as wood chips and char/ash has shown to be successful in research projects. (Pathak, 2007) The successful use and testing of these items is critical for energy generation in an internal combustion engine.

**Wet Packed bed scrubber.**

This is another physical means of separating tars and particulates from the incoming syngas stream. It is a simple and open design that utilizes spheres, rings, or saddles as random packing to increase the contact area of the liquid with the gas. Packed beds are more effective for both gas absorption and liquid-gas heat exchange than particle collection.

**Practicability**

A wet packed bed scrubber system installed and tested by the Indian Institute of Science was an effective and simple way of removing particulates and tar from “producer” gas. Tests were performed on a 20 kW gasifier-combustion engine system. This system included packed bed portions of it and was successful at removing approximately 450 mg/nm3 of tars and particulates from producer gas having less than 600 mg/nm3 to start with. (Bhave, 2007) These packed bed (sand portions 1 - 0.2 mm) were critical to condense out the water vapor added in the clean-up process. Other organic materials may be use to keep from having to “wash sand beds with detergent solution and dry” (Bhave, 2007) and could be used as an additional fuel source to be blended with in-feed material and processed back into a fuel such as wood chips or char (Pathak B. K., 2007).

**Cost**

The costs of just the packed bed scrubber system that will clean the producer gas is realistic and can stay between $50-75K, however, the clean-up and management process associated with handling and managing the collected tars, and particulates will have to be carefully designed and will add significant operational costs to the system.

**Energy Impacts**

Operation will require a pumping system and additional blowers/gas movers to accommodate for the pressure drop associated with adding this technology.

**Non-air environmental impacts.**

The use of rationing rings and media to assist with gas cleaning through inertial deposition and direct interception as a physical means of separation of tars and particulates is effective, however, the collection and condensing of tars a particulates over time will have to be dealt with as operator involvement in clean-up. If an additional organic media can be utilized to collect and retain the tars and particulates for re-use in the process it may work, but 450 mg/nm3 of gas is equivalent to 200 -250 lb/hr with our flow rates and management of this will require an enclosed safe means of delivering the material back for processing. Currently, storage and mechanized delivery space is limited and will require careful consideration and design to accomplish, not to mention the replacement of collection media simultaneously.

**Wet Electrostatic Precipitators (ESPs).**

The syngas would pass through a strong electric field with electrodes. High voltage charges the solid and liquid particles. As the gas passes through a chamber containing anode plates or rods the particles pick up the charge and are collected downstream by a positively charged cathode collector plates. The collected solid particles are cleaned by mechanical means, but a liquid like tar needs cleaning through use of water or other manual methods.

**Practicability**

Collection efficiency is quite high (90% +) for particles to about .5 micron with low pressure drop, however, sparking during operation with a combustible syngas is a major safety risk with high safety and operational costs associated. (Basu, 2010)

**Cost (est.)**

Cost is quite high due to the use of electrodes, high voltage, etc. Costs are typically 4x higher than a standard wet scrubber, meaning nearly $400,000. Safety costs are much higher as well. (Basu, 2010)

**Energy Impacts**

Use of energy is quite high during operation but made up due to low pressure drop.

**Non-air environmental impacts**.

**Dry Scrubbing.**

Dry Scrubbing uses dry materials to absorb/adsorb, provide a barrier, or chemisorption to convert sulfur (acids), nitrogen, HCl into salts that can be more easily removed from the process.

**Dry sorbent injection (DSI).**

Dry sorbent injection (DSI) is a process used to control acid gases by injecting a powder sorbent (usually hydrated lime or soda ash) into the flue gas stream (after or during combustion). The sorbent is usually injected prior to the control device but will be determined based upon the required reaction time. This is usually done through the use of pneumatic conveyance to the sorbet material and injection countercurrent to the gas flow stream for added turbulent mixing. Sometimes an expansion chamber may be included to increase the residence time. In order to achieve proper reactions and removal of acids, ideal temperatures should be between 300-350°F and the injection rate maintained at around 2-4 times the stoichiometric ratios.

**Practicability**

Usually the use of dry injection achieves approximately 50% $SO_2$ and 90% HCl removal. The introduction of the sorbent will require downstream use of a cyclone, bag house, or some other particulate control device.

Although the use of dry injection scrubbing has been successfully demonstrated, the sorbent usage is quite high and the waste sorbent quantities can be a challenge to deal with and dispose of. Moisture in the line can cause the efficiency to drop significantly and if temperatures are not maintained above 300-350°F. Introduction of sorbent can with bends or pressure drops can be problematic and cause clogged lines during operation. Having moisture in the line condensing will intensify this occurrence.

**Cost**

Equipment required is typically a pneumatic line, expansion/mixing chamber, particulate control (cyclone, bag house, etc.) and a blower to introduce the media. The estimated purchase cost of this unit is about $50,000 - $75,000, but may go up due to material usage. The purchase and usage of sorbent material at 2-4 times the necessary stoichiometric numbers is an expensive means of removal compared to other technologies but is dependent upon the sorbent used.

