Mercury Emission Control Technology Review for NorthMet Project Processing Plant

Prepared for
PolyMet Mining Inc.

February 2012
Version 2

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1 Executive Summary

The proposed NorthMet Project (Project) will be a new source of mercury emissions to the air. The "Implementation Plan for Minnesota's Statewide Mercury Total Maximum Daily Load", dated October 2009, requires that new and modified sources of mercury "Employ the best mercury control available". This report is an evaluation of mercury emission control alternatives to verify that best available emission controls have been selected.

Estimated potential mercury emissions from the Project are 4.6 lbs per year. Sources of mercury emissions from the proposed project include:

- The autoclave in the Hydrometallurgical Plant (Autoclave)
- Ore crushing and grinding equipment in the Beneficiation Plant
- Fugitive dust emissions
- Combustion of gaseous fuels for space heating and limited process use.

The Hydrometallurgical Plant will use an Autoclave as part of a process to extract nickel, cobalt, gold and platinum group metals (PGM) from ore concentrate. The proposed project includes a two stage wet scrubbing system to control emissions of mercury and other pollutants from the Autoclave. Controlled mercury emissions from the Autoclave using the proposed two stage wet scrubbing system are calculated to be 4.1 pounds of mercury per year, or about 90% of Project mercury emissions. The concentration of controlled mercury emissions from the Autoclave is calculated to be 1.65 e-5 gr/dscf.

Several mercury control technologies used in the non-ferrous metal mining industry were evaluated, but most were found to be technically infeasible because the mercury concentration in the controlled Autoclave exhaust will be lower than what is feasible with these control systems. Activated carbon may be technically feasible for mercury control in this application, but the Autoclave exhaust will need to be cleaned and dried before treatment with activated carbon. A control cost evaluation was performed on activated carbon controls. Because controlled mercury emissions from the proposed two stage wet scrubbing system will be so low, the use of activated carbon controls will not be economically feasible. The control cost of activated carbon controls for the Autoclave would be $397,000 per pound of mercury. In its evaluation of mercury controls for the gold mining Maximum Achievable Control Technology (MACT) standard 40 CFR 63 Subpart EEEEEEE, the United States Environmental Protection Agency (USEPA) determined that costs above $40,000 per ton mercury removed were not cost effective. No other mercury control system is capable of reducing mercury emissions lower than the proposed two stage wet scrubbing system. Therefore, the proposed two stage wet scrubbing system meets the test of being the best available mercury control system for the Autoclave.

Mercury emissions from ore grinding and crushing are in the form of particle bound mercury and will be controlled by fabric filters which have already been identified as the most effective emission controls for particulates in the "Emission Control Technology Review for NorthMet Project Processing Plant" dated October, 2007 and the February 2012 addendum (version 3).

Fugitive mercury emissions are in the form of particle bound mercury. Fugitive particulate emissions will be controlled by work practices specified in the NorthMet fugitive dust control plan. Measures specified in the dust control plan will be consistent with best practices used for fugitive dust control in the metallic ore mining industry.

The Project will use gaseous fuels for space heating and steam generation. Gaseous fuels are considered clean fuels, and have the lowest mercury content of any available fuel for these applications.

2 Introduction and Background

2.1 Purpose of Study

The proposed NorthMet Project (Project) will be a new source of mercury emissions to the air. The "Implementation Plan for Minnesota's Statewide Mercury Total Maximum Daily Load", dated October 2009, requires that new and modified sources of mercury, that have the potential to emit more than three pounds per year to the air, "Employ the best mercury control available".

The purpose of this report is to document that the proposed mercury control strategy for the Project meets the MCPA's policy requirement to use the best mercury control available per the criteria specified for new and modified sources in Appendix 6 of the implementation plan. Item 1 on page 1 of this appendix defines mercury control requirements as "the best control technically feasible considering environmental, energy and economic impacts".

This report focuses on the Plant Site, where there is the greatest potential for mercury emissions. There is also the potential for a small amount of mercury (~ 0.1 lb/year) to be emitted as a component of fugitive dust at the Mine Site. Fugitive dust at the Mine Site will be controlled with an approved fugitive emission control plan, and further discussion of the Mine Site was not considered necessary in this report.

2.2 Source Description

PolyMet Mining Inc. (PolyMet) plans to construct and operate a mine area near the town of Babbitt, MN, to reactivate portions of the LTV Steel Mining Company (LTVSMC) Taconite Processing Plant and Tailing Basin near Hoyt Lakes, MN and to build an ore processing facility at the former LTVSMC site. The project description is provided in the March, 2011 Draft Alternative Summary for the NorthMet Project Environmental Impact Statement (EIS) and the NorthMet Project Description, version 3, submitted September 13, 2011.

The EIS Co-lead Agencies (Minnesota Department of Natural Resources, US Army Corps of Engineers, and US Forest Service) have concluded the proposed project requires a Supplemental Draft Environmental Impact Statement (SDEIS) and that the proposed approach for addressing mercury emissions should be described in the SDEIS.

Estimated potential mercury emissions from the Project are 4.6 lbs per year. Sources of mercury emissions from the proposed project include:

- The autoclave in the Hydrometallurgical Plant (Autoclave)
- Ore crushing and grinding equipment in the Beneficiation Plant
- Fugitive dust emissions
- Combustion of gaseous fuels for space heating and limited process use.

The Hydrometallurgical Plant will use an Autoclave as part of a process to extract nickel, cobalt, gold and platinum group metals (PGM) from ore concentrate. The proposed project includes a two stage wet scrubbing system to control emissions of mercury and other pollutants from the Autoclave system vent. The mercury control evaluation study will evaluate the effectiveness of the proposed emission control system versus other potential mercury emission control technologies. Controlled mercury emissions from the Autoclave system using the proposed two stage wet scrubbing system are calculated to be 4.1 pounds of mercury per year. The scrubber effluent is recycled within the hydrometallurgical process to conserve water. Water and waste solids discharged from the process which may contain mercury are sent to the Hydrometallurgical Residue Facility. Water from the residue facility is recycled back to the hydrometallurgical process. Please see NorthMet Project Residue Management Plan[1] for details on how solid residues from the Hydrometallurgical Plant, which may contain mercury, will be safely managed.

Ore crushing and grinding will generate particulate emissions which contain trace amounts of mercury. The Project will utilize fabric filters (baghouses and cartridge filters) to control particulate emissions from these sources. Dust collected from the fabric filters will be returned to the process for metallic mineral recovery. The use of fabric filters will ensure that emissions of particulate matter and particle bound mercury emissions are controlled at levels consistent with recent BACT determinations for the metallic ore processing industry. The performance of fabric filter controls proposed for the Project was documented in the report “Emission Control Technology Review, Addendum 01 Version 3” dated February, 2012, and no further review is necessary to show that fabric filters represent the best mercury control technology for ore crushing and grinding operations. Potential controlled mercury emissions from ore crushing and grinding operations are calculated to be 0.001 pounds per year.

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[1] PolyMet Mining, Inc. NorthMet Project Residue Management Plan. Version 1. October 31, 2011.

The Project will use gaseous fuels for space heating equipment and the small amount of process fuel usage. Gaseous fuels have the lowest mercury content of fossil fuels available for use in space heating, and are considered clean fuels. Use of gaseous fuels represents the best mercury control technically feasible for fuel combustion through the use of clean fuels as a pollution prevention technique. Potential mercury emissions from fuel combustion in space heating equipment are calculated to be 0.50 pounds per year.

Fugitive dust emissions may be generated from transportation of Tailings Basin construction material, material handling of LTVSMC tailings used in dam construction and wind erosion at the Flotation Tailings Basins. The fugitive dust from these sources contains trace amounts of particle bound mercury. PolyMet will prepare and implement a fugitive dust control plan that describes the measures PolyMet will take to control these emissions. Dust control measures listed in the plan will be consistent with best management practices and dust control techniques used by other mining facilities in the area. A draft dust control plan is located in Attachment K of the “Emission Control Technology Review for NorthMet Project Processing Plant” dated October, 2007. Potential controlled mercury emissions associated with fugitive dust are calculated to be 0.025 pounds per year.

Flotation concentrate products may also contain a trace amount of mercury, but this material will be damp and handled indoors, so fugitive emissions are not expected to occur. The emission inventory and air dispersion modeling assume a dedicated ventilation system, with dust control, for these activities as a worst case, but this equipment will only be installed if necessary. The worst case emissions were estimated at 0.0005 pounds per year.

2.3 Forms of Mercury Emissions

Mercury can be emitted to the atmosphere in three forms:

- Particle bound mercury
- Oxidized mercury
- Elemental mercury

Particle bound mercury is, as its name implies, mercury which is chemically bound up in dust particles. An example of particle bound mercury is the dust from ore crushing. Mercury exists as a trace element commonly found in metallic ores. When ore is crushed to facilitate further processing, the dust generated during crushing will also contain trace amounts of mercury. Because the mercury is bound up in the ore dust particles, the mercury can be captured along with the dust particles in a particulate control device such as a baghouse.

Elemental mercury is pure mercury. Elemental mercury is released when mercury containing materials are combusted or processed at high temperatures. Under these conditions, mercuric compounds break down and pure mercury is released in a gaseous state. Because it is a gas, it cannot be captured efficiently in a particulate control device. Elemental mercury is not water soluble; so; it cannot be easily captured in a wet scrubber. Elemental mercury can be captured directly by adsorption using activated carbon. Alternatively, it can be oxidized by chemical reactions and then captured in an absorber or wet scrubber.

Oxidized mercury is mercury which through chemical reactions has given up some of its electrons so that is has a positive electrical charge. In this form, mercury will bond with halogens or sulfides to form a salt. Elemental mercury can be oxidized by chlorides, bromides or sulfur compounds. Oxidized mercury is water soluble; so, it can be captured in an absorber or wet scrubber.

2.4 Non-Ferrous Ore Processing

Several types of mercury control technologies were developed to control mercury emissions from non-ferrous metal ore processing. These mercury emission control technologies were included in the evaluation of potential mercury control technologies for use on the Autoclave exhaust. The Nevada Department of Environmental Protection (NDEP) and the United States Environmental Protection Agency (USEPA) have recently evaluated mercury emissions from gold mining operations. Information from these reviews was also included in the review of mercury control options for the Autoclave. The following section provides background information on sources of mercury and mercury emission control technologies used in non-ferrous metallic ore processing.

In non-ferrous metallic ores containing metals such as copper, zinc, tin and lead, the metals are often found in chemical complexes containing sulfur. The sulfur must be removed before the ore can be processed into pure metals. The traditional method of driving off the sulfur is roasting the ore in ovens at temperatures of 1,000° F or more. The sulfur is released from the ore primarily as sulfur dioxide. The roasting process also drives off any carbonaceous material in the ore which could inhibit downstream processing. If sulfur dioxide in the oven exhaust is present in sufficient concentrations, it can be converted to sulfuric acid and sold as a byproduct. The oven exhaust stream must be cooled cleaned and dried before it can be processed into sulfuric acid.

If mercury is present in the ore, it will be volatilized in the roasting ovens and it will be exhausted primarily as elemental mercury. Particle bound and oxidized mercury in the oven exhaust will be removed by particulate controls in the gas cleaning and cooling system. Elemental mercury will pass through these steps, and if not removed, will contaminate the sulfuric acid by-product. To prevent mercury contamination of the sulfuric acid byproduct, the industry developed mercury emission control technologies. All of the gas phase mercury removal processes developed for non-ferrous metal production were designed for removing mercury from the clean/dry oven exhaust prior to entering the sulfuric acid plant.

Alternatively, some non-ferrous metallic ores can be processed in autoclaves to oxidize the sulfur and to prepare the ore for further processing. In preparation for processing in an autoclave, the ore is ground and mixed with water to form a slurry. The slurry is pumped in to the autoclave where pure oxygen is injected. The autoclave operates at temperatures of 350° F to 400° F and a pressure of 300 to 500 pounds per square inch (PSI). Under these conditions, the oxygen reacts with the sulfur to form sulfuric acid. Because autoclaves operate at much lower temperatures than roasting ovens, most mercury is in either particle bound or oxidized form. Upon exiting the autoclave, the slurry goes to a depressurization vessel where non condensable gases are separated from the slurry. As the pressure is reduced in the depressurization vessel, some slurry water vaporizes to form steam. As a result, the depressurization vessel, also referred to as a flash vessel, exhaust is composed primarily of steam and the non condensable gases (carbon dioxide, nitrogen and oxygen) comprise only ten to twenty five percent of the off gas. This off gas will also contain small amounts of sulfur dioxide and mercury. The depressurization vent is scrubbed to remove particulates and other contaminants prior to being exhausted to the atmosphere.

2.5 Recent Regulatory Evaluations of Mercury Emission Controls for the Gold Mining Industry

Gold mining is a non-ferrous metal ore processing industry which can be a significant source of mercury emissions. Gold ore, depending on its composition, may be processed in roasting ovens or in autoclaves. Recent regulatory evaluations of the gold mining industry can provide valuable information on the cost and effectiveness of mercury emission control options for the Autoclave. It must be noted that potential mercury emissions from the Project are less than one tenth of the mercury emissions from a typical autoclave used to process gold ore, so the reduced mercury emission rate is a significant factor when comparing mercury control options for the Project versus the mercury control in the gold mining industry.

A majority of the gold mines in the United States are located in the State of Nevada. The NDEP has studied mercury emissions from gold processing and beginning in May, 2006 implemented a mercury reduction program for thermal processing units located at precious metal mines. As a result, the NDEP has collected a significant amount of information on the cost and performance of several mercury control technologies. The NDEP website contains a database of performance test results on several types of mercury controls used in various stages of the gold production process. One of the air quality permits issued under the mercury reduction program includes a mercury control evaluation for an autoclave system similar in size to that proposed for the Project.

The USEPA recently evaluated mercury emission control options for gold mining under the 40 CFR Part 63 program for control of Hazardous Air Pollutants. Per 40 CFR Part 63 requirements for establishing emission standards, the USEPA reviewed information on mercury emission control technologies in use at gold mines to identify the top emission control systems in operation today, and developed mercury emission standards based on the top performing facilities. The results of this evaluation are summarized in the preamble to the proposed regulations published on April 28, 2010 in the Federal Register Volume 75, No. 81 pages 22470 -22497 and the final regulations published on in Federal Register Volume 76 No. 33 pages 9450 – 9489. Please note that standards issued under 40 CFR 63 Subpart EEEEEEE are not applicable to the Project because the project is intended to produce nickel, cobalt and PGM concentrates as its primary products and the small amount of gold contained in the PGM concentrate is below the deminimus amount specified for the regulation to apply.

3 Emission Control Technology Options

3.1 Description of Emission Control Trains for Non-ferrous Ore Processing

Vent streams from non-ferrous metal ore processing can contain high levels of particulates as well as gaseous pollutants. For those streams with high concentrations of particulate matter, multiple stages of emission control may be required. After primary controls and before second and/or third stage mercury controls, additional gas conditioning and fine particulate removal systems may be needed. To simplify the review of multi stage emission control trains, emission controls have been grouped in first, second and third stage controls. Figure 1 and Figure 2 at the end of this section are block flow diagrams showing emission control trains for ore roasting and autoclaves systems. Figure 3 is a block flow diagram of a mercury control system for the Autoclave system as proposed. Attachments A and B contain examples of gas treatment systems for sulfuric acid plants at non-ferrous ore processing facilities. Attachment A is the Autotec gas treatment and conditioning system. Attachment B contains Hugo Petersen gas conditioning and mercury removal systems.

First stage emission controls

Typically particulate controls are the first stage in the emission control system; this is done so that particulate matter will not adversely affect downstream processes and second and/or third stage emission control systems. Particulate controls also control particle bound mercury, and in some cases oxidized and some elemental mercury are removed.

Second stage emission controls

The second stage mercury controls are designed to control relatively high mercury concentrations. Historically, these controls were designed to treat non-ferrous metal processing off gas streams prior to being used as feedstock for sulfuric acid production. In second stage controls, gas phase mercury is absorbed into a scrubbing liquid and, in most cases; the mercury then reacts with chemicals in the scrubbing solution for permanent capture.

In some cases, gaseous mercury concentrations are high enough that mercury can be captured by condensation. Condensation occurs when a gas is cooled to temperatures below the dew point of chemical compounds in the gas. In gold processing, mercury condensers are typically used when gold concentrate is heated to remove mercury (retort furnaces) which has been concentrated along with the gold.

Condensation can also be used to remove excess water from gas streams. This is done in cases where the water content of the off gas stream would adversely affect the operation of an emission control system by diluting reagents in the scrubbing solution or interfering with the adsorption process in activated carbon controls. In this report, condensation of water is classified as gas conditioning to differentiate it from mercury condensation.

Third stage emission controls

Third stage mercury controls evaluated are controls best suited to controlling streams with low mercury concentrations. These technologies may also be used effectively as polishing controls downstream of controls used in high mercury concentration applications. In third stage controls, gas phase mercury is captured by adsorption (activated carbon) and/or chemical reaction.

3.2 Mercury Emission Control Options for Autoclave Exhaust

Particulate (first stage) controls evaluated include:

- Wet Scrubbers and Venturi Scrubbers
- Fabric Filters (baghouse or cartridge filter)
- Dry Electrostatic Precipitators (Dry ESPs)
- Wet Electrostatic Precipitators[2] (Wet ESPs)
- Cyclones and Mechanical Collectors

Absorption/Chemical Reaction (second stage) controls evaluated include:

- Wet scrubbers and venturi scrubbers
- Sodium hypochlorite scrubbers
- Boliden Norzink Process (calomel scrubbers)
- Outokumpu Process (sulfuric acid scrubbing)
- Bolkem Process (sulfuric acid scrubbing)
- Sulfide Precipitation (hydrogen sulfide reagent)
- Hg Condensation

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[2] Wet ESPs may also be included in gas conditioning systems downstream of the primary particulate control system.

Adsorption/Chemical Reaction (third stage) controls evaluated include:

- Activated Carbon
- Sulfur Impregnated Activated Carbon
- Selenium Filter

Condensation:

- Heat Exchangers for Mercury Condensation

Figure 1 on the following page is a block flow diagram of a mercury control system for a gold ore roaster. Its design is similar to other non-ferrous ore processing system as described in Section 2.4. There are two gold ore roasting systems in Nevada which are equipped with similar mercury emission control systems. One system has a dry ESP followed by a wet scrubber for primary particulate control; the other system has a venturi scrubber. These systems remove particle bound and oxidized forms of mercury. After primary particulate control, the gas stream is cooled and then goes through a wet ESP for fine particulate control and some additional mercury removal. After the fine particulates are removed, the gas goes through fluoride and mercury removal systems. Only one of the facilities has a fluoride scrubber. Both facilities use calomel scrubbers for mercury control. The calomel scrubbers can remove the elemental mercury which could not be effectively captured in the upstream control systems. After mercury scrubbing; one plant's off gas serves as feed to a sulfuric acid plant; the other plant's exhaust is clean enough to vent directly to atmosphere.