**Energy Impacts**

Low energy impacts

**Non-air Environmental Impacts**

This is primarily the waste sorbent generated in the process.

**Barrier filters (dry – candle, ceramic, fabric, biomass, etc.).**

Barrier filters collect tars, particulates, etc. though porosity. This creates a physical barrier in the path of the gas. One special feature that can be inherent in this type of filtration is the use of catalytic agents to facilitate tar cracking. Significant development has been focused on “dry” scrubbing systems that could be utilized to remove acids, tars, and particulates. These include “hot gas” clean-up methods and include candle filters and bag filters.

**Practicability**

Because these type of barrier filters either require a mechanical or operator means of maintenance and removal of “filter cakes”, stress and shock associated with this can damage the filter media (especially if it is bag or candle filters) and can cause significant down time during operation. Companies that were actively seeking to market their systems for cleaning of syngas from gasification have stepped out of the market due to issues related to failures, clogging, and pressure drops associated with this (reference of conversations with Tri-mer).

The use of and collection of components/particulates in solid form will reduce the usage, handling, and dealings with liquid waste bi-products, however, the cost of installation and the known industry operational hurdles may hold up further development. The high temperature application of most of these barrier filters can also cause challenges in either re-heating or only used in post combustion processes. Their currently is no simple heat capture mechanisms that can be simply applied to allow for waste heat capture for these units.

**Cost (est)**

The cost is more focused on the O&M side as filter media will be the determining factor moving forward. The filtration media will also be the driving cost factor for initial purchase cost as well.

**Energy Impacts**

Because porosity is used for separation, there is a significant pressure drop when these are used in the line. This pressure drop will increase as the porosity is filled with particulates and tars. Use of these should be further downstream to allow for initial clean-up and collection.

**Non-air environmental impacts**

Filters have a lifespan and sometimes can't be recharged to be reused. It is important to try to select organic media so that the waste material has an opportunity to be reintroduced into the waste stream for further processing. This would eliminate the generation of waste associated with spent media. This can be a challenge either way because typically the filtration media waste generated is considered hazardous due to the volatile organic compounds (VOCs) that are stored and released with handling. Procedures will have to be in place to protect the staff managing and handling the waste.

**Biofiltration.**

Biofiltration passes VOC laden gas stream slowly through a bed of material which contains a culture of living microorganisms, such as fungi, bacteria, or algae. These microorganisms are designed to absorb and metabolize specific VOCs in the process gas stream. It is unclear if integrating this technique into our process stream would be efficient. Operation would require specialized technician to maintain microorganism batches and operate biofiltration equipment. Contamination of microorganism batches is a concern.

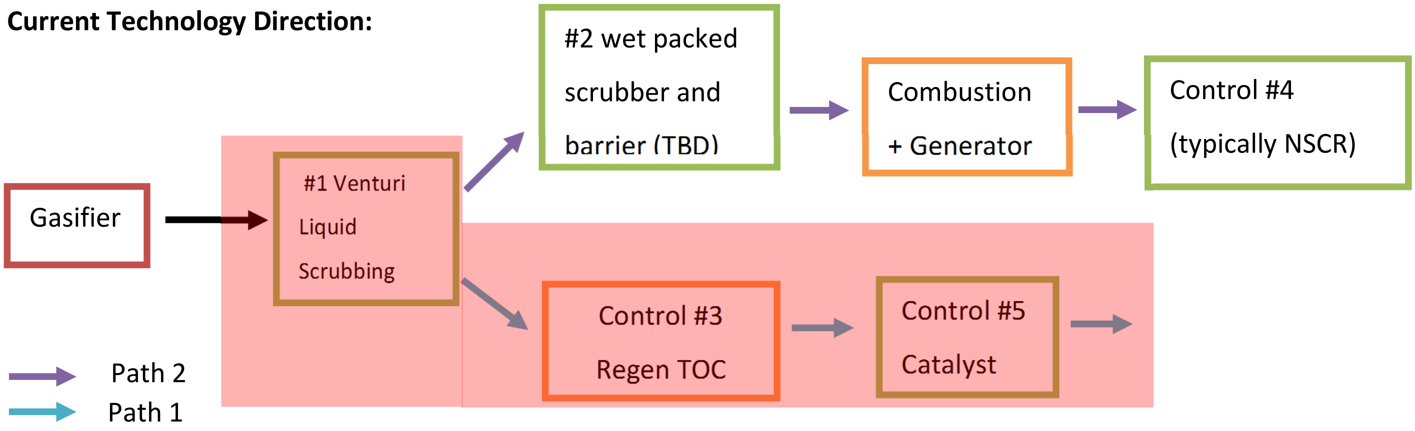
**Catalyst filtration.**

Typically these areas are focused on “hot gas” clean-up as means to remove elements using catalysts. This typically means temperatures of the syngas need to remain above 200°C. Because catalyst filtration will only work at higher temperatures, either the syngas has to react with the catalyst prior to being cooled through liquid scrubbing or after the syngas is cleaned and combusted. DZF does not believe that the catalyst will be affective (high probability of “poisoning”) in being exposed to tars, particulates, and some acids prior if installation occurred prior to liquid scrubbing.

There has been significant work performed on the use of catalytic reforming/cracking of tars produced from gasifiers, but consistently poisoning, coking, carbon deposition build-up, sintering, and attrition cause reduced lifespan of the sometimes quite expensive catalysts. (Woolcock, 2013)

DZF has determined the best use of catalysts is downstream after the gasifier and combustion.

**Current Technology Direction:**



**Path #1 (shaded in pink)**

**#1 Venturi Liquid Scrubbing:**

DZF has been testing and developing liquid scrubbing of the producer gas for a few years. Initially, limited clean-up was associated with the start-up/shut-down operation of control #3 but with more stringent air emission requirements in OWSI (EEEE), adjustments had to be made accordingly. In order to use higher efficiency downstream combustion equipment scrubbing will be required at all times (even during start-up and shut-down). This will affect the maintenance schedule but ensure that emission requirements are being met and ensure that start-up and shut-down time frames stay within EEEE requirements.

Further design details will be provided as necessary in the future as equipment is developed.

**#3 Regenerative Thermal Oxidizer Control/#5 Catalyst (RCO):**

Efficiency is very important to the successful operation of the facility and DZF will require an RTO to provide this efficiency. The ceramic media utilized to preheat the incoming syngas could also include and be a testing ground for catalysts to increase removal in the event the emission standards are not being met with Venturi scrubbing alone for SOx. This catalyst(s) focus would be the removal of SOx and NOx. The location, testing, and catalyst selection will have to be assessed and further modeled.

Further design details will be provided as necessary in the future as the equipment is developed.

# REFERENCES

Agency, E. P. (2002). *Air Pollution Control Fact Sheet - Venturi scrubber.*

Basu, P. (2010). *Biomass Gasification and Pyrolysis - Practical Design and Theroy.* Kidlington, Oxford, OX5 1 GB UK: Elsevier Inc.

Bhave, A. V. (2007). A wet packed bed scrubber-based producer gas cooling-cleaning system. *Elsevier - Renewable Energy 33 (2008)*, 1716-1720.

Das, T. R. (1988). *Handbook of Biomass Downdraft Gasifier Engine Systems.* Golden, CO: Solar Technical Infomration Program - Solar Energy Research Institute - US Department of Energy.

Government, U. S. (2014, June 11). *Electronic Code of Federal Regulations, Title 40: Protection of the Environment, Part 60: Standards of Performance for New Stationay Sources, Subpart EEE - Standards of Performance for Other Solid WAst Incineration Units.....* Retrieved June 10, 2014, from U.S. Government Printing Office: http://www.ecfr.gov/cgi-bin/retrieveECFR?gp=&r=SUBPART&n=40y7.0.1.1.1.95

Niessen, W. R. (2010). *Combustion and Incineration Processes.* Boca Raton, FL: CRC Press / Taylor and Francis Group.

Pathak, B. K. (2007). *Design and Development of Sand Bed.* International Energy Journal 8, pg 15-20.

Pathak, B. K. (2007). Design and Development of Sand Bed Filter for Upgrading Producer Gas to IC Engine Quality Fuel. *International Energy Journal 8* , 15-20.

Rabou, L. R. (2009). Tar in Biomass Producer Gas, the Energy research Centre of the The Netherlands (ECN) Experience: An Enduring Challenge. *Energy Fuels 2009*, 6189-6198.

Woolcock, P. J. (2013). A review of cleaning technologies for biomass-derived syngas. *Biomass and Bioenergy (52)*, 54-84.