Figure 2 on the following page is a block flow diagram of a mercury control system for gold ore autoclaves. All gold ore autoclave systems in Nevada are equipped with venturi scrubbers as the primary controls for mercury and other pollutants. Most existing gold autoclaves vent to atmosphere after the venturi scrubber. For additional mercury control, an activated carbon adsorption system can be added as a polishing mercury emission control. However, the autoclave exhaust is to hot and its moisture content is too high for activated carbon. Therefore, additional gas conditioning equipment is needed to cool and reduce the humidity of the autoclave exhaust to meet carbon adsorption system operating requirements.

Figure 3 on the page following Figure 1 and Figure 2 is a block flow diagram of a mercury control system for the Autoclave as proposed. To incorporate activated carbon controls, a gas conditioning system would be required between the packed bed scrubber outlet and the activated carbon bed.

Figure 1 Example Gold Ore Roaster Mercury Emission Control System

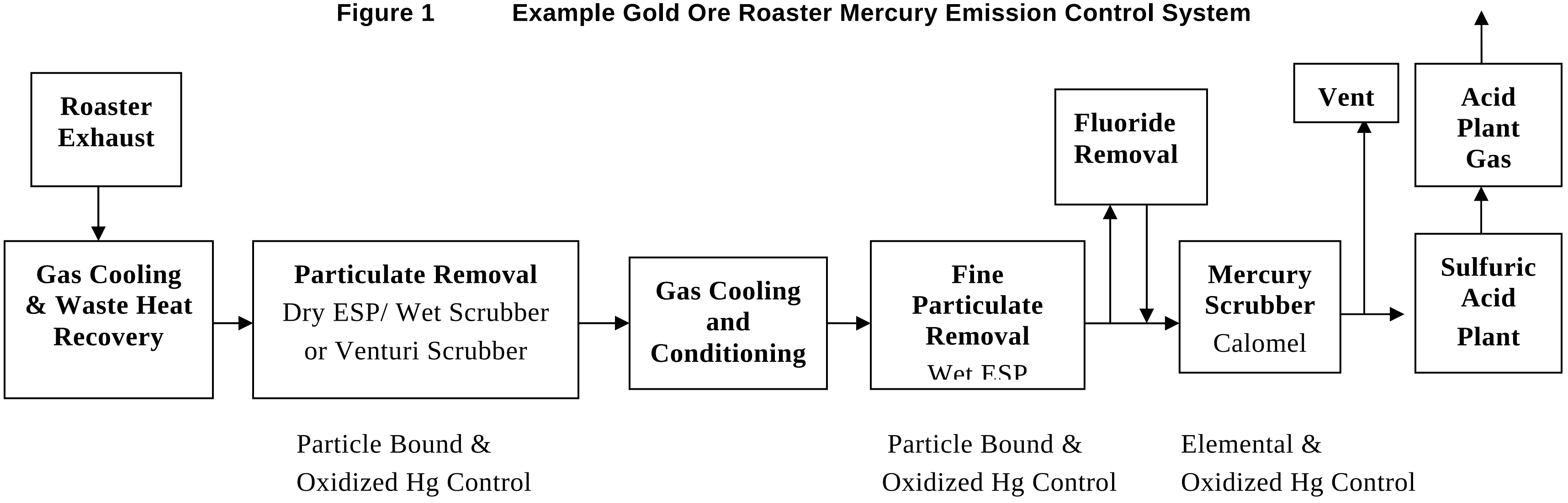


Figure 2 Example Gold Ore Autoclave Mercury Emission Control System

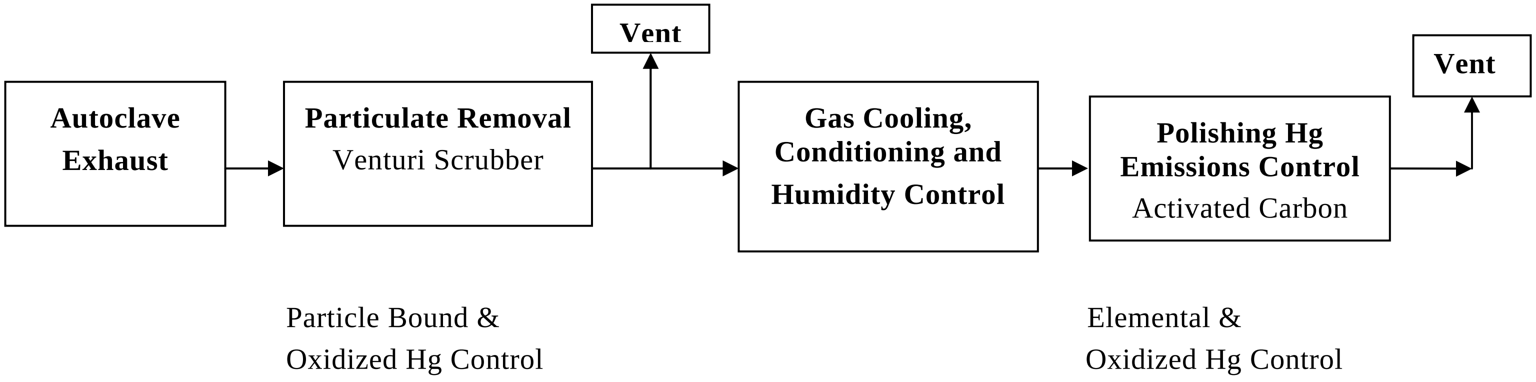
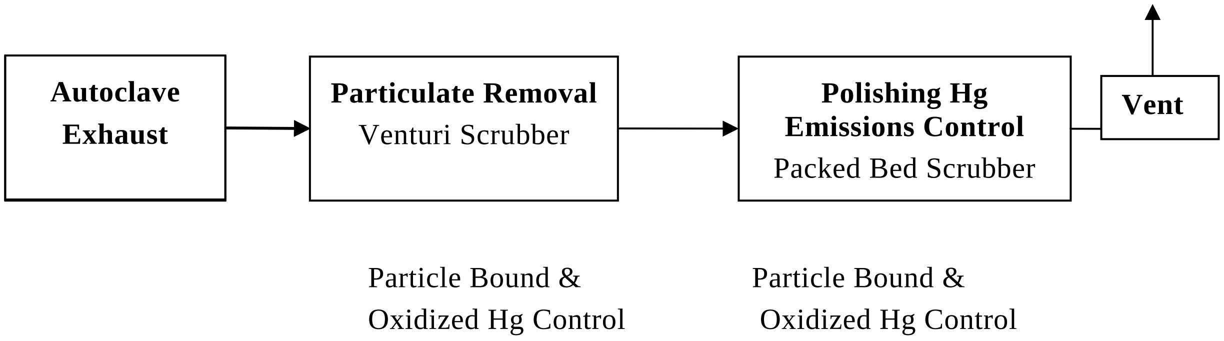


Figure 3 Project Proposed Autoclave Mercury Emission Control System



4 Technical Feasibility of Emission Control Technologies

4.1 Autoclave Exhaust Conditions

Table 4-1 below is a comparison of the design data for the Autoclave vent stream vs. the vents off of two gold mine autoclave systems. The Goldstrike mine is located in Elko, Nevada; the Placer Dome Campbell mine is located in Balmertown, Ontario Canada. All three systems have similar temperatures and high moisture contents. Flow rates for the Project are similar to the Barrick Goldstrike mercury control system designed to accommodate the flow from all six autoclaves. The Project’s proposed two stage scrubber system vent has mercury concentrations which are about one tenth of the single stage scrubber exhaust at Placer Dome and Barrick gold mines. To meet the 40 CFR Part 63 Subpart EEEEEEE standards, Barrick will install an activated carbon mercury control system like the one shown in Figure 2. Assuming a 90% control rate for activated carbon, the Barrick mercury concentration would be reduced levels similar to the Autoclave exhaust with two stage scrubbing.

Table 4-1 Comparison of Autoclave Exhaust Steams

Autoclave Vent Stream vs. Gold Mine Autoclave Vent Streams			
	Project Design	**Placer Dome Campbell Mine[1]**	**Barrick Goldstrike Mine[2]**
Controls	**Two stage Venturi/Packed Bed Scrubber**	**Single Stage Venturi Scrubber**	**Single Stage Packed Bed Scrubber**
Composition Mole %			
N2	3.3%	4.7%	
CO		0.01%	
CO2	5.2%	0.2%	
O2	4.1%	10.7%	
H2O	87.5%	84.5%	71.7%
Total	100.0%	100.0%	
Temperature F	202	185	194
Flow			
ACFM	37,268	5,955	51,760
SCFM	29,724	4,875	41,761
DSCFM	3,302	757	11,820

Autoclave Vent Stream vs. Gold Mine Autoclave Vent Streams			
	Project Design	**Placer Dome Campbell Mine[1]**	**Barrick Goldstrike Mine[2]**
Controls	**Two stage Venturi/Packed Bed Scrubber**	**Single Stage Venturi Scrubber**	**Single Stage Packed Bed Scrubber**
Exhaust Mercury Conc			
gr/dscf	1.65E-05	2.06E-04	1.45E-04
mg/Sm^3	0.037	0.464	0.326

1. Emissions Summary and Dispersion Modeling Report, Appendix E dated February, 2003 for Placer Dome – Campbell Mine.
2. Calculated from data in the Barrick Goldstrike autoclave permit application. See footnote 4.

4.2 First Stage Mercury Control Options

4.2.1 Venturi Scrubbers/Wet Scrubbers

Wet scrubbers, also termed particulate scrubbers, remove particles from process exhaust gas by capturing the particles in liquid droplets (usually water) and separating the droplets from the gas stream. The droplets transport the particulate out of the gas stream.

Scrubbers may capture particulates through the following mechanisms:

- Impaction of the particle directly into a target droplet;
- Interception of the particle by a target droplet as the particle comes near the droplet; or
- Diffusion of the particle through the gas surrounding the target droplet until the particle is close enough to be captured.

Scrubbers are generally classified according to the liquid contacting mechanism used. The most common scrubber designs are spray-chamber scrubbers, cyclone spray chambers, orifice and wet-impingement scrubbers, and venturi scrubbers. Wet scrubbers require a waste water discharge or recycling of scrubber water to the process. Scrubber control efficiency for particulate matter under normal loading conditions typically is in the 98 – 99+ percent range. Scrubber efficiency is a function of pressure drop across the scrubber. So, higher collection efficiencies will consume more electrical power to operate the scrubber blower. Reduced efficiencies will occur when the inlet particle concentration is low.

A venturi scrubber enhances particulate removal through turbulent mixing. The inlet to the venturi is a conical shaped section which tapers from the inlet duct diameter down to the venturi throat. The venturi throat is a narrow cylindrical section. Gas velocity must increase to pass through the narrow opening in the venturi throat. As a result of the increase in gas velocity, highly turbulent flow patterns are created. Water injected into the throat is broken into fine droplets and mixed intimately with gases by the turbulent flow. Particulate matter, mercury and other pollutants the off gas are captured by the water droplets and removed. The venturi outlet is a tapered section which has an increasing diameter. This reduces the venturi outlet gas velocity and turbulence and which allows the water droplets to combine and form larger droplets. When the gas enters the settling chamber the enlarged water droplets are separated from the off gases. A demister at the settling chamber outlet captures entrained water droplets to minimize the amount of free water in the venturi scrubber exhaust.

Wet scrubbers are feasible in this application. As noted above, all gold ore autoclave systems in Nevada use venturi scrubbers. No active U.S. gold mines outside the state of Nevada use autoclaves. One gold mining autoclave application in Canada (the Campbell Mine) uses a packed bed scrubber.

4.2.2 Baghouses

A fabric filter (baghouse or cartridge filter) consists of a number of fabric bags or cartridges placed in parallel inside of an enclosure. Particulate matter is collected on the surface of the bags as the gas stream passes through them. A dust cake forms on the outside of the filter as particles are collected. The dust cake provides additional particle filtration which contributes to the overall baghouse particulate collection efficiency.

The main operating limitations of a baghouse are that the material collected must be dry and operating temperature is within the temperature limitations of the bag material. If the off gas is saturated with water and/or it contains free water, the filter cake will become wet and blind off the filter, stick to the filter media or clog up the dust hoppers and dust removal system.

The Autoclave exhaust will be saturated with water and will contain free water droplets. Therefore, a baghouse is not feasible on the autoclave exhaust. No gold ore autoclave systems use baghouses or cartridge filters as particulate controls.

4.2.3 Dry Electrostatic Precipitators

A dry electrostatic precipitator applies electric forces to separate suspended particles from the flue gas stream. In an ESP, an intense electrostatic field is maintained between high-voltage discharge electrodes, typically wires or rigid frames, and grounded collecting electrodes, typically plates. A corona discharge from the discharge electrodes ionizes the gas passing through the precipitator, and gas ions subsequently ionize the particles. The electric field drives the negatively charged particles to the collecting electrodes.

Periodically, the collecting electrodes are rapped mechanically to dislodge collected particulate matter, which falls into hoppers for removal.

ESP installations are not feasible in applications where the combination of sparking and dry material creates the potential for dust explosion or in wet applications where the presence of liquid water could cause shorting of the electrodes.

The Autoclave exhaust will be saturated with water and will contain free water droplets. Therefore, a dry ESP is not feasible on the Autoclave exhaust. Dry ESPs are used for particulate control in gold ore roasting. No gold ore autoclave systems use dry ESPs as particulate controls.

4.2.4 Wet Electrostatic Precipitators

A wet electrostatic precipitator operates in the same manner as a dry ESP; it applies electric forces to separate suspended particles from the flue gas stream. Particle removal in a wet ESP is accomplished with water sprays instead of mechanical cleaning methods. Electrical grids are depowered during cleaning to prevent shorting. As a result of using water sprays, wet ESPs generate wastewater which must be treated to remove suspended particles and dissolved solids. Alternatively, scrubber water can be recycled to the process if this is allowed by process chemistry.

Wet ESP control efficiency under normal loading conditions typically is in the 98 - 99+ percent range. Reduced efficiencies will occur when the inlet particle concentration is low. Outlet particle concentrations of filterable particulates as measured by USEPA Method 5 can be as low as 0.005 gr/dscf.

Wet ESPs are used for fine particulate control in gold ore roasting. No gold ore autoclave systems use wet ESPs for particulate control. Use of a wet ESP on the Autoclave exhaust may be feasible.

4.2.5 Cyclones/Mechanical Collectors

Mechanical collectors use a variety of mechanical forces to collect particulate matter:

- Inertial separators use inertia and gravity to remove larger particles from smaller ones.
- Cyclones use centrifugal force to separate particulate matter from gas streams.

Drop-out boxes are typically used as inertial separators. Larger particles are trapped in drop-out boxes as the inertia they contain forces them to go straight as the rest of the gas stream turns to flow into and out of the drop-out box. Particles are also removed by gravitational settling in the drop-out box. Inertial separators can only remove the larger dust particles (>75 microns). They are typically used upstream of other control devices in high inlet dust loading cases.

Cyclone separators are designed to remove particles by inducing a vortex as the gas stream enters the chamber, causing the exhaust gas stream to flow in a spiral pattern. Centrifugal forces cause the larger particles to concentrate on the outside of the vortex and consequently slide down the outer wall and fall to the bottom of the cyclone, where they are removed. The cleaned gas flows out of the top the cyclone.

If off gas entering a cyclone or mechanical collector is saturated with water and/or it contains free water, the dust will become wet and stick to the dust collector walls and/or clog up the dust removal system.

The autoclave exhaust will be saturated with water and will contain free water droplets. Therefore, mechanical separators and cyclones are not feasible on the autoclave exhaust. No gold ore autoclave systems use cyclones or mechanical collectors for particulate control.

4.3 Second Stage Mercury Emission Controls

Most second stage mercury control systems use absorption. As noted above, water based scrubbers can be used to effectively capture particle bound mercury. Oxidized mercury is water soluble, so water based absorbers (wet scrubbers) can be used for enhanced oxidized mercury control. The removal efficiency of absorption systems can be enhanced through the use of additives and reagents to increase the solubility of the mercury and/or chemically bond with the mercury to permanently capture it.

One gas phase mercury control system was also identified. In this process, a chemical reaction results in formation of a solid phase mercury compound that is removed from the off gas stream by particulate emission controls.

4.3.1 Venturi Scrubbers/Wet Scrubbers

The most common wet scrubber designs are spray-chambers, packed bed towers, tray tower absorbers and venturi scrubbers. For emission control by absorption, gas/liquid contact is a key factor in maximizing the amount of gaseous pollutants which can be absorbed by the scrubbing solution. Spray towers and venturi scrubbers use water sprays to generate liquid surface area which contacts contaminated gas flowing through the spray tower or venturi scrubber. Packed towers are filled with specially shaped objects (packing) to provide a large area for gas liquid contact. The scrubbing liquid is pored over the top of the packing material and trickles down through the bed coating the outside of the packing. Contaminated gas flows up through the tower and flows over, around and through openings in the packing so that contaminants in the gas can be absorbed by the scrubbing liquid flowing over the packing. Tray tower scrubbers have a number of internal trays. Each tray has a weir which holds scrubbing liquid on top of the tray and it has openings in the tray which force the contaminated gas to flow up through the liquid on each tray. The weir system on the trays allows the scrubbing liquid to flow down through the tower over each tray. The contaminated gas flows up through the tower contacting the scrubbing liquid on each tray.

Venturi scrubbers and wet scrubbers are feasible second stage mercury controls for the Autoclave exhaust.

4.3.2 Sodium Hypochlorite Scrubber

Sodium hypochlorite can be used to oxidize elemental mercury; thus making it water soluble and available for capture by absorption in a wet scrubber. In Nevada, there is one gold mine[3] where sodium hypochlorite is added to a wet scrubber to enhance mercury removal. Scrubbers must maintain a hypochlorite concentration of 1,000 ppm. Stack test data from the scrubber outlet has an average controlled mercury concentration of 1.68 e-4 gr/dscf[4]. The Autoclave scrubber outlet concentration is calculated to be 1.65 e-5 gr/dscf, which is ten times less than the mercury concentration at the outlet of the hypochlorite scrubber. Because the Autoclave scrubber outlet mercury concentration is so low, the use of sodium hypochlorite is considered technically infeasible for mercury control on the Autoclave exhaust.

In addition, the additional chlorine in the scrubber discharge could have an adverse impact on processes using water recycled from the autoclave scrubber.

4.3.3 Boliden Norzink Process (Calomel Scrubber)

The Boliden Norzink process uses a mercuric chloride solution which reacts with elemental mercury to form a mercuric chloride precipitate, known as calomel. Thus, the Boliden Norzink process is often referred to as a “calomel” scrubber. The reaction is as follows:

$$HgCl_{2\ (H2O\ solution)} + Hg_{(gas)} \rightarrow Hg_2Cl_{2\ (solid)}$$

Calomel produced by this reaction may be sold for the production of elemental mercury or disposed of. A portion of the calomel collected from the process may be regenerated to mercuric chloride for reuse in the scrubber using chlorine gas.

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[3] Newmont Mining Corporation - Twin Creeks Mine uses sodium hypochlorite scrubbers to remove mercury from its carbon kiln exhaust streams.