## APPENDIX

### Appendix G.1 Direct Fired Thermal Oxidizer.

| DIRECT FIRED THERMAL OXIDIZER | | | | | |
|---|---|---|---|---|---|
| | | | | 26.25 | 105 |
| **Direct Capital Costs** | | | | | |
| Purchased equipment costs | | | | *low value* | *high value* |
| TOC (EC) + auxiliary equipment | | 1 | A | **7,980** | **31,920** |
| Instrumentation | | 0.13 | A | 1,037 | 4,150 |
| Sales taxes | | 0.00 | A | 0 | 0 |
| Freight | | 0.05 | A | 399 | 1,596 |
| | Purchased equipment cost, PEC | 1.18 | B=A* | 9,416 | 37,666 |
| | | | | | |
| Direct installation costs | | | | | |
| Foundations & supports | | 0.08 | B | 753 | 3,013 |
| Handling & erection | | 0.13 | B | 1,224 | 4,897 |
| Electrical Piping | | 0.04 | B | 377 | 1,507 |
| Piping | | 0.02 | B | 188 | 753 |
| Insulation for ductwork | | 0.02 | B | 188 | 753 |
| Painting | | 0.01 | B | 94 | 377 |
| | Direct installation costs | 0.30 | B | 2,825 | 11,300 |
| | | | | | |
| Site preparation | | 0 | SP | 0 | 0 |
| Buildings | | 0 | Bldg. | 0 | 0 |
| | | | | | |
| Total Direct costs (DC) | | 0.30 | B | 2,825 | 11,300 |
| | | 0.00 | SP | 0 | 0 |
| | | 0.00 | Bldg. | 0 | 0 |
| | | 0.30 | TOTAL | 2,825 | 11,300 |
| | | | | | |
| Indirect Costs (installation) | | | | | |
| Engineering/Consulting | | 0.25 | B | 2,354 | 9,416 |
| Construction and field expenses | | 0.05 | B | 471 | 1,883 |
| Contractor fees | | 0.10 | B | 942 | 3,767 |
| Start-up | | 0.02 | B | 188 | 753 |
| Performance test | | 0.01 | B | 94 | 377 |
| Contingencies | | 0.03 | B | 282 | 1,130 |
| | Total Indirect Costs, IC | 0.46 | B | 4,332 | 17,326 |
| | | | | | |
| Total Capital Investments = DC + IC | | 1.76 | B | **16,573** | **66,291** |
| | | | | | 2.0768 |
| **Direct Annual costs, DC** | | | | | |

| Operating labor | | | $/hr. | $ | $ |
|---|---|---|---|---|---|
| Operator (1000/yr.) | 0.5 | hr./shift | 12.95 | 6,475 | 6,475 |
| Supervisor (15% of operator) | 15% | | 12.95 | 971 | 971 |
| Op. materials | 0 | | 0 | 0 | 0 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Maintenance | | | | | | |
| | Labor (954 shifts/yr.) | 0.5 | hr./shift | 14.95 | 7,131 | 7,131 |
| | Materials (% of labor) | 100% | | 14.95 | 7,131 | 7,131 |
| Utilities | | | | | | |
| | Natural Gas | 11% of 18,000 scf/hr.; 4000h/yr. | $/kft3 | 3.3 | 26,136 | 26,136 |
| | Electricity | 28,000 kWh (=4000*7) | $/kWh | 0.059 | 1,652 | 1,652 |
| **Total DC** | | | | | 49,497 | 49,497 |
| **Indirect Annual Cost, IC** | | 40% | Operation, sup., and maintenance labor and main. Material | | 40% | 40% |
| Overhead | | | | | 8,683 | 8,683 |
| **TOTAL DIRECT ANNUAL COST** | | | | | **58,180** | **58,180** |

## AMORTIZATION

| **DIRECT FIRED THERMAL OXIDIZER** | Low | High | |
|---|---|---|---|
| | **16,573** | **66,291** | Total Capital Investment |
| | **4%** | **4%** | Interest Rate |
| | **10** | **10** | Term (yrs.) |
| | 12.33% | 12.33% | CRF** (10yrs, 4%) |
| | 2,043 | 8,173 | Capital Cost/yr. |
| | 58,180 | 58,180 | Operating Cost/yr. |
| | **60,223** | **66,353** | **TOTAL Annual Costs** |

| | **Tons/yr.** | **Annual Costs (range)** | | **Cost/ton (range)** | |
|---|---|---|---|---|---|
| CO Abatement | 285 | 60,223 | 66,353 | 211 | 233 |
| VOC Abatement | 3 | 60,223 | 66,353 | 20,074 | 22,118 |
| SOx* Abatement | 6 | 60,223 | 66,353 | 10,037 | 11,059 |
| NOx Abatement | 0.75 | 60,223 | 66,353 | 80,298 | 88,471 |

| | | | | | |
|---|---|---|---|---|---|
| **TOTAL pollutants abated** | **294.75** | **60,223** | **66,353** | **204** | **225** |

* H2S will be abated in the liquid scrubber control. Doing so will reduce the available H2S that will react in the TOC to become SOX.

**Capital Recovery Factor (CRF)

***Catalytic cost for carbon monoxide (CO) abatement not included.

## Appendix G.2 Regenerative Thermal Oxidizer.

| **REGENERATIVE THERMAL OXIDIZER (RTO)** | | | | |
|---|---|---|---|---|
| | | | 35 | 140 |
| **Direct Capital Costs** | | | | |
| Purchased equipment costs | | | *low value* | *high value* |
| TOC (EC) + auxiliary equipment | 1 | A | **10,640** | **42,560** |
| Instrumentation | 0.13 | A | 1,383 | 5,533 |
| Sales taxes | 0.00 | A | 0 | 0 |
| Freight | 0.05 | A | 532 | 2,128 |
| Purchased equipment cost, PEC | 1.18 | B=A* | 12,555 | 50,221 |
| | | | | |
| Direct installation costs | | | | |
| Foundations & supports | 0.08 | B | 1,004 | 4,018 |
| Handling & erection | 0.13 | B | 1,632 | 6,529 |
| Electrical Piping | 0.04 | B | 502 | 2,009 |
| Piping | 0.02 | B | 251 | 1,004 |
| Insulation for ductwork | 0.02 | B | 251 | 1,004 |
| Painting | 0.01 | B | 126 | 502 |
| Direct installation costs | 0.30 | B | 3,767 | 15,066 |
| | | | | |
| Site preparation | 0 | SP | 0 | 0 |
| Buildings | 0 | Bldg. | 0 | 0 |
| | | | | |
| Total Direct costs (DC) | 0.30 | B | 3,767 | 15,066 |
| | 0.00 | SP | 0 | 0 |
| | 0.00 | Bldg. | 0 | 0 |
| | 0.30 | TOTAL | 3,767 | 15,066 |
| | | | | |
| Indirect Costs (installation) | | | | |
| Engineering/Consulting | 0.25 | B | 3,139 | 12,555 |
| Construction and field expenses | 0.05 | B | 628 | 2,511 |
| Contractor fees | 0.10 | B | 1,256 | 5,022 |
| Start-up | 0.02 | B | 251 | 1,004 |
| Performance test | 0.01 | B | 126 | 502 |
| Contingencies | 0.03 | B | 377 | 1,507 |
| Total Indirect Costs, IC | 0.46 | B | 5,775 | 23,102 |
| | | | | |
| Total Capital Investments = DC + IC | 1.76 | B | **22,097** | **88,389** |
| | | | | 2.0768 |
| **Direct Annual costs, DC** | | | | |

| Operating labor | | | $/hr. | $ | $ |
|---|---|---|---|---|---|
| Operator (1000/yr.) | 0.5 | hr./shift | 12.95 | 6,475 | 6,475 |
| Supervisor (15% of operator) | 15% | | 12.95 | 971 | 971 |
| Op. materials | 0 | | 0 | 0 | 0 |
| Maintenance | | | | | |
| Labor (954 shifts/yr.) | 0.5 | hr./shift | 14.95 | 7,131 | 7,131 |
| Materials (% of labor) | 100% | | 14.95 | 7,131 | 7,131 |
| Utilities | | | | | |
| Natural Gas | 8% of 18,000 scf/hr.; 4000h/yr. | $/kft3 | 3.3 | 19,008 | 19,008 |
| Electricity | 28,000 kWh (=4000*7) | $/kWh | 0.059 | 1,652 | 1,652 |
| **Total DC** | | | | 42,369 | 42,369 |
| **Indirect Annual Cost, IC** | 40% | Operation, sup., and maintenance labor and main. Material | | 40% | 40% |
| Overhead | | | | 8,683 | 8,683 |
| **TOTAL DIRECT ANNUAL COST** | | | | **51,052** | **51,052** |

## AMORTIZATION

| **REGENERATIVE THERMAL OXIDIZER (RTO)** | Low | High | |
|---|---|---|---|
| | **22,097** | **88,389** | Total Capital Investment |
| | **4%** | **4%** | Interest Rate |
| | **10** | **10** | Term (yrs.) |
| | 12.33% | 12.33% | CRF** (10yrs, 4%) |
| | 2,724 | 10,898 | Capital Cost/yr. |
| | 51,052 | 51,052 | Operating Cost/yr. |
| | **53,776** | **61,949** | **TOTAL Annual Costs** |

| | **Tons/yr.** | **Annual Costs (range)** | | **Cost/ton (range)** | |
|---|---|---|---|---|---|
| CO Abatement | 285 | 53,776 | 61,949 | 189 | 217 |
| VOC Abatement | 3 | 53,776 | 61,949 | 17,925 | 20,650 |

| | | | | | |
|---|---|---|---|---|---|
| SOx* Abatement | 6 | 53,776 | 61,949 | 8,963 | 10,325 |
| NOx Abatement | 0.75 | 53,776 | 61,949 | 71,702 | 82,599 |
| **TOTAL pollutants abated** | **294.75** | 53,776 | 61,949 | 182 | 210 |

* H2S will be abated in the liquid scrubber control. Doing so will reduce the available H2S that will react in the TOC to become SOX.