[4] Data from NDEP Mercury Emissions Management System Online located on the NDEP mercury website at http://ndep.nv.gov/bapc/hg/clearinghouse.html

The Boliden Norzink Process was originally developed as a pretreatment step to prepare non-ferrous metal processing off gas in sulfuric acid production plants. It is the most widely used mercury control technology used in non-ferrous metallic ore processing. The United Nations Program Environment November 2010 report[5] on controlling mercury emissions states that the Boliden Norzink process has a mercury control efficiency of 90% to 95% in base metal smelting operations. This process is used to control mercury emissions from roasting operations at two gold mining facilities in Nevada. The Gold Quarry mine uses calomel scrubbers to pre-treat the feed to a sulfuric acid plant. The Goldstrike mine uses calomel scrubbing only for mercury control.

The Nevada MACT[6] analysis for autoclave operation at the Barrick Goldstrike mine reports that calomel scrubbing can reduce mercury concentrations down to 1 e-5 gr/dscf to 2 e-5 gr/dscf. This report also states that calomel scrubbers have not been used to control mercury emissions from gold ore processing autoclaves. The NDEP Mercury Emission Data Management System (MEMS) Database shows that the average mercury concentration from the Goldstrike calomel scrubber was 2.94 e-4 gr/dscf. The Autoclave scrubber outlet concentration is calculated to be 1.65 e-5 gr/dscf, which is within the reported limit on mercury control exhaust streams from calomel scrubbers and ten times less than the average mercury concentration at the outlet of the Goldstrike ore roasting calomel scrubber system. Because the Autoclave scrubber outlet mercury concentration is so low, the use of calomel scrubbers is considered technically infeasible for mercury control on the Autoclave exhaust.

The Gold Quarry mine results are not representative for this application because testing was conducted at the exhaust of the sulfuric acid plant. In a sulfuric acid plant, the sulfuric acid removes additional mercury. Therefore the reported results are lower than what is achievable with calomel scrubbing alone.

4.3.4 Outokumpu Process

The Outokumpu process removes mercury in non-ferrous ore processing off gas streams by absorption in sulfuric acid by the following reaction:

$$Hg + H_2SO_4 + \frac{1}{2} O_2 \rightarrow HgSO_4 + H_2O$$

The Outokumpu process is used to pre-treat smelter off gas prior use of the off gas as feedstock in a sulfuric acid plant. The off gas is scrubbed with an 80% to 90% sulfuric acid solution at a temperature range of

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[5] Study on mercury sources and emissions, and analysis of cost and effectiveness of control measures "UNEP Paragraph 29 study"

[6] Application for Mercury Air Quality Operating Permit to Construct, Appendix 3 - Nevada MACT Analysis dated February, 2008, prepared for Barrick Goldstrike Mines Inc. Elko, NV. by Air Sciences Inc

265° F to 300° F. Mercury sulfate is recovered as a precipitate from the scrubbing solution. Estimated mercury control using this method on high concentration streams is 90%.

Use of this process would require PolyMet to bring additional sulfuric acid site and would require additional neutralization equipment to treat the spent sulfuric acid.

The web site "Sulphuric Acid on the Web™ (ww.sulphfuric-acid.com) reports in the Gas Cleaning System – Mercury Removal page[7] that the Outokumpu process has a mercury control efficiency of 90%, which slightly less than the Boliden Norzink process (calomel scrubber). The best performance the Outokumpu process could achieve would be 1 e-5 gr/dscf to 2 e-5 gr/dscf versus the Autoclave scrubber outlet concentration of 1.65 e-5 gr/dscf. Therefore, the Outokumpu process would be considered technically infeasible on the Autoclave exhaust.

4.3.5 Bolkem Process

The Bolkem process removes mercury in non-ferrous ore processing off gas streams by absorption in sulfuric acid by the following reaction:

$$H_2SO_4 + Hg \rightarrow Hg_2SO_4$$

The Bolkem Process is also used to pre-treat smelter off gas prior to use of the off gas as feedstock in a sulfuric acid plant. The off gas is scrubbed in two drying towers in series with sulfuric acid solutions of 80% H_2SO_4 and 93% H_2SO_4 at a temperature range of less than 120° F. The mercurous sulfate is oxidized to mercuric sulfate by oxygen in the strong acid solution (93%). A bleed stream of the 93% acid is treated with sodium thiosulfate to precipitate the mercury as mercuric sulfide.

Use of this process would require PolyMet to bring additional sulfuric acid site and would require additional neutralization equipment to treat the spent sulfuric acid.

The web site "Sulphuric Acid on the Web™ reports that the Bolkem process has a mercury control efficiency of approximately 90%, slightly less than the Boliden Norzink process (calomel scrubber). Therefore, the Bolkem process would be considered technically infeasible for the same reasons stated above for a calomel scrubber.

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[7] The address of the mercury removal page is http://www.sulphuric-acid.com/techmanual/GasCleaning/gcl_hg.htm

4.3.6 Sulfide Precipitation

Sulfide Precipitation is a gas phase mercury control process. Sulfide precipitation can be used to pre-treat non-ferrous ore processing off gas prior use of the off gas as feedstock in a sulfuric acid plant. Hydrogen sulfide (H_2S) gas is injected into the smelter off gas stream at a stoichiometric ratio of 1.5 to 2.0. Mercuric sulfide is formed by the following reactions:

$$2\,H_2S + SO_2 \rightarrow 3\,S + 2\,H_2O$$
$$S + Hg \rightarrow HgS_{(solid)}$$
$$H_2S + Hg \rightarrow HgS_{(solid)} + H_2$$

Mercuric sulfide particles are recovered in downstream particulate emission controls

Use of this process would require PolyMet to generate hydrogen sulfide gas on site, and to install gas cleaning equipment to remove residual H_2S from the off gas stream after sulfide precipitation is complete.

The web site "Sulphuric Acid on the Web™ reports that the sulfide precipitation process has a mercury control efficiency of approximately 90%, slightly less than the Boliden Norzink process (calomel scrubber). Therefore, sulfide precipitation would be considered technically infeasible for the same reasons stated above for a calomel scrubber.

4.3.7 Selenium Scrubber

A selenium scrubber process removes mercury in non-ferrous ore processing off gas by the reaction of amorphous selenium in a 20% to 40% solution of sulfuric acid. Mercury vapors are captured in the sulfuric acid solution by absorption in a packed column.

The mercury - selenium reaction is as follows:

$$Hg + Se \rightarrow HgSe$$

Use of this process would require PolyMet to bring additional sulfuric acid on-site and would require additional neutralization equipment to treat the spent sulfuric acid. Is would also require the use of selenium, a hazardous material.

The web site "Sulphuric Acid on the Web™ (ww.sulphfuric-acid.com) reports in the Gas Cleaning System – Mercury Removal page[8] that the selenium scrubbers have a mercury control efficiency of approximately

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[8] The address of the mercury removal page is http://www.sulphuric-acid.com/techmanual/GasCleaning/gcl_hg.htm

90%, slightly less than the Boliden Norzink process (calomel scrubber). Therefore, selenium scrubbing is considered technically infeasible for the same reasons stated above for a calomel scrubber.

4.3.8 Mercury Condenser

In gold processing, mercury condensers are typically used when gold concentrate is heated to remove mercury (retort furnaces) which has been concentrated along with the gold. Condensation occurs when a gas is cooled to temperatures below the dew point of chemical compounds in the gas. The Nevada MACT[9] analysis for autoclave operation at the Barrick Goldstrike mine reports that mercury condensation can reduce mercury concentrations down to 6.1 e-3 gr/dscf. The Autoclave scrubber outlet concentration is calculated to be 1.65 e-5 gr/dscf. Because the Autoclave scrubber outlet mercury concentration is so low, the use of mercury condensers is not considered technically feasible for mercury control.

4.4 Third Stage Mercury Emission Controls

Third stage mercury controls are controls best suited to controlling streams with low mercury concentrations. These technologies may also be used effectively as polishing controls downstream of controls used in high mercury concentration applications. In third stage controls, gas phase mercury is captured by adsorption (activated carbon) and/or chemical reaction.

4.4.1 Gas conditioning requirements

The effectiveness of the thirds stage mercury controls being evaluated is limited by the temperature, and moisture content of the gas being treated. Excessive particulate matter may also reduce the effectiveness of mercury controls. The temperature and water content of a gas steam may be reduced by quench cooling with water injection or/or through the use of heat exchangers. Air, water and refrigerants may be used as cooling media in heat exchanger systems. Wet ESPs are typically used for fine particulate control upstream of second stage mercury controls in non-ferrous metal ore processing due to the moisture content of the off gas downstream of quench cooling systems. After cooling and drying, gas reheating may be required to adjust the final relative humidity of the off gas before third stage treatment.

4.4.2 Activated Carbon

The mercury compounds in the waste gas stream are adsorbed on the surface of the activated carbon by intermolecular forces. All forms of mercury can be captured using activated carbon. Due to the low volume of off gas, activated carbon beds are used for mercury control in the gold mining industry. Due to similar off

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[9] Application for Mercury Air Quality Operating Permit to Construct, Appendix 3 - Nevada MACT Analysis dated February, 2008, prepared for Barrick Goldstrike Mines Inc. Elko NV. by Air Sciences Inc

gas characteristics of gold autoclave exhaust and the Autoclave exhaust, carbon beds are an appropriate option for treating the Autoclave exhaust.

Carbon adsorption rates are limited by the moisture content of the off gas. Capillary water condensation can occur in the activated carbon pores. Most adsorption sites are located within the pore space of activated carbon, and the presence of liquid water due to capillary condensation effectively blocks off these adsorption sites. In its analysis for activated carbon control of mercury emissions from autoclaves in the gold mining industry (FR 75, No. 81 Page22483), USEPA notes that because the autoclave venturi exhaust is saturated with water, “a refrigeration unit or condenser would be needed to remove water that would otherwise adversely affect the adsorptive capacity of the carbon adsorber”.

The MACT analysis for controlling mercury emissions from the Barrick Goldstrike mine, referenced in footnote 4, included one option where a large carbon bed was proposed instead of a refrigeration system to dry the autoclave off gas before a normal sized carbon adsorption bed. However, this analysis noted that it was uncertain whether this approach was feasible. This is because mercury adsorption rates slow significantly in air steams which have relative humidity above 60% to 80%. Literature from Scotia International of Nevada, Inc, a vendor who provides activated carbon mercury controls for the gold mining industry, indicates that at higher relative humidity conditions, reactions in the activated carbon bed drop down to 1% to 5% of the normal reaction rate. A copy of this presentation is located in Attachment D Therefore, use of carbon adsorption without a refrigeration system to dry the autoclave exhaust is not considered a viable option.

Activated carbon adsorption is considered technically feasible in this application provided that gas conditioning is used to dry the gas sufficiently to prevent liquid water deactivation of the activated the carbon.

4.4.3 Sulfur Impregnated Activated Carbon

The effectiveness of carbon adsorption for mercury control can be improved through the use of sulfur impregnated carbon. Mercury reacts with the sulfur to form mercury sulfide (HgS). Mercury sulfide has a lower vapor pressure than elemental mercury and is more readily adsorbed by the activated carbon. In the case of mercury, chemisorptions occurs and the mercury becomes chemically bound to the carbon

Sulfur impregnated activated carbon also has a nominal design operating temperature of 100° F to 130° F and a recommended moisture level is 60% to 80% relative humidity. Therefore gas conditioning is required if sulfur impregnated activated carbon is used for mercury control on an autoclave exhuast stream.

4.4.4 Selenium Filter

A selenium filter works in the same way as a selenium scrubber. Mercury vapors react with amorphous selenium with the following reaction:

$$Hg + Se \rightarrow HgSe$$

A selenium filter can effectively hold up to 10% to 15% of its theoretical mercury capacity and then it must be regenerated. The web site "Sulphuric Acid on the Web™ (ww.sulphfuric-acid.com) reports in the Gas Cleaning System – Mercury Removal page[10] that the selenium filters have a mercury control efficiency of 90% as a third stage mercury control, which is about the same as activated carbon. Outotec, a Finnish company, markets selenium filters as third stage controls for pre-treatment of smelter off gas before the off gas is used as sulfuric acid plant feedstock. The Outotec web site does not list a mercury control efficiency for selenium filters, but it does claim the use of a selenium filter will reduce the mercury content of the sulfuric acid from a range of 0.3 ppm to 0.5 ppm Hg down to 0.05 ppm Hg which is consistent with a 90% mercury control rate.

Installation of this process would require PolyMet to use selenium, a hazardous material as a reagent in a selenium filter. Spent selenium filter media would have to be sent off site for regeneration or disposal.

4.5 Technical Feasibility Summary

Due to the high moisture content of the Autoclave exhaust, dry controls such as baghouses and fabric filters are technically infeasible. Wet scrubbers are suitable and first or second stage mercury controls. Wet EPSs are also feasible and are well suited for fine particulate control in gas conditioning systems. Activated carbon controls are feasible as third stage mercury controls, but will require use of gas conditioning systems to cool and dry the Autoclave exhaust before it can be introduced into an activated carbon mercury control system. Selenium filters may also be feasible, but they do not offer a significant benefit in mercury control efficiency or significantly reduce gas conditioning requirements.

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[10] The address of the mercury removal page is http://www.sulphuric-acid.com/techmanual/GasCleaning/gcl_hg.htm

5 Evaluation of Technically Feasible Controls

5.1 First Stage Controls

Venturi scrubbers, wet scrubbers and wet ESPs are all feasible controls which can provide a high level of particulate control.

Because autoclaves operate at high pressure (300 - 500 psi), the autoclave off gas must be de-pressured prior to first stage treatment. Some of this pressure can be used to operate a venturi scrubber whereas the off gas steam must be fully de-pressured to use other wet scrubbing systems or a wet ESP. Gold mine autoclave systems in the United States all use venturi scrubbers. PolyMet proposes to use a venturi scrubber for its first stage mercury control.

5.2 Second Stage Controls

Venturi scrubbers, wet scrubbers and wet ESPs are all feasible controls which can provide a high level of particulate control and some level of absorption to capture soluble mercury compounds. Because first stage controls are primarily for particulate control, particulate control in the second stage is less important. Wet scrubber designs such as spray-chambers, packed bed towers and tray tower scrubber offer the advantage of providing sufficient gas/liquid contact to promote efficient absorption of soluble mercury vapors. Most mercury from autoclaves is in the form of oxidized mercury which is water soluble. Therefore, spray-chambers, packed bed towers and tray towers scrubbers are the best alternative for second stage mercury controls in this application. PolyMet proposes to use a packed bed scrubber for its second stage mercury control.

The estimated mercury control efficiency for the proposed scrubber system is 25% for elemental mercury and 90% for particle bound and oxidized mercury. Based on limited Project related available data on mercury speciation, a control efficiency of 25% was assumed in the emission inventory for the Autoclave Vent and 63% for the Autoclave Flash Vessel.[11] Actual performance is expected to be better than the values used in the emission inventory, based on typical speciation of autoclave mercury emissions.

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[11] Mercury collected in pre-train knockout during pilot plant testing assumed to be in a particle bound or oxidized form; mercury detected in train or upper bound based on detection limit assumed to be in elemental form due to absence of project specific data to the contrary (i.e. worst case assumption).

5.3 Third Stage Controls

Activated carbon controls are technically feasible if used in combination with a gas conditioning stream to dry and cool the autoclave exhaust. The next step is to determine whether or not activated carbon controls are economically feasible. As noted in Section 4.1, the Autoclave exhaust properties are similar to the gold ore autoclave exhaust streams. However, the mercury content is approximately one tenth of both the gold ore autoclaves (1.65 e-5 vs. 1.45 e-4 gr/dscf) and the Autoclave water content is 87.5% vs. 71.1% at the Barrick Goldstrike mine. Given these similarities, it is reasonable to use cost information from the Barrick Goldstrike NDEP MACT analysis as a basis for the Project cost evaluation. A capital cost of $8,320,000 is estimated for activated carbon control for the Project using the six tenths power law factor to account for economy of scale, and the ratio of flow rates from each system in actual cubic feet per minute. Annual operating costs of $1,464,000 per year were estimated using the flow rate ratio for power costs and USEPA control cost manual[12] factors for labor (Barrack hourly pay rates), maintenance, overhead and indirect operating costs. Costs were adjusted to account for regional differences in electric prices. As noted in the Barrick Goldstrike MACT analysis, the most significant cost is the electrical power needed to operate the gas conditioning system. This results in an estimate mercury control cost of $397,000 per pound mercury which is economically infeasible when compared to the USEPA cost analysis in the gold mining MACT analysis. Control cost calculations are located in Attachment C. In its cost analysis of mercury controls for gold mining in FR 76 No 33 page 9465 USEPA determined that $11,000 per pound mercury removed was feasible for carbon control on gold mining autoclaves, but in the proposed rules at FR 75 No. 81 pages 22,483 USEPA determined that $44,000 per pound mercury was not cost effective for additional controls on melt furnaces and that $100,000 per pound of mercury for additional carbon controls on autoclaves was not feasible. Therefore, the cost of carbon controls on the Autoclave is economically infeasible at $397,000 per pound of mercury removed.

As noted above, a selenium filter may be feasible for use as a third stage mercury control, but they do not offer any advantages over activated carbon controls for mercury control. Selenium filters require a dry gas feed, so gas conditioning costs are expected to be similar to activated carbon controls. Selenium filters are expensive produce and regenerate, so it is likely that selenium filters would be even more expensive than activated carbon. Lastly, selenium is a hazardous material; so, its use would create the potential for adverse environmental impacts.

PolyMet proposes no third stage mercury control.

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[12] EPA/452/B-02-001 Carbon Adsorbers September, 1999

6 Conclusion

The proposed mercury control system for the Autoclave is a venturi scrubber for the first stage scrubber and a packed bed scrubber as the second stage mercury control. Use of a venturi scrubber as a first stage control has the advantages of being able to utilize the Autoclave exhaust pressure to enhance particulate control; other wet scrubbing systems cannot do this. In the United States, all gold mining applications use venturi scrubbers; so, selection of a venturi scrubber is consistent industry practices. Data on mercury control on autoclaves for other types of mining were not readily available.

The proposed second stage mercury control for the Project is a packed bed scrubber. This type of wet scrubber is most effective at removing gaseous pollutants; so, it will be effective at removing any oxidized mercury which has not been captured in the venturi scrubber. No gold mining facilities in the United States have two stage wet scrubbing systems for mercury control.

Chemical scrubbing systems have been identified by the USEPA as a viable third stage mercury control for gold mining autoclave systems in the United States. However, the Autoclave exhaust is projected to have mercury concentrations at levels which are equal to the exhaust gas concentrations of gold mining autoclave systems with chemical scrubbing systems. Activated carbon controls would be technically feasible at for the Project, but, like gold mining, a gas conditioning system would be required to dry and cool the Autoclave off gas. Using the cost data in the Barrick Goldstrike NDEP MACT analysis as a reference, PolyMet has shown that activated carbon controls are not economically feasible. Because so little mercury will be in the Autoclave exhaust after passing through a venturi scrubber and a packed bed scrubber, the cost of further reducing mercury emissions on a $/ton mercury removed exceeds the mercury control cost deemed economically feasible by USEPA in its review of mercury emission controls for the gold mining industry.