**Capital Recovery Factor (CRF)

***Catalytic cost for carbon monoxide (CO) abatement not included.

## Appendix G.3 Recuperative Thermal Oxidizer.

| | | | | | |
|---|---|---|---|---|---|
| **RECUPERATIVE THERMAL OXIDIZER (RecTO)** | | | | | |
| | | | | 35 | 140 |
| **Direct Capital Costs** | | | | | |
| Purchased equipment costs | | | | *low value* | *high value* |
| TOC (EC) + auxiliary equipment | | 1 | A | **10,640** | **42,560** |
| Instrumentation | | 0.13 | A | 1,383 | 5,533 |
| Sales taxes | | 0.00 | A | 0 | 0 |
| Freight | | 0.05 | A | 532 | 2,128 |
| | Purchased equipment cost, PEC | 1.18 | B=A* | 12,555 | 50,221 |
| Direct installation costs | | | | | |
| Foundations & supports | | 0.08 | B | 1,004 | 4,018 |
| Handling & erection | | 0.13 | B | 1,632 | 6,529 |
| Electrical Piping | | 0.04 | B | 502 | 2,009 |
| Piping | | 0.02 | B | 251 | 1,004 |
| Insulation for ductwork | | 0.02 | B | 251 | 1,004 |
| Painting | | 0.01 | B | 126 | 502 |
| | Direct installation costs | 0.30 | B | 3,767 | 15,066 |
| Site preparation | | 0 | SP | 0 | 0 |
| Buildings | | 0 | Bldg. | 0 | 0 |
| Total Direct costs (DC) | | 0.30 | B | 3,767 | 15,066 |
| | | 0.00 | SP | 0 | 0 |
| | | 0.00 | Bldg. | 0 | 0 |
| | | 0.30 | TOTAL | 3,767 | 15,066 |
| Indirect Costs (installation) | | | | | |
| Engineering/Consulting | | 0.25 | B | 3,139 | 12,555 |
| Construction and field expenses | | 0.05 | B | 628 | 2,511 |
| Contractor fees | | 0.10 | B | 1,256 | 5,022 |
| Start-up | | 0.02 | B | 251 | 1,004 |
| Performance test | | 0.01 | B | 126 | 502 |
| Contingencies | | 0.03 | B | 377 | 1,507 |

| | | | | | |
|---|---|---|---|---|---|
| Total Indirect Costs, IC | 0.46 | B | | 5,775 | 23,102 |
| Total Capital Investments = DC + IC | 1.76 | B | | **22,097** | **88,389** |
| | | | | | 2.0768 |
| **Direct Annual costs, DC** | | | | | |
| Operating labor | | | $/hr. | $ | $ |
| Operator (1000/yr.) | 0.5 | hr./shift | 12.95 | 6,475 | 6,475 |
| Supervisor (15% of operator) | 15% | | 12.95 | 971 | 971 |
| Op. materials | 0 | | 0 | 0 | 0 |
| Maintenance | | | | | |
| Labor (954 shifts/yr.) | 0.5 | hr./shift | 14.95 | 7,131 | 7,131 |
| Materials (% of labor) | 100% | | 14.95 | 7,131 | 7,131 |
| Utilities | | | | | |
| Natural Gas | 9.6% of 18,000 scf/hr.; 4000h/yr. | $/kft3 | 3.3 | 22,810 | 22,810 |
| Electricity | 28,000 kWh (=4000*7) | $/kWh | 0.059 | 1,652 | 1,652 |
| **Total DC** | | | | 46,170 | 46,170 |
| **Indirect Annual Cost, IC** | 40% | Operation, sup., and maintenance labor and main. Material | | 40% | 40% |
| Overhead | | | | 8,683 | 8,683 |
| **TOTAL DIRECT ANNUAL COST** | | | | **54,854** | **54,854** |

## AMORTIZATION

| **RECUPERATIVE THERMAL OXIDIZER (RecTO)** | Low | High | |
|---|---|---|---|
| | **22,097** | **88,389** | Total Capital Investment |
| | **4%** | **4%** | Interest Rate |
| | **10** | **10** | Term (yrs.) |
| | 12.33% | 12.33% | CRF** (10yrs, 4%) |
| | 2,724 | 10,898 | Capital Cost/yr. |
| | 54,854 | 54,854 | Operating Cost/yr. |
| | **57,578** | **65,751** | **TOTAL Annual Costs** |

| | Tons/yr. | Annual Costs (range) | | Cost/ton (range) | |
|---|---|---|---|---|---|
| CO Abatement | 285 | 57,578 | 65,751 | 202 | 231 |
| VOC Abatement | 3 | 57,578 | 65,751 | 19,193 | 21,917 |
| SOx* Abatement | 6 | 57,578 | 65,751 | 9,596 | 10,959 |
| NOx Abatement | 0.75 | 57,578 | 65,751 | 76,771 | 87,668 |
| **TOTAL pollutants abated** | **294.75** | 57,578 | 65,751 | 195 | 223 |

* H2S will be abated in the liquid scrubber control. Doing so will reduce the available H2S that will react in the TOC to become SOX.