Therefore, the two stage wet scrubber system proposed for the Project provides the level of mercury control which meets Minnesota Pollution Control Agency’s policy requirement to install best available mercury controls.

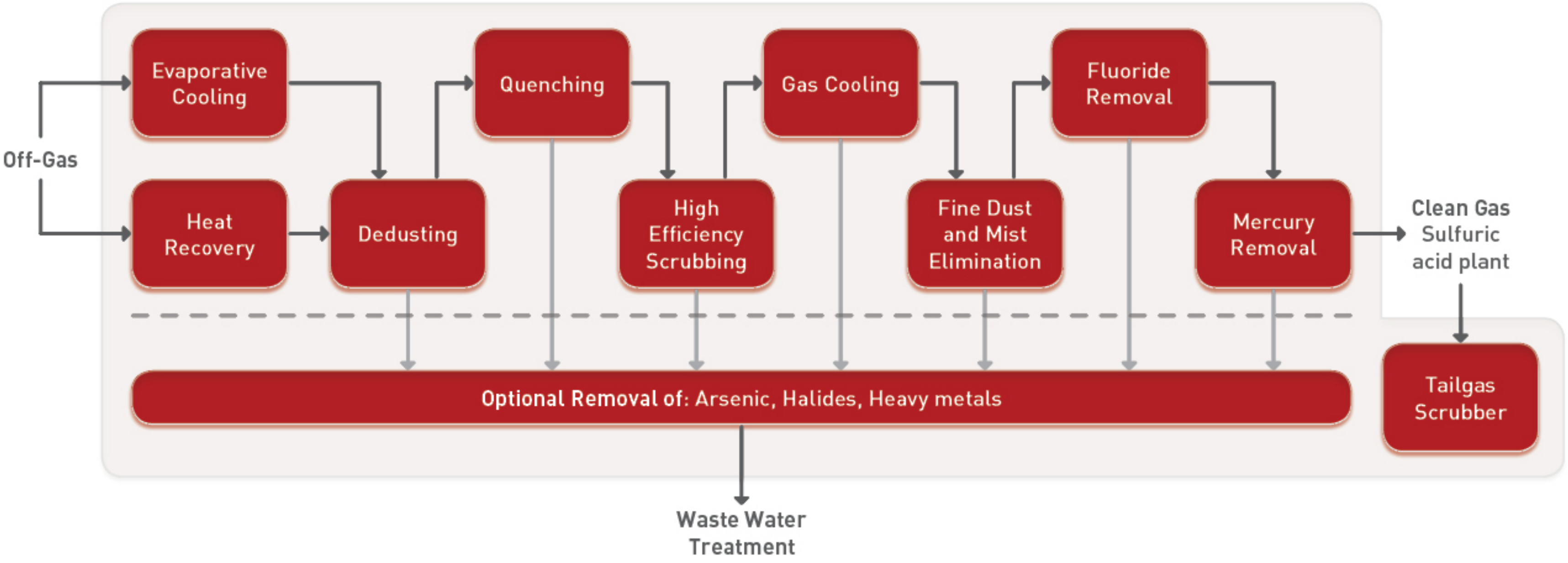
Attachments

Attachment A

Autotec Gas Treatment and Conditioning System

Attachment A

Outotec Gas Cleaning System Flow Diagram



Attachment B

Hugo Petersen Gas Conditioning and Mercury Removal Systems

HUGO PETERSEN - COMPETENCE IN GAS CLEANING SYSTEMS DOWNSTREAM NONFERROUS METALURGICAL PLANTS

Axel Schulze
HUGO PETERSEN

The Company

HUGO PETERSEN has developed from the traditional firm of the same name that was established in 1906 in Berlin and is an engineering company specialising in general plant engineering now based in Wiesbaden.
HUGO PETERSEN has many years wide-ranging experience in process plant engineering, primarily in the field of **Sulphuric Acid Processes** and **Gas Cleaning**.
Together with its main shareholder, Chemieanlagenbau Chemnitz GmbH (CAC), a company with over 40 years experience in the international plant engineering business, HUGO PETERSEN implements turnkey new plants from initial consultancy right through to commissioning.
In addition, HUGO PETERSEN can offer its clients improvements and revamps of existing plant systems.
Initial consulting, planning and implementation take place within the context of a lean company organisation with experienced engineers and specialists.
In all respects, many years of experience guarantee expertise over a wide range of possible applications.
For clients from the chemicals and metallurgical industries, as well as those in metals processing, HUGO PETERSEN GmbH’s breadth of experience means not just an efficient introduction to new methods and processes, but also their full implementation.

In addition, along with design and construction for individual components, the company’s range of services also covers supply of complete plants, as well as modernisation projects and revamps in line with local conditions and existing quality requirements
With own technologies and patents in the field of gas cleaning and sulphuric acid, supplemented by licences and cooperation projects, HUGO PETERSEN ensures expertise over a wide range of applications.
With specialists and expert knowledge in these fields of application, HUGO PETERSEN is your partner of choice, supporting you and bringing your acid, and project to a successful conclusion.

Gas Cleaning Plant (GCP)

Components and Arrangement of Gas Cleaning Plants downstream Nonferrous Metallurgical Plants mainly depending on the following terms:

- Gas Conditions of the upstream Process
- Sulphuric Acid Quality
- Requirements of Local Authorities

Generally HUGO PETERSEN Design has the following principles:

- Low Pressure Drop
  → low operation costs as well as reduced wear and tear

- Self adaptable Process Operation
  → reduces manual or control loops impact, means less operational problems and high efficient operation as no risk of bad control

- No movable Parts in the Gas Stream
  → less maintenance

- High corrosion resistant Material
  → extended life cycle of the plant

Based on the different requirements the choice of single units and arrangements can be subdivided as follows:

Conventional Arrangement

- Pre-quench Tower for Gas Conditioning and Preliminary Cooling
- Post-quench Tower for Gas Conditioning and Secondary Cooling
- Cooling Tower for Gas Condensation and HF-Removal
- Primary and Secondary Wet Electrostatic Precipitator (WESP) for remaining Dust and Mist Removal

High Dust Arrangement

- Pre-quench Tower
- Jet Scrubber or Post-quench Tower incl. PETERSEN Spray Separator (PSS)
- Primary WESP
- Cooling Tower
- Secondary WESP

Additional Mercury and / or Heavy Metal Removal

- Calomel Process
- Thiosulphate Process
- Activated Coke Filter

Tail Gas Scrubbing

- Hydrogen Peroxide Scrubber (SUPER^{OX})
- Ammonium Scrubber

Conventional Arrangement

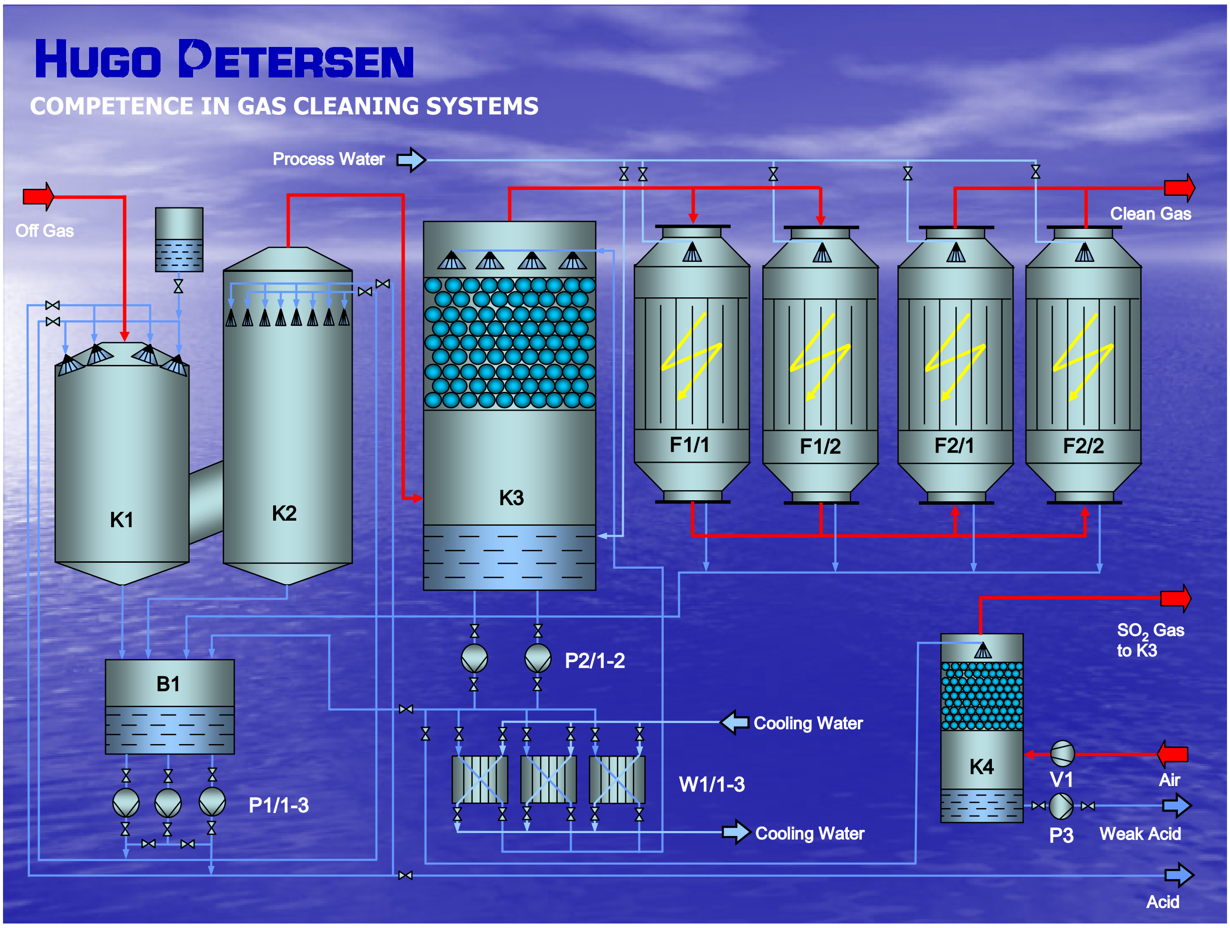
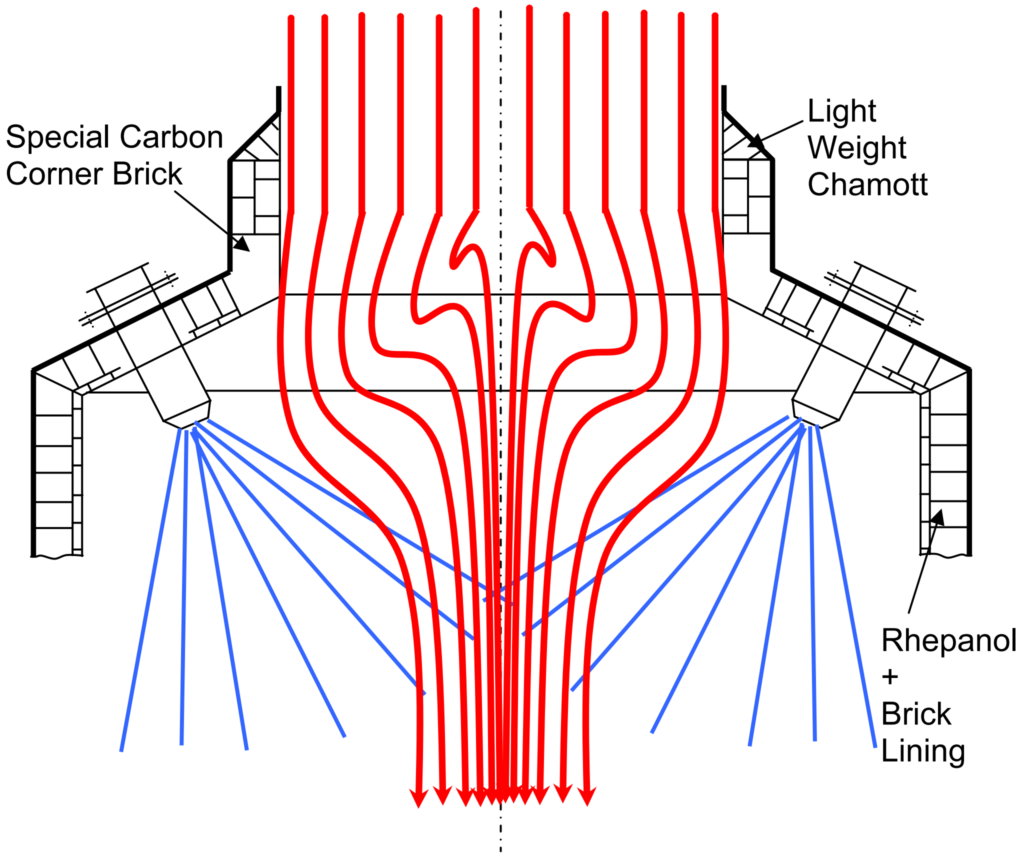


Diagram 1: Conventional Arrangement incl. SO_2-Stripping Tower

The hot gases from the upstream plant are led via hot dust precipitators to the top inlet of the pre-quench tower K1 which is a void tower. At the downward flow the hot gases are cooled down by app. 10 up to 50 weight % sulphuric acid.
Due to the special design of the pre-quench tower enabling an internal re-circulation, a safe cooling down is achieved by partial evaporation of the circulation liquid.
Due to this spraying the gas temperature is reduced to the equilibrium of the vapour pressure of the circulated sulphuric acid depending on the acid concentration.



Principle scheme of the gas flow on top of the Pre-quench tower

The gases leave the pre-quench tower K1 and enter the post-quench tower K2.
In both towers partly dust, HCl and HF are removed as well as Arsenic, Antimony etc.
The remaining part of the sprayed liquid is collected in the bottom part of the quench towers and led via the quench liquid pump tank B1 which serves the pumps P1.
Two separate lines, each with one pump, serves the sprays at the pre-quench tower and the spray lines of the post-quench tower. The flow rate to the spray nozzles of the pre-quench tower is monitored, and in case of failure of one line the other line serves enough liquid for safe and uniform cooling down of the gases.
Due to partial evaporation the circulation system has always a need for liquid which is fed by a cross flow from the fluoride scrubbing tower K3.

Downstream the post-quench tower an optional additional gas stream, coming from the Stripping Tower K4 is mixed with the cooled and pre-cleaned gases.
The mixed gases enter the cooling tower K3 wherein the gases pass a packed bed which is irrigated with cooled liquid. Due to the intense contact between the gas and the liquid within the packed bed the gas temperature is reduced down to normally between ranges of 30 – 40 °C.

When cooling down also partial condensation takes place and all liquids are collected in the base part of the tower K3 which is acting as pump tank for the circulation pumps P2.
Due to the low temperature the main part of HCl, as well as the remaining part of arsenic, is removed in the scrubbing tower.

The circulation liquid pass a set of acid coolers W1 wherein the heat is transferred to cooling water and the temperature of the circulation liquid is reduced to the required temperature. Downstream the coolers the liquid is evenly distributed by sprays or optional via an acid irrigation system on the top of the packing of the cooling tower. The condensed water vapour is discharged dependent on the level of the quench-tower pump tank to the pump tank of the quench towers.

The remaining amount of liquid is discharged in dependence of the cooling tower bottom liquid level, either directly to the waste water treatment or via the above mentioned SO_2-Stripper K4 to the waste water treatment.
After passing the cooling tower K3 the gases are lead to the two stages wet electrostatic precipitator system.

The wet electrostatic precipitator system in our example consists of totally four precipitators arranged in series consisting of two primary and two secondary WESP's.
The mist and droplet laden gases enter the shell at the top of the first stage WESP's (F1/1-F1/2) and passes through guide vanes and two perforated plates which distribute the gas evenly throughout the shell.

The gases then flow downward through the collector tubes and exit centrally through the bottom of the shell of the WESP's.

The second stage WESP's (F2/1-F2/2) are connected to the first stage WESP's by gas ducts, so that the gases flow from the bottom of the first stage WESP's to the bottom of the second stage WESP's.

The bottom vestibule of the second stage WESP's is equipped with guide vanes and two perforated plates as well, to assure that the gas is evenly distributed throughout the collection tubes.

The gases leave the second stage WESP's through the top vestibule to the downstream drying tower.

In the electrostatic precipitator systems mainly the remaining acid mist and dust are removed to the required emission data.

While it is imperative that the gases flow upward in the second stage to prevent re-entrainment, it is beneficial to have the gas flow downward in the first stage. In effect, the gases at the inlet of the first stage carry a lot of coarse entrained droplets from the cooling system upstream of the WESP-system which will provide a so called "self-cleaning effect" on the collecting surface and reduce the danger of built-up of solids on the collecting surface to a minimum.

As the gas enters the intense electrical field induced between the electrodes and the collector tubes by the high voltage electrode, particles suspended in the gases become charged and migrate under the influence of electrostatic forces towards the collection surfaces.

The accumulated mist particles or droplets form a liquid film on the grounded collector surface and are drained back to the pump tank of the quench towers.

The electrostatic field is established by stepping up low voltage alternating current (AC) in a transformer to a high voltage and then rectifying it to direct current (DC) with a rectifier. The rectified current is then delivered to a system of high voltage electrodes which are suspended in the centre of each of the uniformly spaced collecting pipes. The high voltage system is electrically insulated from the collecting pipes by special porcelain insulators.

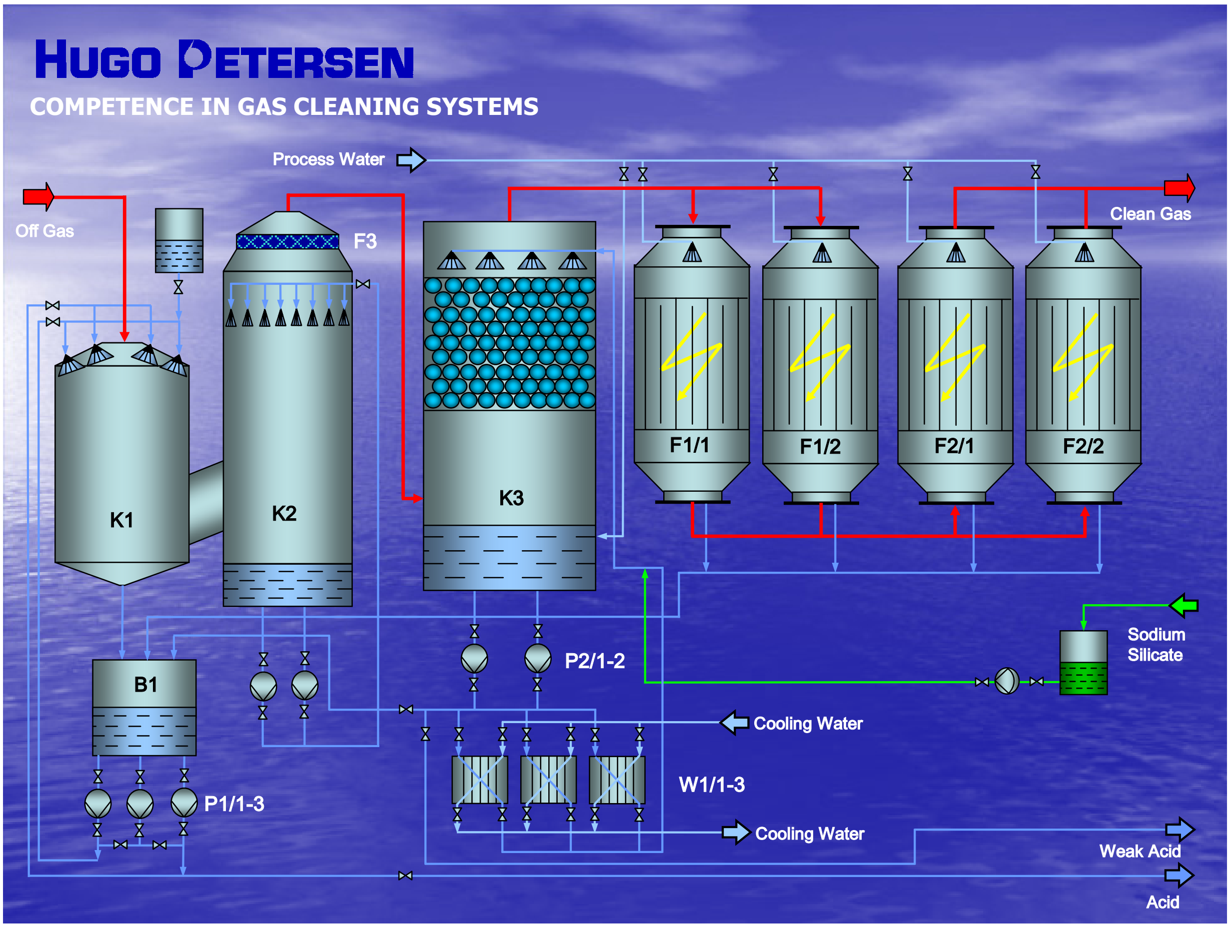
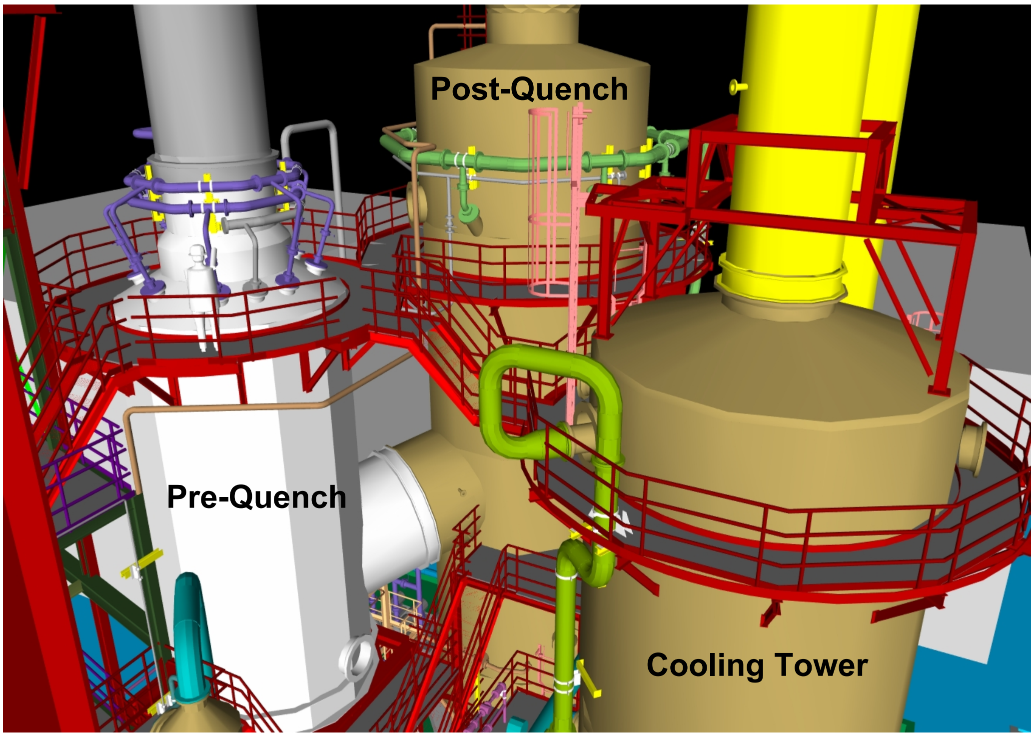


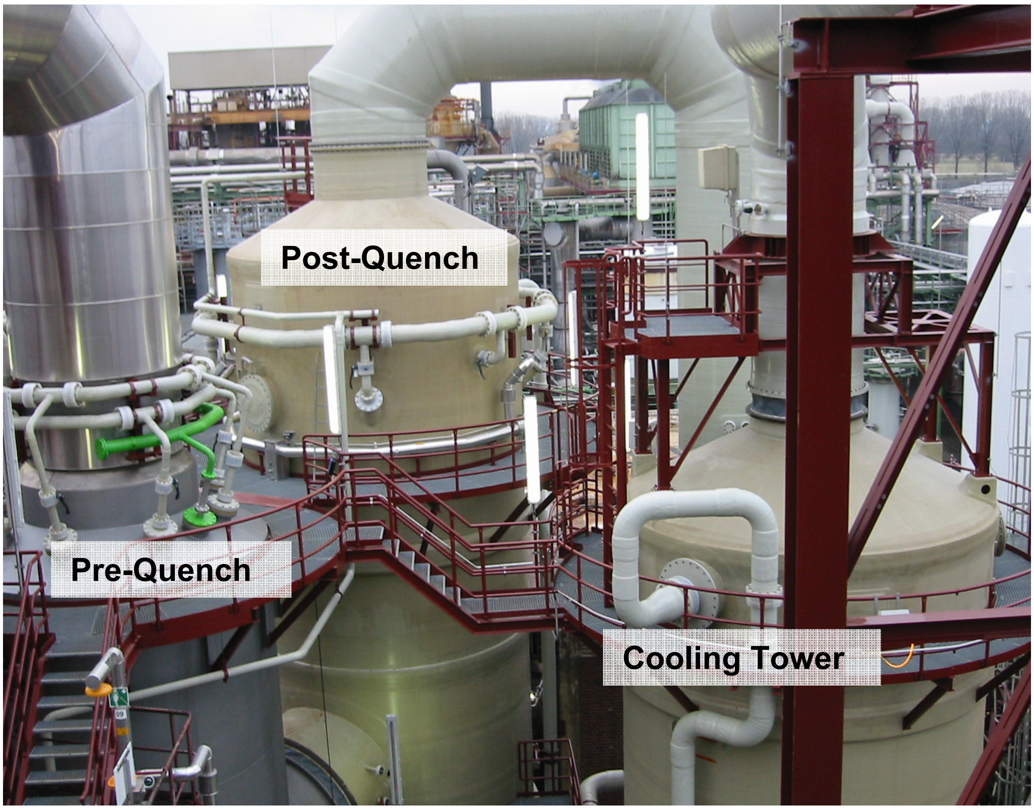
Diagram 2: Conventional Arrangement incl. HF-Removal and separated Quench Tower Circulation

The separation of the liquid circuits of the quench towers allows running the two quench systems with different concentrations of sulphuric acid to increase the concentration of the discharged acid by keeping the outlet temperature of the post-quench tower at low level and to avoid a carry over of concentrated sulphuric acid to the cooling tower.
By adding sodium silicate to the circulation system of the cooling tower fluorides in the off gas can be nearly completely removed.

The main benefits of the HUGO PETERSEN Gas Cleaning Design are:

- Safety Operation due to different independent liquid circuits
- High Availability
- Minimized Control and Operating Efforts
- Minimized Process Water Consumptions
- High Removal Efficiencies
- Space Saving Arrangement





Typical Arrangement of a Pre- / Post-Quench incl. Cooling Tower

High Dust Arrangement

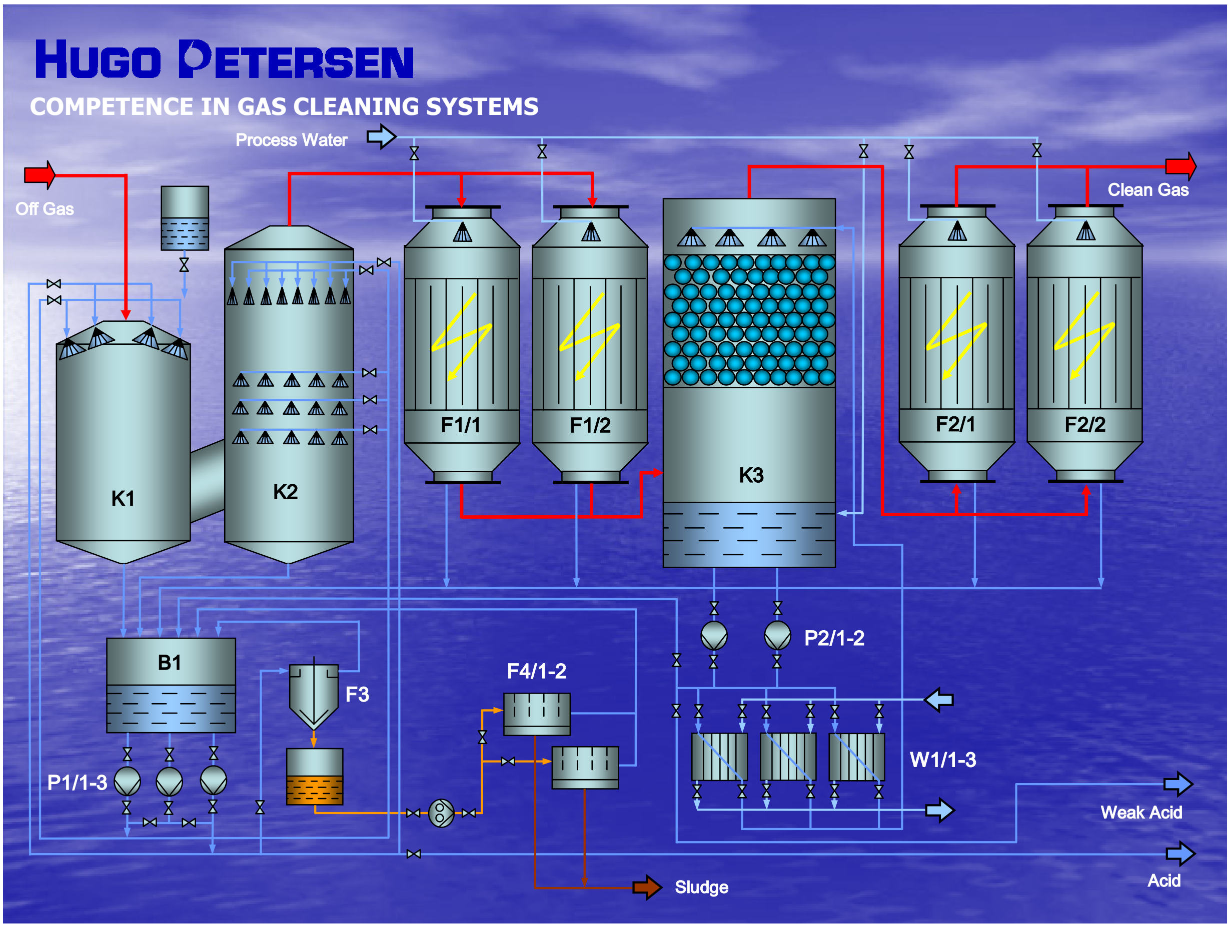


Diagram 3: High Dust Arrangement incl. PPS-System

The post quench-tower is designed as a PETERSEN-Spray Scrubber (PSS) with totally four scrubbing stages, working with high pressure to remove main parts of dust, mist and arsenic components.

The PSS is designed for maximum flow to achieve an efficiency rate of app. 95 % to due big sized particles.

In case of lower gas flow rates, the removal efficiency will increase due to the increasing of the liquid / gas relation.

A further modification is the arrangement of the first wet electrostatic precipitation system F1/1-2 upstream the cooling tower K3 to remove remaining solid contents as it is required to produce a clean weak acid.

The circulation liquids of the quench towers and the flushing liquids of the WESPs are continuously discharged via a sludge precipitator F3 and a redundant filter press system F4/1-2 to keep a constant solid content in the liquids.
The removed sludge can be disposed in the upstream process.

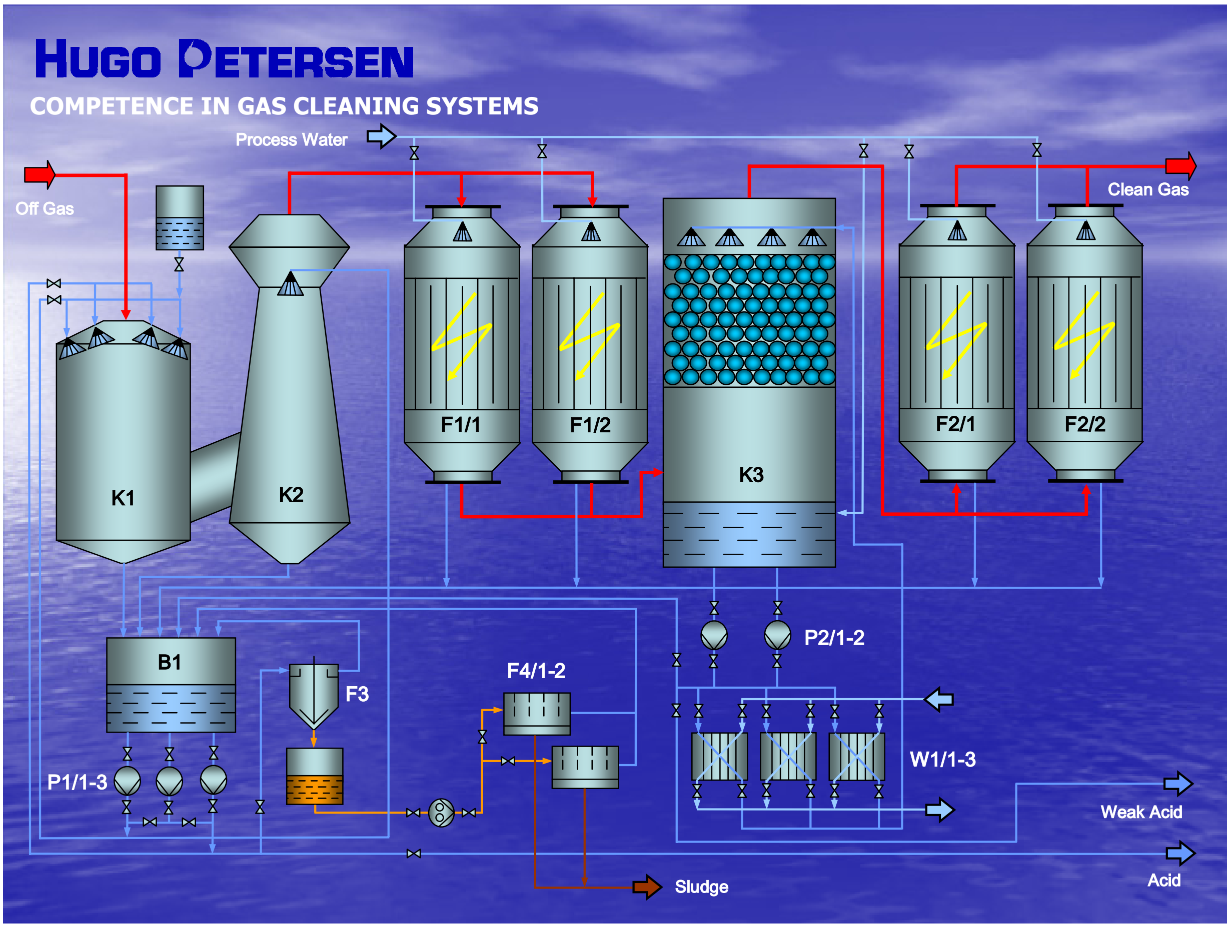


Diagram 4: High Dust Arrangement incl. Jet Scrubber Unit

This arrangement should be preferred in case of low or medium gas flow rates.
The main benefit of both installations is the low pressure loss as the removal energy is brought in by the liquid.
A further benefit is that there is no need for regulation in case of unsteady gas flow rates.

Mercury / Heavy Metal Removal Systems

In general the remaining mercury content of the feed occurs partially in vapour form and, depending on the operation temperature of the cooling units, partially as particulates.
The particulates are nearly totally separated in the wet electrostatic precipitators, the mercury vapour appear as a contaminant in the product sulphuric acid as it is absorbed by strong acid in the downstream drying and absorption units due to the following reactions:

1. Reaction between dissolved mercury in the acid and elementary mercury in the roaster gas

$$HgSO_4 + Hg^0 \rightarrow Hg_2SO_4$$

2. Oxidization of the formed mercurous sulphate by strong acid and oxygen in the gas to mercuric sulphate

$$Hg_2SO_4 + H_2SO_4 + \tfrac{1}{2} O_2 \rightarrow 2HgSO_4 + H_2O$$

Calomel Process

The Calomel Process is based on the oxidation of mercury vapour by mercury chloride to form microbus chloride (calomel) due to the main chemical reactions:

Packed Bed Tower: $Hg^0 + HgCl_2 \rightarrow Hg_2Cl_2$ (calomel)
Regeneration: $Hg_2Cl_2 + Cl_2 \rightarrow 2\ HgCl_2$

The mercury containing cleaned gas downstream the final wet electrostatic precipitation units passes through a packed bed tower K4 where a solution of mercury chloride is circulated via pumps.

A double stage mist eliminator at the top of the tower prevents the carry over of scrubbing solution.

During the reaction between the gas and scrubber solution insoluble Hg chloride (calomel) is precipitated. A part of the calomel containing solution is pumped to the Settler F1.

There the product (calomel) is isolated from the system by decantation as a heavy sludge. A portion of the calomel is then separated from the process.

The remaining calomel is re-oxidized in the chlorinator vessel B1 with the oxidant chlorine (Cl_2) dosed by an injection mixer R1 and via circulation pumps to Hg chloride ($HgCl_2$).
A strong solution of Hg chloride (HgCl2) is prepared in this manner and stored separately in the strong solution vessel B2 via suction filter F2.

The solution is fed into the circulation system via diaphragm dosing pumps at a rate that corresponds to the consumption according to the calomel process reaction.