**Capital Recovery Factor (CRF)

***Catalytic cost for carbon monoxide (CO) abatement not included.

## Appendix G.4 Regenerative Catalytic Oxidizer (RCO).

| **CATALYTIC OXIDIZER** | | | | |
|---|---|---|---|---|
| | | | 48 | 200 |
| **Direct Capital Costs** | | | | |
| Purchased equipment costs | | | *low value* | *high value* |
| TOC (EC) + auxiliary equipment | 1 | A | **14,592** | **60,800** |
| Instrumentation | 0.13 | A | 1,897 | 7,904 |
| Sales taxes | 0.00 | A | 0 | 0 |
| Freight | 0.05 | A | 730 | 3,040 |
| Purchased equipment cost, PEC | 1.18 | B=A* | 17,219 | 71,744 |
| | | | | |
| Direct installation costs | | | | |
| Foundations & supports | 0.08 | B | 1,377 | 5,740 |
| Handling & erection | 0.13 | B | 2,238 | 9,327 |
| Electrical Piping | 0.04 | B | 689 | 2,870 |
| Piping | 0.02 | B | 344 | 1,435 |
| Insulation for ductwork | 0.02 | B | 344 | 1,435 |
| Painting | 0.01 | B | 172 | 717 |
| Direct installation costs | 0.30 | B | 5,166 | 21,523 |
| | | | | |
| Site preparation | 0 | SP | 0 | 0 |
| Buildings | 0 | Bldg. | 0 | 0 |
| | | | | |
| Total Direct costs (DC) | 0.30 | B | 5,166 | 21,523 |
| | 0.00 | SP | 0 | 0 |
| | 0.00 | Bldg. | 0 | 0 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | 0.30 | TOTAL | | 5,166 | 21,523 |
| Indirect Costs (installation) | | | | | | |
| Engineering/Consulting | | 0.25 | B | | 4,305 | 17,936 |
| Construction and field expenses | | 0.05 | B | | 861 | 3,587 |
| Contractor fees | | 0.10 | B | | 1,722 | 7,174 |
| Start-up | | 0.02 | B | | 344 | 1,435 |
| Performance test | | 0.01 | B | | 172 | 717 |
| Contingencies | | 0.03 | B | | 517 | 2,152 |
| | Total Indirect Costs, IC | 0.46 | B | | 7,921 | 33,002 |
| Total Capital Investments = DC + IC | | 1.76 | B | | **30,305** | **126,269** |
| | | | | | | 2.0768 |
| **Direct Annual costs, DC** | | | | | | |
| Operating labor | | | | $/hr. | $ | $ |
| Operator (1000/yr.) | | 0.5 | hr./shift | 12.95 | 6,475 | 6,475 |
| Supervisor (15% of operator) | | 15% | | 12.95 | 971 | 971 |
| Op. materials | | 0 | | 0 | 0 | 0 |
| Maintenance | | | | | | |
| Labor (954 shifts/yr.) | | 0.5 | hr./shift | 14.95 | 7,131 | 7,131 |
| Materials (% of labor) | | 100% | | 14.95 | 7,131 | 7,131 |
| Utilities | | | | | | |
| Natural Gas | 15% of 18,000 scf/hr.; 4000h/yr. | | $/kft3 | 3.3 | 35,640 | 35,640 |
| Electricity | 28,000 kWh (=4000*7) | | $/kWh | 0.059 | 1,652 | 1,652 |
| **Total DC** | | | | | 59,001 | 59,001 |
| **Indirect Annual Cost, IC** | | 60% | Operation, sup., and maintenance labor and main. Material | | 60% | 60% |
| Overhead | | | | | 13,025 | 13,025 |
| **TOTAL DIRECT ANNUAL COST** | | | | | **72,026** | **72,026** |

## AMORTIZATION

| **CATALYTIC OXIDIZER** | Low | High | |
|---|---|---|---|
| | **30,305** | **126,269** | Total Capital Investment |
| | **4%** | **4%** | Interest Rate |

| | | |
|---|---|---|
| **10** | **10** | Term (yrs.) |
| 12.33% | 12.33% | CRF** (10yrs, 4%) |
| 3,736 | 15,568 | Capital Cost/yr. |
| 72,026 | 72,026 | Operating Cost/yr. |
| **75,762** | **87,594** | **TOTAL Annual Costs** |

| | **Tons/yr.** | **Annual Costs (range)** | | **Cost/ton (range)** | |
|---|---|---|---|---|---|
| CO Abatement | 285 | 75,762 | 87,594 | 266 | 307 |
| VOC Abatement | 3 | 75,762 | 87,594 | 25,254 | 29,198 |
| SOx* Abatement | 6 | 75,762 | 87,594 | 12,627 | 14,599 |
| NOx Abatement | 0.75 | 75,762 | 87,594 | 101,016 | 116,791 |
| **TOTAL pollutants abated** | **294** | 75,762 | 87,594 | 258 | 298 |

* H2S will be abated in the liquid scrubber control. Doing so will reduce the available H2S that will react in the TOC to become SOX.