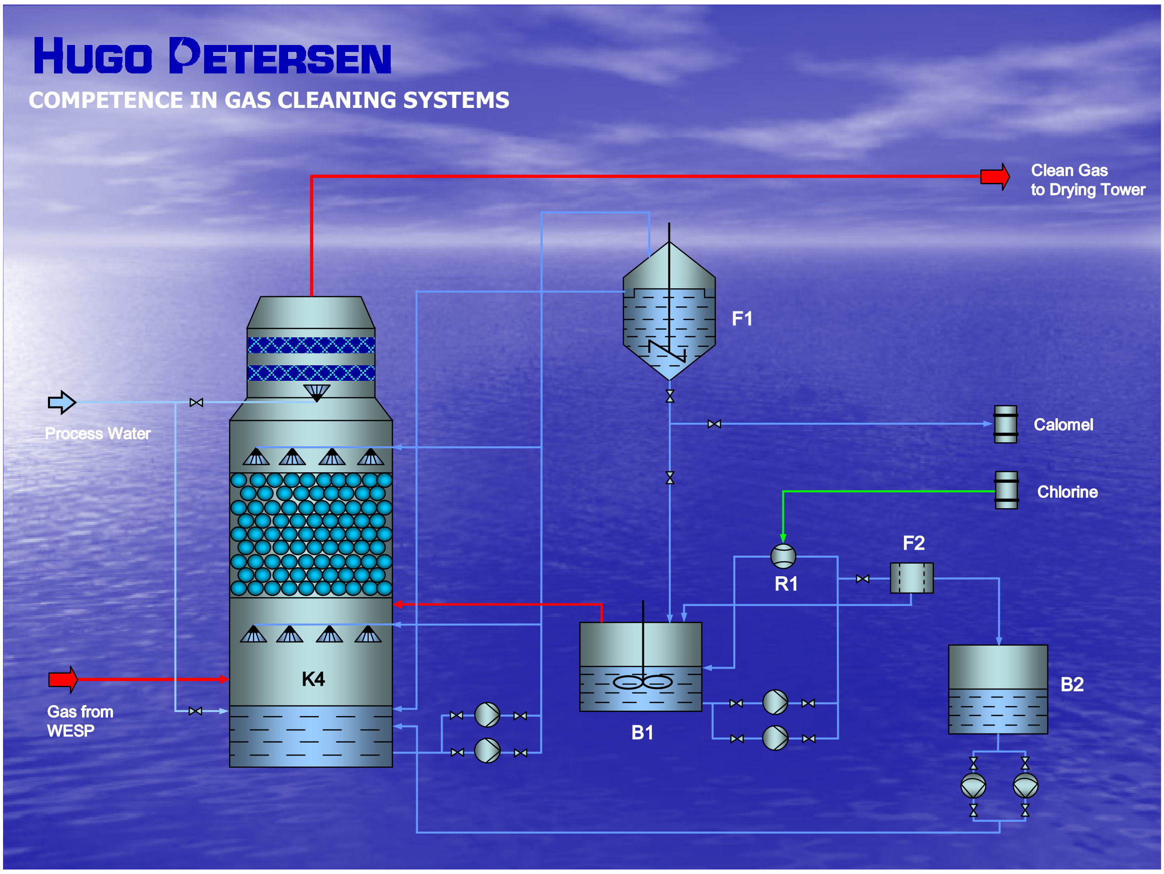


Diagram 5: Typical Arrangement of the Calomel Process

Main Benefits:

- Most popular Method for Removing Mercury
- High Efficiency (Sulphuric Acid with less than 0.5 ppm Mercury can be produced from a gas containing 150 ppm mercury)

Thiosulphate Process

The absorption efficiency of mercury depends on the acid strength and acid temperature. The lower the acid temperature and the higher the acid concentration, the higher is the absorption efficiency.

To avoid an accumulation of mercury in the product acid it is essential to absorb the mercury vapour in a two stages drying tower unit K1 / K2 running with different acid concentrations whereas the acid concentration in the second drying tower should be higher than the acid concentration of the downstream absorption units.

The mercury containing acid of the drying towers has to be cleaned before discharging into the absorption circuits.

Therefore the acid streams are gathered and treated in reaction units with Sodium-Thiosulphate ($Na_2S_2O_3$ x 5 H_2O).

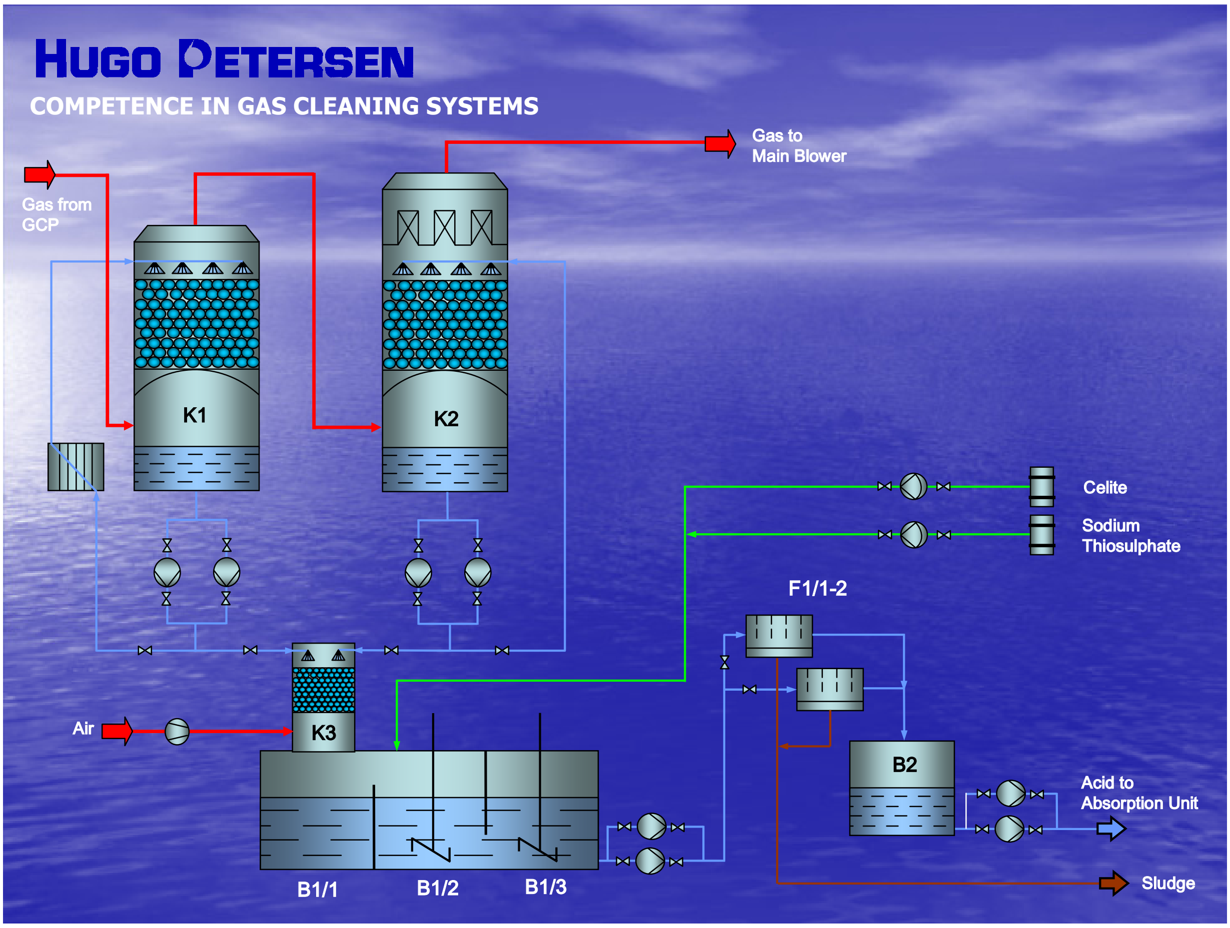


Diagram 6: Thiosulphate Acid Purification Process

The total amount of acid of both drying towers is stripped with air in the stripping tower K3 to remove the dissolved sulphur dioxide before being sent to the sampling vessel B1/1.

Afterwards the stripped acid is discharged to the reaction tank B1/2 in which a solution of 40 % sodium thiosulphate and celite as a filter aid medium are added by stirring.
Sulphur is formed according to the reaction:

$$H_2SO_4 + Na_2S_2O_3 \rightarrow S + SO_2 + Na_2SO_4 + H_2O$$

The sulphur reacts with the mercury in the acid to form mercuric sulphide, which is precipitated.

The temperature in this stage is nearly 50 °C and the acid concentration is about 80 weight-percent.

The treated acid overflows to a maturing tank B1/3 also equipped with a stirrer in which the reaction is completed.

As some sulphur dioxide and even some hydrogen sulphide are formed in the purification process, the tanks have to be ventilated.

From the maturing tank the acid is pumped via the acid pumps to the filter press F1/1-2 where the precipitates are removed.

The deposit collected in the filter press contains about 40 % solids and 60 % acid. The deposit could be re-circulated to the pyro-metall-unit.

The cleaned clear acid is finally discharged into a regenerated acid tank B2 and can be discharged to the absorption units.

Activated Lignite Coke Adsorber

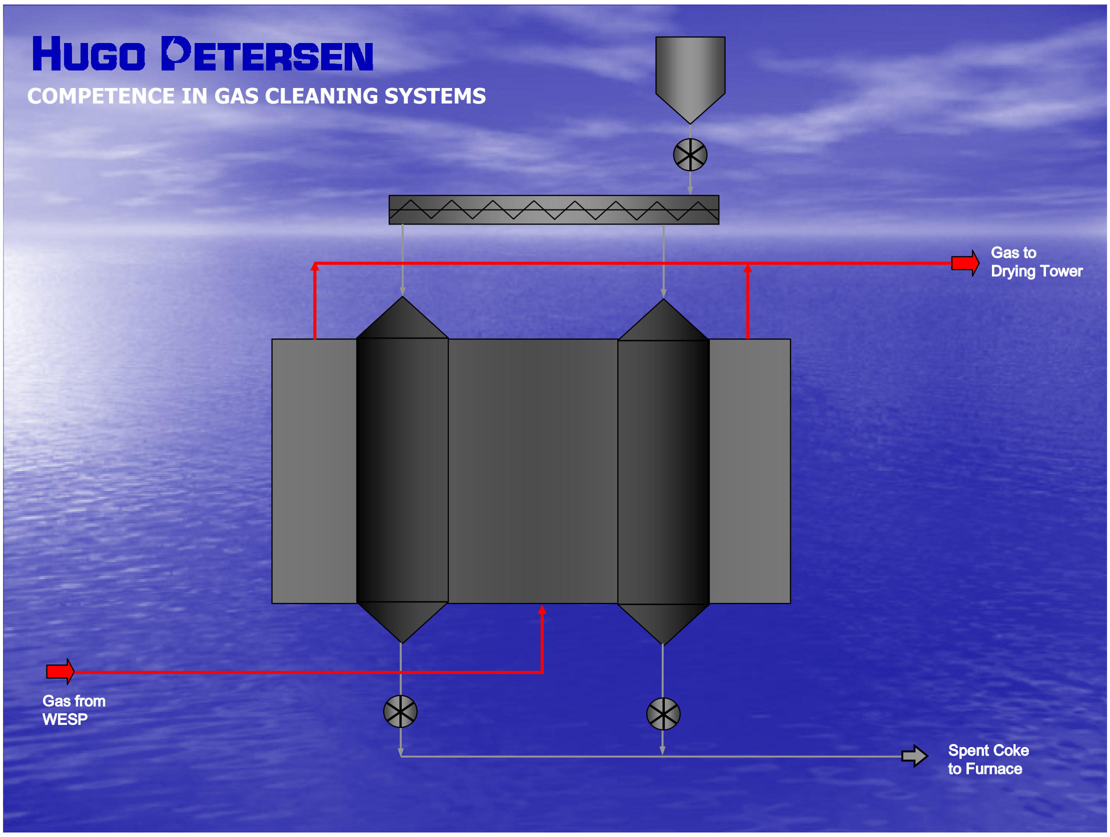


Diagram 7: Activated Coke Filter

An adsorber working with activated lignite coke or hearth furnace coke located downstream the final wet electrostatic precipitation system is able to reduce emissions of Hg^0 and Hg^{2+} to the required values in wet operation.

Furthermore the remaining contents of As, Cu, Fe, Pb, Zn, Sb and Cd, as well as organic solvents or various hydrocarbons are reduced.

Due to its high adsorption capacity a minimum of adsorbent is used.
The spent adsorbent can be disposed in the upstream furnace.
Depending on the amount of contaminants in the gas the fixed bed has to be moved discontinuously.

Advantages of an activated lignite coke adsorber in comparison to an activated carbon adsorber:

Operating of the activated HOK adsorber below the dew-point of the wet SO_2 gas means no developing of so called "hot spots".

- No fire- and explosion-detections and -protections are required
- No minimum-flow gas necessary
- No inertizing of the adsorbent necessary
- No cost- and energy-intense reheating necessary of the wet SO_2 gas above the dew-point
- No Residues for Disposal
- Low operating-costs

Tail Gas Scrubbing

Tail gas scrubbing as a means of polishing off-gases from chemical processes, but specially sulphuric acid plants, is a well-known process step, which HUGO PETERSEN has developed to a grade of quality and level, that economically and environmentally the plants will be ready for the future approaches of environmental protection agency acts.

Hydrogen Peroxide Scrubber (SUPER^{OX})

The SUPER^{OX}-Process is a treatment technology based on sulphuric acid mixed with H_2O_2, which guarantees the absorption of SO_2 and oxidation to sulphuric acid as follows:

$$H_2O_2 + SO_2 + H_2O \rightarrow H_2SO_4{*}H_2O$$

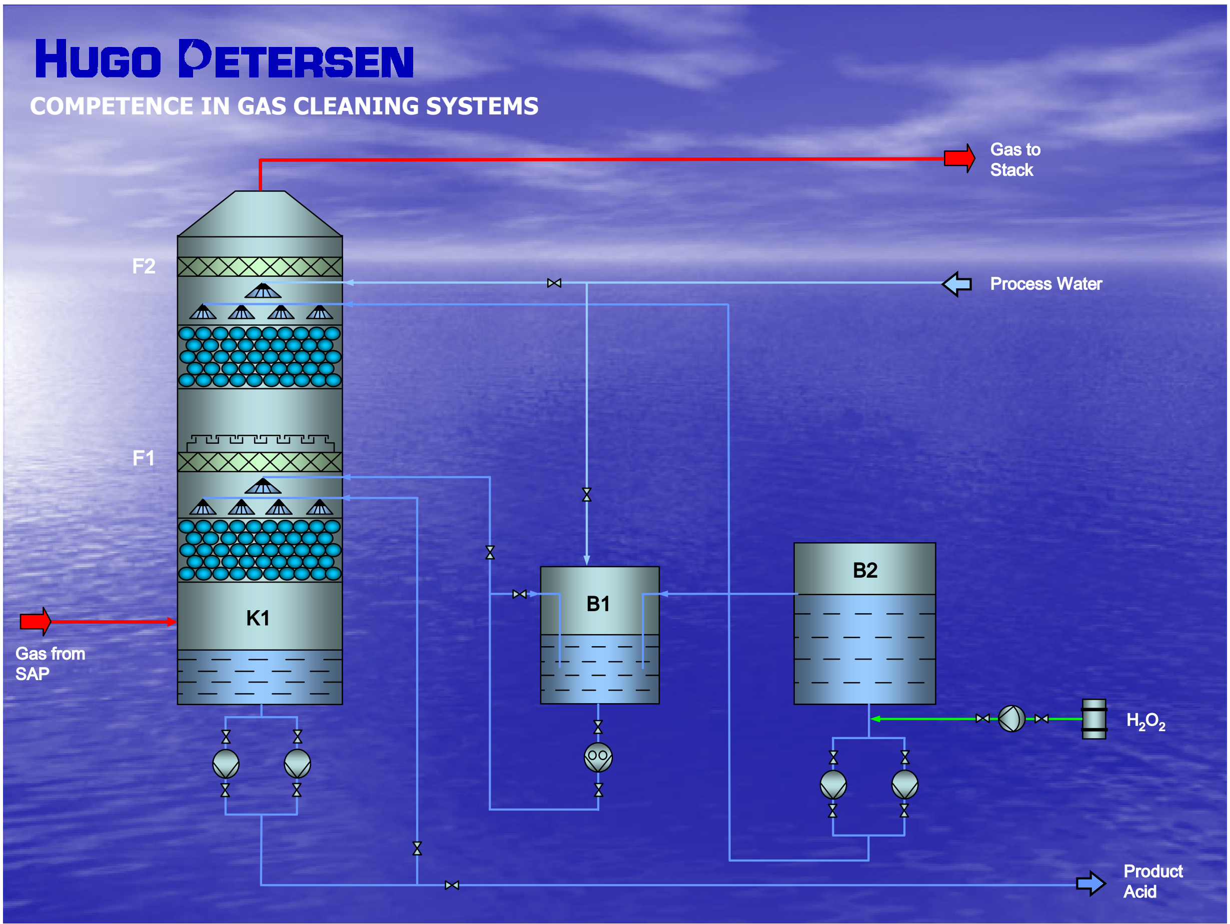


Diagram 8: HUGO PETERSEN SUPER^{OX} Plant

The special design guarantees a sulphuric acid concentration of 50-60% by extreme low remaining H_2O_2 in the product stream.

The produced sulphuric acid can be used as dilution medium in the absorption section of the upstream sulphuric acid plants.

To minimize the H_2O_2 content of the discharged sulphuric acid, as well as to reach a high acid strength, each scrubbing tower exists of two stages.

The gas from the upstream plant is entering the scrubbing tower K1 in counter current flow to the liquids at the bottom and passing the first packing stage.

At the first stage the process gas is cooled down to its saturation temperature by circulation of 50 - 60 % sulphuric acid.

The amount of used process water depends on the SO_2-inlet content of the process gas and on the amount of produced sulphuric acid.

At the first stage the remained H_2O_2 of the upper second stage is reduced by oxidation of sulphuric dioxide as well.

The liquids of the first stage are collected in the scrubbing tower sump, circulated via pumps and distributed above the packing layer via a liquid irrigation system to ensure the distribution of washing acid over the packed bed and to avoid the formation of additional acid mist.

In dependence on the SO_2 content of the process gas an amount of 50 - 60 % sulphuric acid is discharged to the sulphuric acid plant.

Downstream the first stage the process gas is lead and distributed via a droplet separator F1 and an intermediate bottom to the second stage.

In the second stage the main part of sulphuric dioxide is removed by circulation of washing acid with an even higher H_2O_2-content than in the first stage.

Due to the lower acid concentration the gas temperature decreases and an additional amount of water is evaporated as well.

The liquid of the second stage is collected in an extra tank B2, circulated via two pumps and distributed in the same way as in the first stage.

The continuous hydrogen peroxide dosing via a dosing pump is controlled by a SO_2-measurement located downstream the peroxide scrubbers and an external gas-flow-rate signal. The hydrogen peroxide is dosed in the circulation circuit of the second stage at the suction side of the circulation pump to get a better intimate mixing.

The process gas finally enters a wire-mesh droplet separator F2 before it is lead to the stack. Depending on the design of the stack an additional gas-reheating system will be required.