**Capital Recovery Factor (CRF)

***Catalytic cost for carbon monoxide (CO) abatement not included.

## Appendix G.5 Single Stage Venturi / Ejector Venturi scrubbers.

| **Single Stage Venturi / Ejector Venturi scrubbers** | | | | |
|---|---|---|---|---|
| | | | 63.0482456 | 189.144737 |
| **Direct Capital Costs** | | | | |
| Purchased equipment costs | | | *low value* | *high value* |
| TOC (EC) + auxiliary equipment | 1 | A | **19,167** | **57,500** |
| Instrumentation | 0.13 | A | 2,492 | 7,475 |
| Sales taxes | 0.00 | A | 0 | 0 |
| Freight | 0.05 | A | 958 | 2,875 |
| Purchased equipment cost, PEC | 1.18 | B=A* | 22,617 | 67,850 |
| Direct installation costs | | | | |
| Foundations & supports | 0.08 | B | 1,809 | 5,428 |
| Handling & erection | 0.13 | B | 2,940 | 8,821 |
| Electrical Piping | 0.04 | B | 905 | 2,714 |
| Piping | 0.02 | B | 452 | 1,357 |
| Insulation for ductwork | 0.02 | B | 452 | 1,357 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Painting | | 0.01 | B | | 226 | 679 |
| | Direct installation costs | 0.30 | B | | 6,785 | 20,355 |
| Site preparation | | 0 | SP | | 0 | 0 |
| Buildings | | 0 | Bldg. | | 0 | 0 |
| Total Direct costs (DC) | | 0.30 | B | | 6,785 | 20,355 |
| | | 0.00 | SP | | 0 | 0 |
| | | 0.00 | Bldg. | | 0 | 0 |
| | | 0.30 | TOTAL | | 6,785 | 20,355 |
| Indirect Costs (installation) | | | | | | |
| Engineering/Consulting | | 0.40 | B | | 9,047 | 27,140 |
| Construction and field expenses | | 0.05 | B | | 1,131 | 3,393 |
| Contractor fees | | 0.10 | B | | 2,262 | 6,785 |
| Start-up | | 0.02 | B | | 452 | 1,357 |
| Performance test | | 0.01 | B | | 226 | 679 |
| Contingencies | | 0.03 | B | | 679 | 2,036 |
| | Total Indirect Costs, IC | 0.61 | B | | 13,796 | 41,389 |
| Total Capital Investments = DC + IC | | 1.91 | B | | **43,198** | **129,594** |
| | | | | | | 2.2538 |
| **Direct Annual costs, DC** | | | | | | |
| Operating labor | | | | $/hr. | $ | $ |
| Operator (1000/yr.) | | 0.5 | hr./shift | 12.95 | 6,475 | 6,475 |
| Supervisor (15% of operator) | | 15% | | 12.95 | 971 | 971 |
| Op. materials | | 0 | | 0 | 0 | 0 |
| Maintenance | | | | | | |
| Labor (954 shifts/yr.) | | 0.5 | hr./shift | 14.95 | 7,131 | 7,131 |
| Materials (% of labor) | | 100% | | 14.95 | 7,131 | 7,131 |
| Utilities | | | | | | |
| Natural Gas | | n/a | $/kft3 | 3.3 | 0 | 0 |
| Electricity | | 56,000 kWh (=4000*7) | $/kWh | 0.059 | 3,304 | 3,304 |
| **Total DC** | | | | | 25,013 | 25,013 |
| **Indirect Annual Cost, IC** | | 80% | Operation, sup., and maintenance labor and main. Material | | 80% | 80% |
| Overhead | | | | | 17,367 | 17,367 |
| **TOTAL DIRECT ANNUAL COST** | | | | | **42,379** | **42,379** |
| **AMORTIZATION** | | | | | | |

# Attachment G- OSWI 60.2895 Air Pollution Control Alternatives

## RACT Analysis

| **Single Stage Venturi / Ejector Venturi scrubbers** | Low | High | |
|---|---|---|---|
| | **43,198** | **129,594** | Total Capital Investment |
| | **4%** | **4%** | Interest Rate |
| | **10** | **10** | Term (yrs.) |
| | 12.33% | 12.33% | CRF** (10yrs, 4%) |
| | 5,326 | 15,978 | Capital Cost/yr. |
| | 42,379 | 42,379 | Operating Cost/yr. |
| | **47,705** | **58,357** | **TOTAL Annual Costs** |

| | **Tons/yr.** | **Annual Costs (range)** | | **Cost/ton (range)** | |
|---|---|---|---|---|---|
| Hydrochloric Acid (HCl) | 7 | 47,705 | 58,357 | 6,815 | 8,337 |
| Hydrogen Sulfide (H2S)* | 2.6 | 47,705 | 58,357 | 18,348 | 22,445 |
| **TOTAL pollutants abated** | **9.6** | **47,705** | **58,357** | **4,969** | **6,079** |

* H2S will be abated in the liquid scrubber control. Doing so will reduce the available H2S that will react in the TOC to become SOX.

**Capital Recovery Factor (CRF)

***Catalytic cost for carbon monoxide (CO) abatement not included.