The main benefits of the SUPER^{OX} process are:

- No Waste Products
- High Concentration of Product Acid
- Nearly no remaining Peroxide in the Product Acid
- High Flexibility concerning required Emission Values
- Space Saving Arrangement

Ammonium Scrubber

The ammonium sulphate process is based on the following reactions:

$$2\,NH_3 + SO_2 + H_2O \rightarrow (NH_4)_2SO_3$$

And the oxidation with sulphuric acid:

$$(NH_4)_2SO_3 + H_2SO4 \rightarrow (NH_4)_2SO_4 + SO_2 + H_2O$$

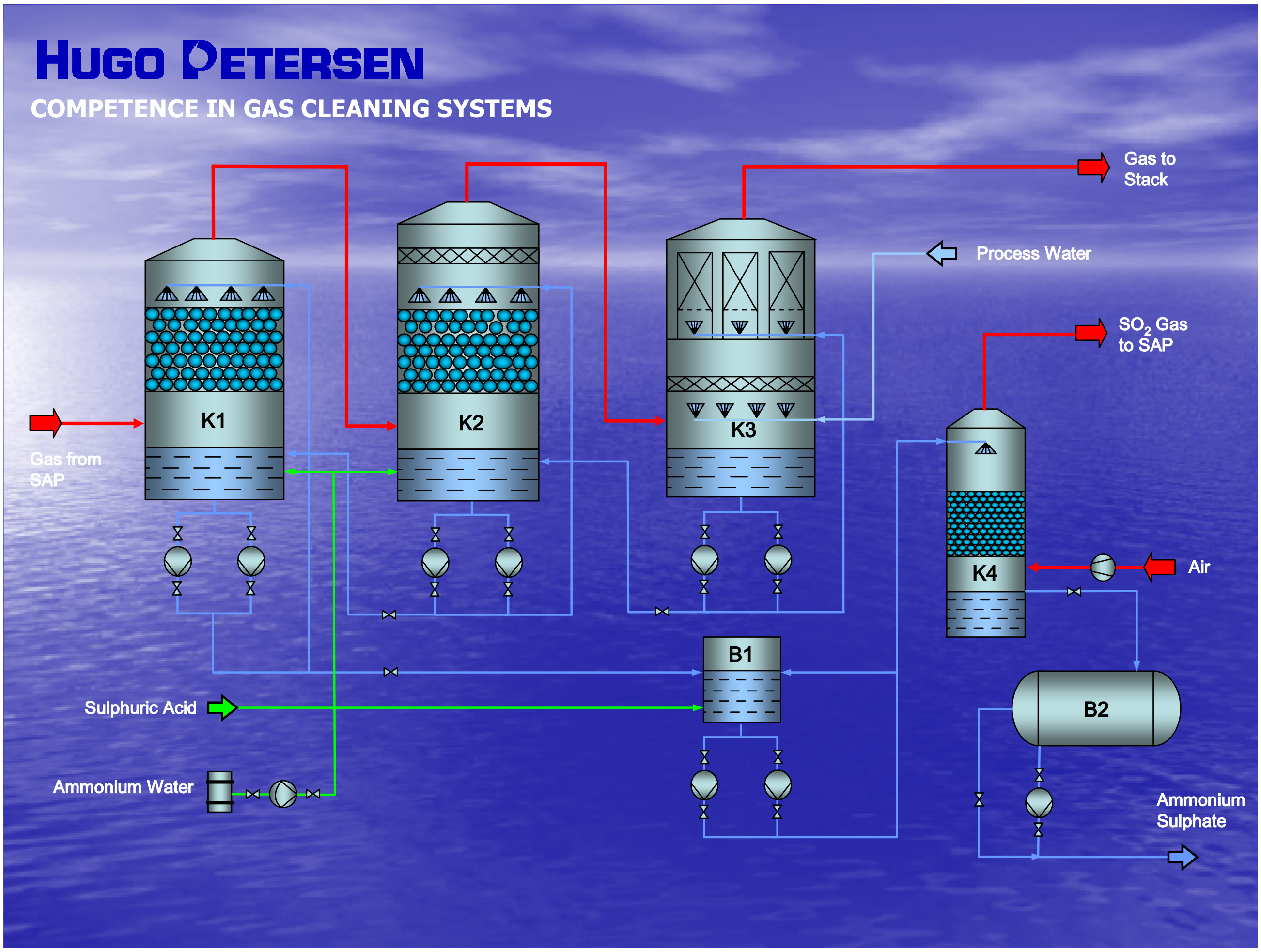


Diagram 9: Ammonium Sulphate Scrubbing Plant

The gas from the upstream plant is entering the scrubbing tower K1 in counter current flow to the liquids at the bottom and passing the packing.

SO_2 is absorbed by adding ammonium water and formation of ammonium sulphite.
The pre-cleaned gas is led to the second tower K2 where the remaining SO_2 is absorbed in the same way.

The continuous ammonium water dosing in both scrubbing towers is controlled via pH-value of the circulation liquids.

The second scrubbing tower is operating at lower concentrations to minimize the ammonium content in the cleaned gas.

Downstream the second scrubbing unit a final tower K3 is installed for elimination of ammonium sulphite mist.
The mist elimination system consists of two stages, a first wire-mesh stage continuously flushed with process water and a second candle filter stage, flushed with circulation liquid.
Alternatively to the final tower K3 a WESP-system can be installed as well.

The ammonium sulphite containing liquids of the towers K2 and K3 are level controlled discharged to the first scrubbing tower K1 where the liquid concentration is increased due to water vaporization.

Depending on the temperature and water content of the incoming gas concentrations more than 40 weight-percent are achievable.

The high concentrated ammonium sulphite liquid is discharged to the reaction vessel B1 where the liquid is oxidized to ammonium sulphate by adding of sulphuric acid of the upstream plant.

In the stripping K4 the due to the reaction formed SO_2 is separated from the liquid with ambient air.

Due to the high vapour pressure of SO_2 above the liquid an outlet concentration of 15 Vol-% of the stripping gas can be reached.
The SO_2 gas is finally led back to the sulphuric acid plant.

Optionally an amount of SO_2 gas can be re-circulated upstream the first scrubbing tower to increase the production of ammonium sulphate, if required.
The produced ammonium sulphate is discharged via overflow from the stripping tower to the storage tank B2.

The main benefits of the ammonium sulphate process are:

- No Waste Products
- Variable Production Rates in case of Recirculation

Let us come to together and develop the optimal solution for you!

The Author

Axel Schulze, Managing Director, HUGO PETERSEN GmbH

More than 25 years professional experience in design management, process design, erection supervision, commissioning of gas cleaning and H_2SO_4-plants in Germany and overseas

Sulphuric Acid Plants

- Cinkarna – Celje, Slovenia
  Start-up commissioning and test run sulphuric acid plant of 500 to/day
- Th. Goldschmidt - Mannheim, Germany
  Start up commissioning of sulphuric acid plant of 200 to/day, utilisation of SO_2 and NO_x containing the Petersen Fattinger process for sulphuric acid and nitric acid included commissioning of pilot plants, start up and test procedures

- Research and development for SO_2 concentration and recovery plants for production of liquid SO_2 and deviates as sulphuric acid ammonia sulphate SO_3 and elemental sulphur
- Sales and presentation of Hugo Petersen's sulphuric acid technology in Europe and overseas
- UST-Kamenogorsk, Kazakhstan,
  Process design management for gas cleaning plant downwards zinc and lead smelter, responsible for preparation and performing of the final guarantee test of a 928 to/day sulphuric acid plant downwards of a copper smelter incl. heavy metal and effluent treatment plant
- ENAMI – Chile
  Process design manager for complete sulphuric acid plant, including heavy metal removal (Hg, Se, As) and effluent treatment plant, process design management for gas cleaning plant (dry and wet cleaning process), for removal of Hg, As, SO_2, HCl, NOx, HF, HBr, downwards of burning process for contaminated earth.
- Cinkarna - Slovenia
  Design manager and project manager for the expansion and modification of 240 to/day sulphuric acid plant,
- Outokumpu - Finland
  Preparation of basic design for the tender of sulphuric acid plant R7
- Outokumpu - Finland
  Engineering Management of gas cleaning plant R6 for sulphuric acid plant downwards a copper smelter

Attachment C

Mercury Control Cost Calculations

Attachment C, Revised 2/24/2012
PolyMet Mercury Control Evaluation for NorthMet Project
Activated Carbon Control Cost Using Barrick Goldstrike 2007 Cost Estimate

					Barrick Goldstrike	NorthMet
Capital Cost [1]					**$10,133,000**	**$8,320,000**
Direct Operating Costs	**$/hr**	**Hr/Shift**	**Shift/day**	**Day/yr**	**Annual Cost**	**Annual Cost**
Operating Labor + 15% for Supervision [2]	$12.00	0.5	2	360	$4,968	$4,968
Maintenace Labor [2]	$13.20	0.5	2	360	$4,752	$4,752
Maintenance Materials [7]	100% of Maintenance Labor				$4,752	$4,752
Utilities [3, 4]	Ref Elec ¢/kW	9.0	MN Elect ¢/kW	6.5	$620,142	$322,479
Total Direct Opearting Costs					**$634,614**	**$336,951**
Indirect Operating Costs [5]						
Overhead	60%	of labor and maint materials			$8,683	$8,683
Administrative charges	2%	of Total Capital Investment			$202,660	$166,400
Property tax	1%	of Total Capital Investment			$101,330	$83,200
Insurance	1%	of Total Capital Investment			$101,330	$83,200
Captal Recovery [6] annual int rate/equipment life	7%	20	yrs / CRF ->	0.0944		$785,349
Total Indirect Operating Costs					**$414,003**	**$1,126,832**
Annual Operating and Maintenance Cost					**$1,049,000**	**$1,464,000**
Estimated Barrick Goldstrike Autoclave Mercury Emissions		28.1	lb Hg/yr			
NorthMet Autoclave Annual Mercury Emissions		4.1	lb Hg/yr			
Annual Mercury Reduction at 90% Control lb/yr						**3.7**
Mercury Control Cost $/lb Hg removed						**$397,000**
Barrick Goldstrike Design Flow	51,760	acfm				
NorhtMet Design Flow	37,268	acfm				
Flow Ratio	0.720					

NorthMet Cost Estimate Assumptions

1. Use Barrick capital cost times ratio of flows in acfm to 0.6 power to account for economies of scale

2. Use Barrick labor and maintence materials costs - both units similar sized so labor expenses should be the same.

3. Use Barrick power cost times ratio of flow rates in acfm

4. Powercost adjusted by 2011 electricity prices industrial in MN (6.5 ¢/kW) , EIA 2011 year to date vs 9¢/kW used in Barrack Cost Analysis

5. Use EPA control cost manual factors for overhead, adminstration, property tax aind insurance

6. Captial recivery cost not included in Barrick Goldstrike analysis; added to NorthMet cost analysis per MPCA request

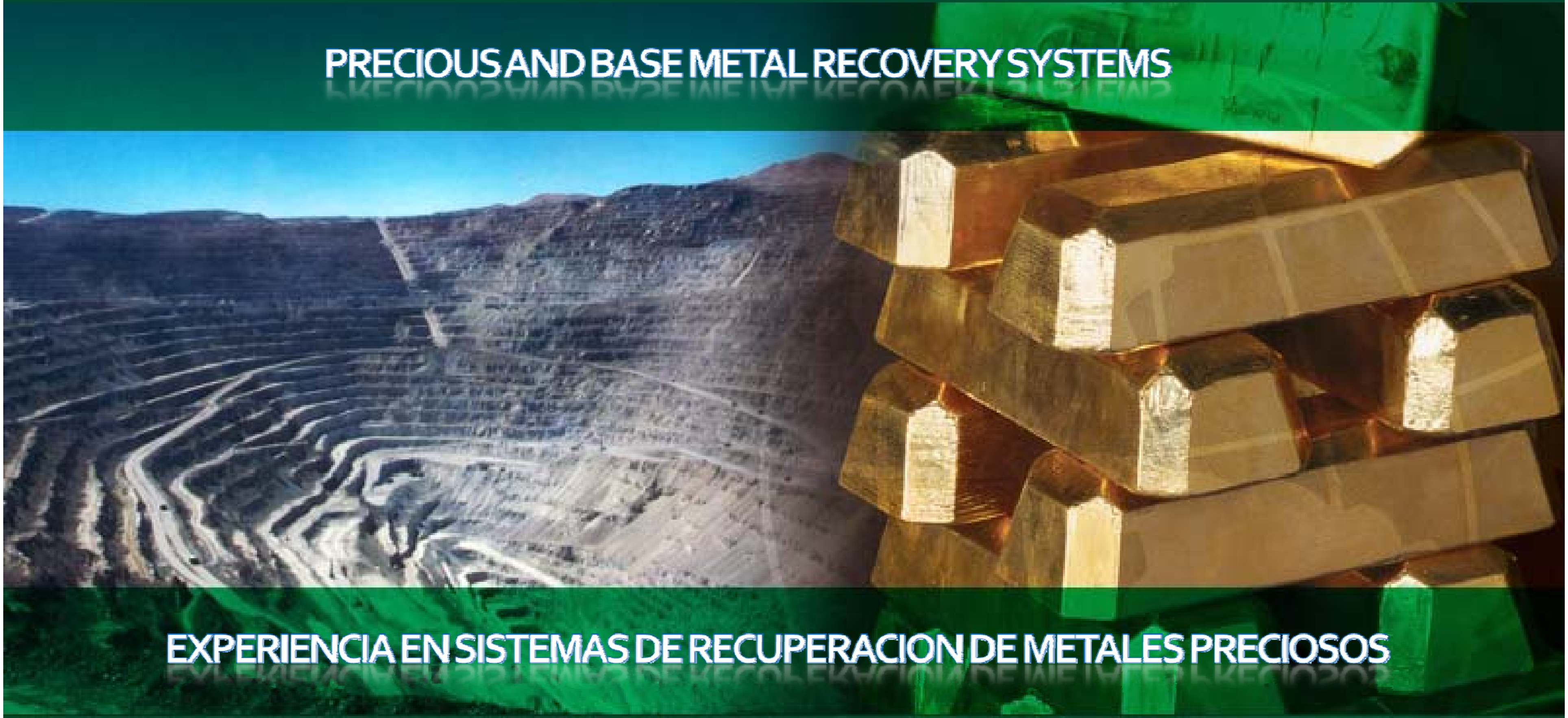
7. Activated carbon costs are not significant due to the low mercury emission rates. $124/yr (37 lbs) for Polymet and $941 lb/yr Barrick (280 lbs) assuming 10 lb ACI/lb Hg and $3.35/lb sulfur impregnated activated carbon. These costs fall well within the standard maitenance material cost allotment. Therefore, the current calculations do not need to be adjusted for differences in activated carbon consumption.

Attachment D

Scotia International of Nevada Mercury Control Presentation

S.I.O.N.

Scotia International of Nevada, Inc.



PRECIOUS AND BASE METAL RECOVERY SYSTEMS

EXPERIENCIA EN SISTEMAS DE RECUPERACION DE METALES PRECIOSOS

S.I.O.N.

Scotia International of Nevada, Inc.

DESIGN, MANUFACTURE, INSTALLATION AND START-UP

CARBON COLUMN SYSTEMS

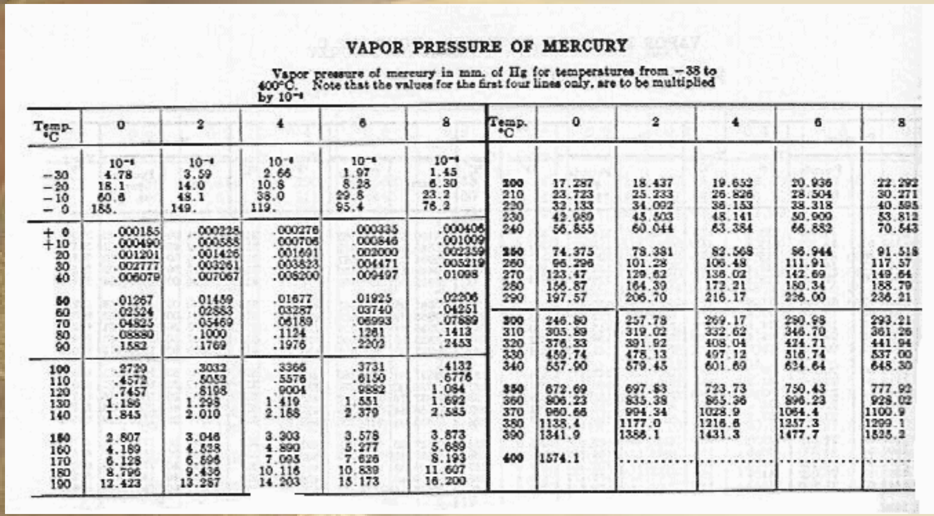
WWW.SCOTIACORP.COM

MERCURY REMOVAL FROM GAS STREAMS

MERCURY REMOVAL OVERVIEW

- Mercury is cyanide soluble and therefore is removed from the ore and follows through the process solution.
- Mercury is adsorbed onto the activated carbon in the same manner as the gold. Gold is adsorbed more strongly than mercury and therefore displaces some of the mercury on the loaded carbon.
- Some of the mercury is removed by stripping of the carbon and goes to the electrowinning circuit.
- The remaining mercury is left on the stripped carbon and is removed from the carbon during regeneration.

MERCURY CHEMISTRY



VAPOR PRESSURE OF MERCURY

Vapor pressure of mercury in mm. of Hg for temperatures from −38 to 400°C. Note that the values for the first four lines only, are to be multiplied by 10^{-6}

Temp. °C	0	2	4	6	8
	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}
−30	4.78	3.59	2.66	1.97	1.45
−20	18.1	14.0	10.8	8.28	6.30
−10	60.8	48.1	38.0	29.8	23.2
− 0	185.	149.	119.	95.4	76.2
+ 0	.000185	.000228	.000276	.000335	.000406
+10	.000490	.000588	.000706	.000846	.001009
20	.001201	.001426	.001691	.002000	.002359
30	.002777	.003261	.003823	.004471	.005219
40	.006079	.007067	.008200	.009497	.01098
50	.01267	.01459	.01677	.01925	.02206
60	.02524	.02883	.03287	.03740	.04251
70	.04825	.05469	.06189	.06993	.07889
80	.08880	.1000	.1124	.1261	.1413
90	.1582	.1769	.1976	.2202	.2453
100	.2729	.3032	.3366	.3731	.4132
110	.4572	.5052	.5576	.6150	.6776
120	.7457	.8198	.9004	.9882	1.084
130	1.186	1.298	1.419	1.551	1.692
140	1.845	2.010	2.188	2.379	2.585
150	2.807	3.046	3.303	3.578	3.873
160	4.189	4.528	4.890	5.277	5.689
170	6.128	6.596	7.095	7.626	8.193
180	8.796	9.436	10.116	10.839	11.607
190	12.423	13.287	14.203	15.173	16.200
200	17.287	18.437	19.652	20.936	22.292
210	23.723	25.233	26.826	28.504	30.271
220	32.133	34.092	36.153	38.318	40.595
230	42.989	45.503	48.141	50.909	53.812
240	56.855	60.044	63.384	66.882	70.543
250	74.375	78.381	82.568	86.944	91.518
260	96.296	101.28	106.48	111.91	117.57
270	123.47	129.62	136.02	142.69	149.64
280	156.87	164.39	172.21	180.34	188.79
290	197.57	206.70	216.17	226.00	236.21
300	246.80	257.78	269.17	280.98	293.21
310	305.89	319.02	332.62	346.70	361.26
320	376.33	391.92	408.04	424.71	441.94
330	459.74	478.13	497.12	516.74	537.00
340	557.90	579.45	601.69	624.64	648.30
350	672.69	697.83	723.73	750.43	777.92
360	806.23	835.38	865.36	896.23	928.02
370	960.66	994.34	1028.9	1064.4	1100.9
380	1138.4	1177.0	1216.8	1257.3	1299.1
390	1341.9	1386.1	1431.3	1477.7	1525.2
400	1574.1	....	....	....	....

- Mercury is the only metallic element that is a liquid (m.p. -38°C) at room temperature. Gallium melts at 30°C.
- Mercury has a boiling point of 357°C (675°F).
- Mercury's vapor pressure is high for a metal but low compared to water. Mercury at 20°C is 0.0012 mmHg, where water has the same vapor pressure at -79°C. At 100°C, mercury has a vapor pressure of 0.2729 mmHg or the same as water at -68°C.

MERCURY CHEMISTRY

- The mercury in the gas stream can be elemental **(gaseous)** or particulate bound **(adsorbed onto particles).**
- Mercury's molecular weight is 200.59 g/mole and its density is 13.53 grams.
- Many metals are soluble in mercury and form amalgams (such as silver and mercury fillings for teeth).
- Mercury Sulfide (Hg_2S) is highly insoluble with a K_{sp} of 10^{-54} **(mercurous sulfide)** but can oxidize to a slightly higher solubility compound metacinnabar (HgS).
- The chlorides of mercury, Calomel, **(mercurous)** Hg_2Cl_2 and **(mercuric)** $HgCl_2$ are also used for mercury recovery.

SULFUR AND MERCURY

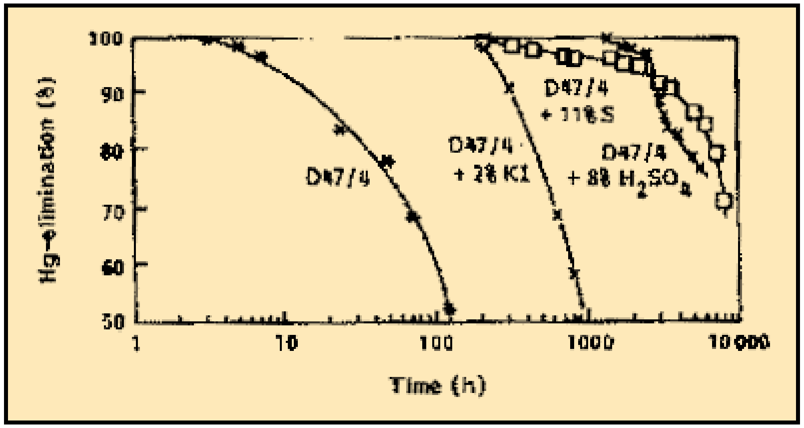
- The basis for removal of mercury using sulfur is the reaction:

$$2\,Hg^{o} + S^{o} \longrightarrow Hg_2S$$
$$Hg_2S + S^{o} \longrightarrow 2HgS$$

The mercury is transformed into a solid material with volatility reducing the vaporization hazards associated with mercury.

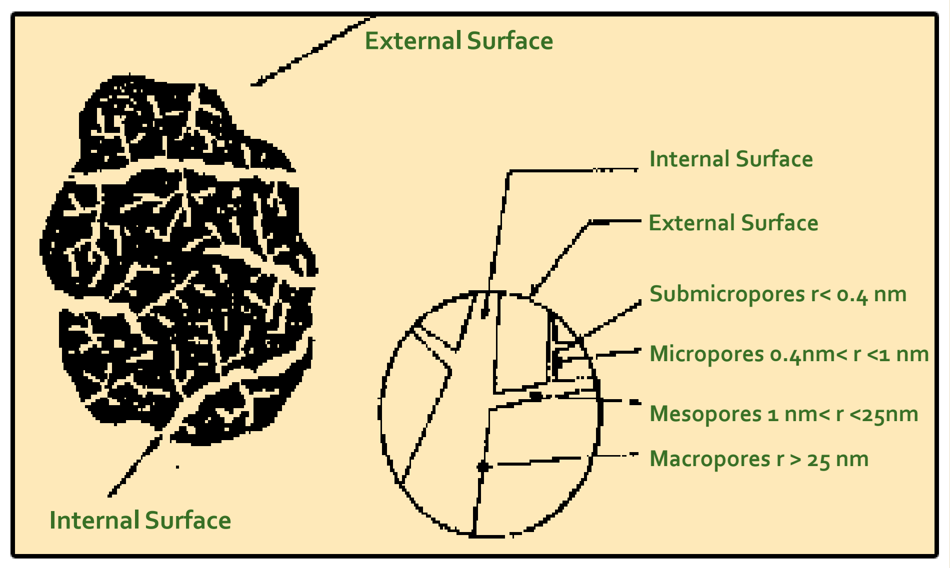
ACTIVATED CARBON AND IMPREGNATED CARBON

- Activated Carbon will adsorb gaseous mercury onto its surface.



Mercury elimination rates of non-impregnated and impregnated activated carbon

ACTIVATED CARBON AND IMPREGNATED CARBON

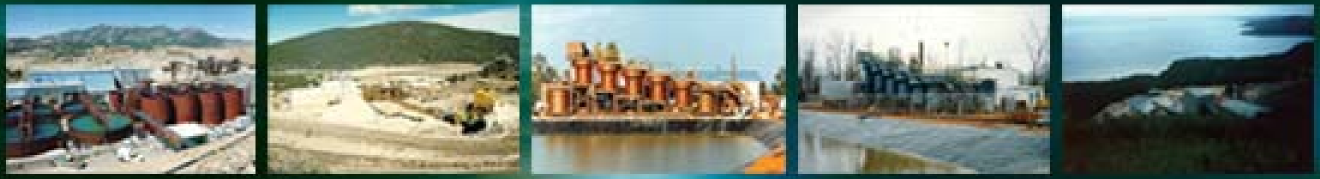


- But other impregnates, such as, iodide, sulfuric acid or sulfur adsorb significantly more. The increased amount adsorbed is due to the high concentration of adsorbate on the activated carbon, KI (2%), H_2SO_4 (8%) and sulfur (11 to 15%). The sulfur reaction rate is higher, so it is commonly used for mercury treatment of gas streams.

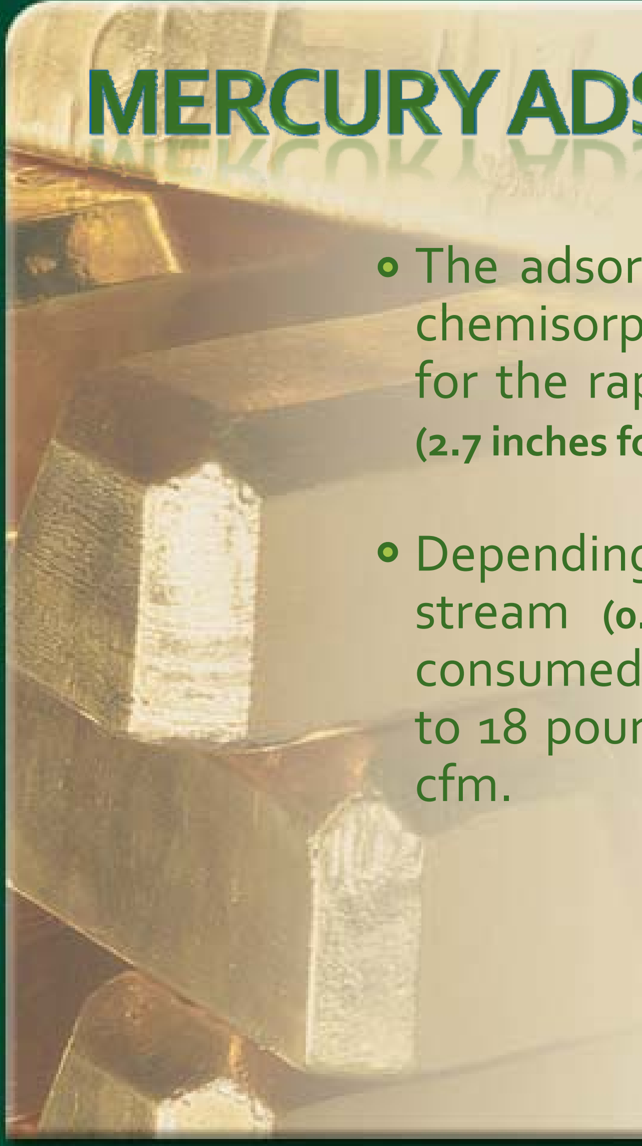
ACTIVATED CARBON

- The extruded carbon used in making the 4mm pellets for impregnated carbon has a surface area between 1000 to 1100 m^2/g.

- The high internal surface area is why the carbon has a density of ~0.52 g/cc. This high surface area allows for the high adsorption of the reactants.

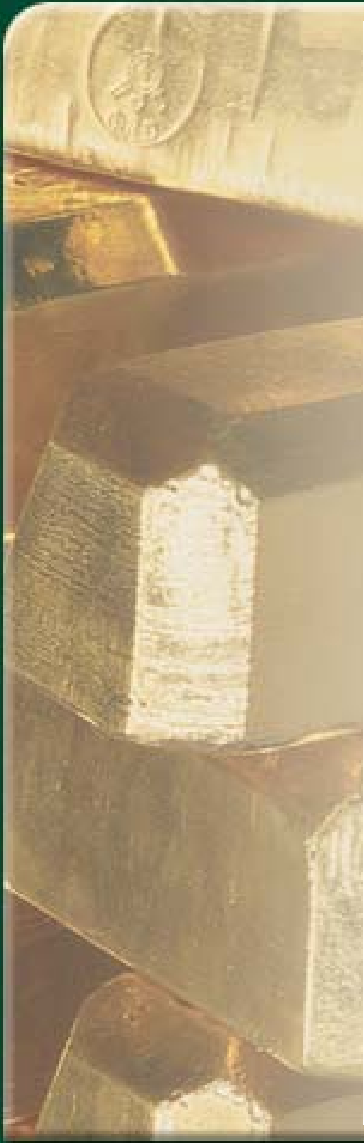


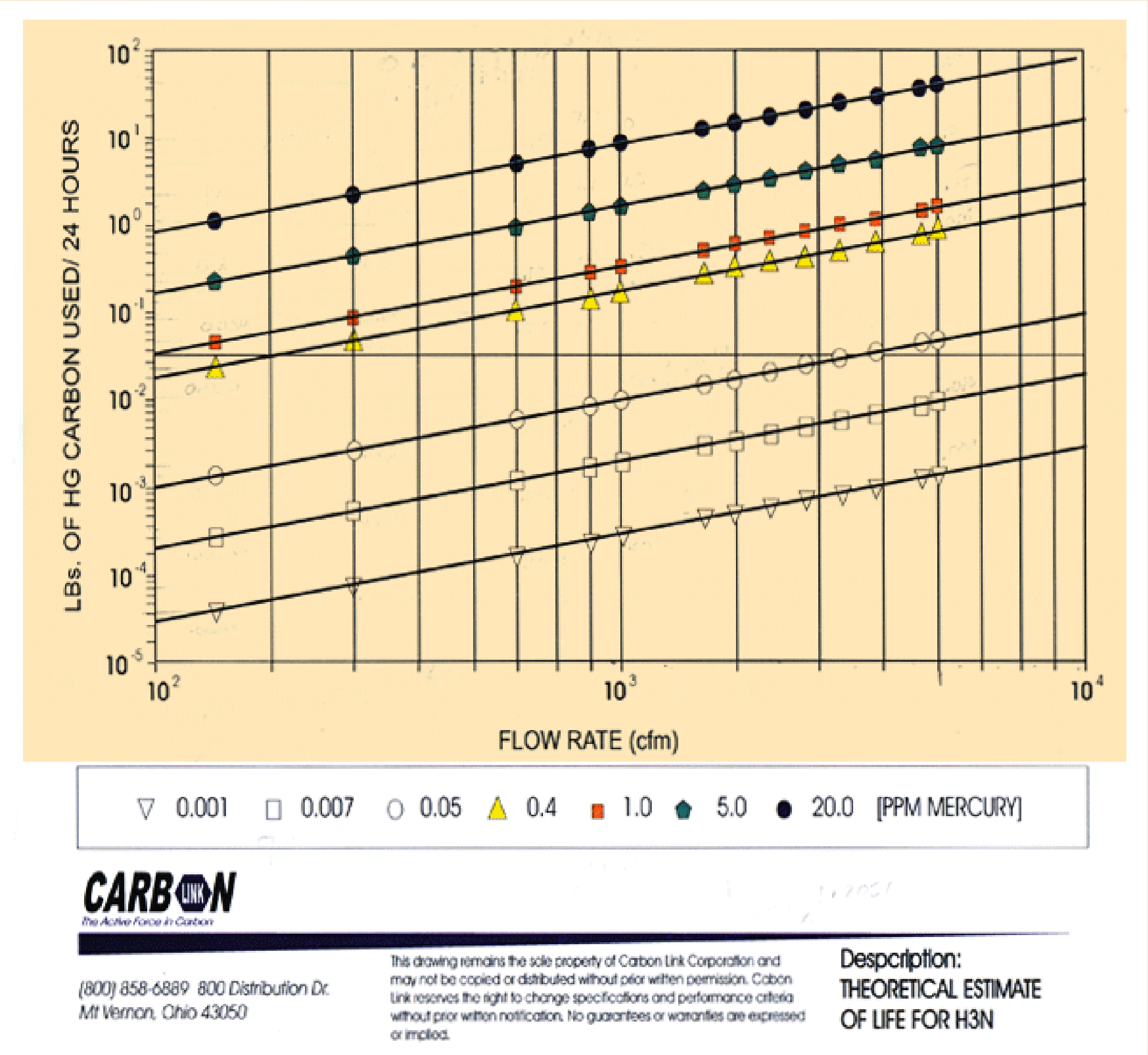
MERCURY ADSORPTION



- The adsorption of mercury onto the sulfur surface is a chemisorption process. The chemisorption is the reason for the rapid reaction rates and the low transfer length **(2.7 inches for 98% adsorption)** at linear flow rates of 75 fpm.

- Depending on the mercury concentration in the gas stream **(0.001 ppm to 20 ppm)**, the amount of carbon consumed **(becoming completely loaded)** ranges from 0.0007 to 18 pounds per 24 hours period at a flow rate of 3000 cfm.





CARBON LINK
The Active Force in Carbon

(800) 858-6889 800 Distribution Dr.
Mt Vernon, Ohio 43050

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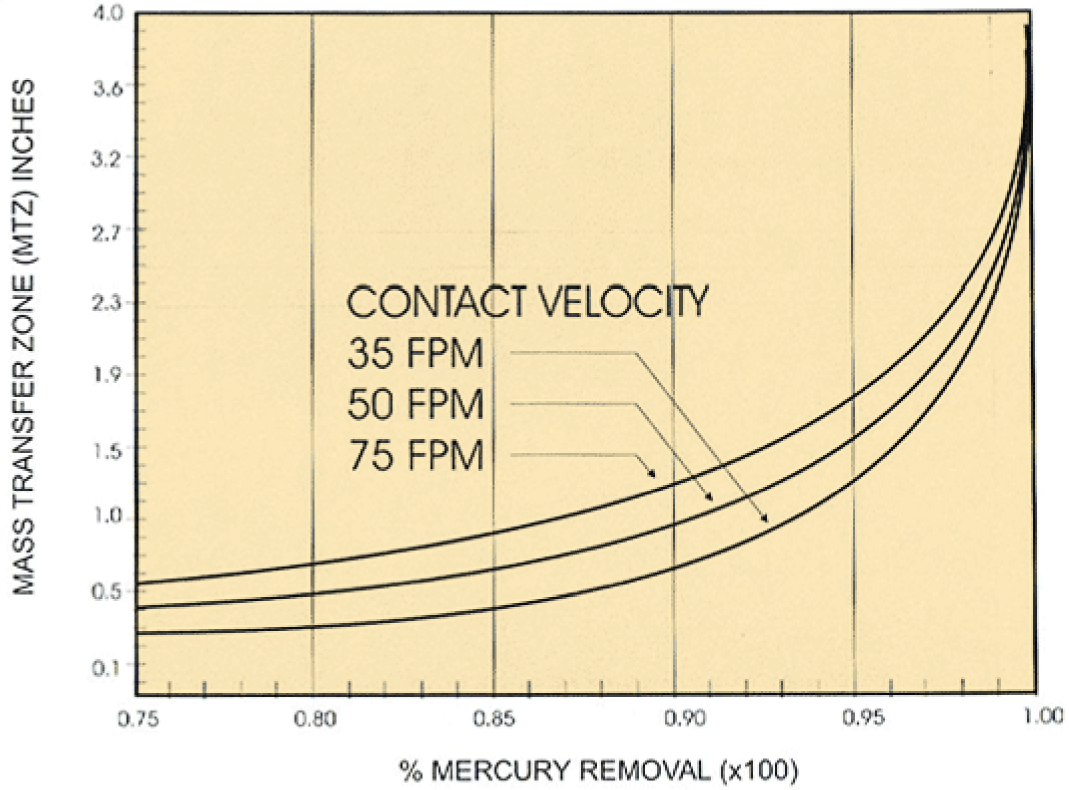
Despcription:
THEORETICAL ESTIMATE
OF LIFE FOR H3N



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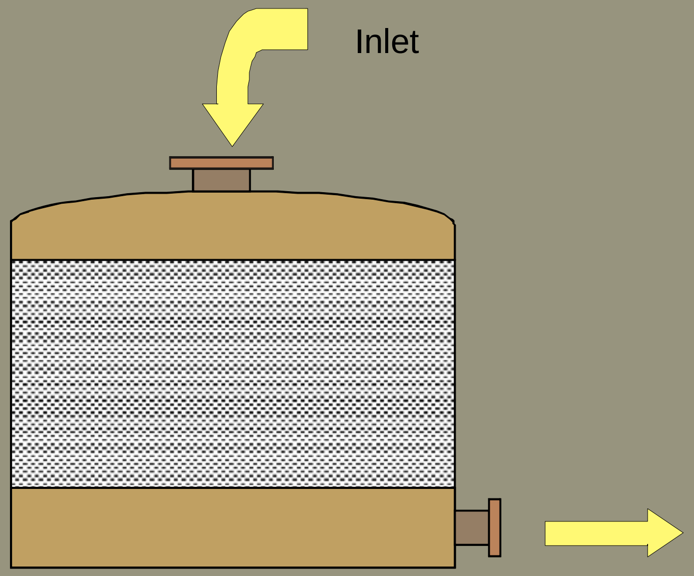
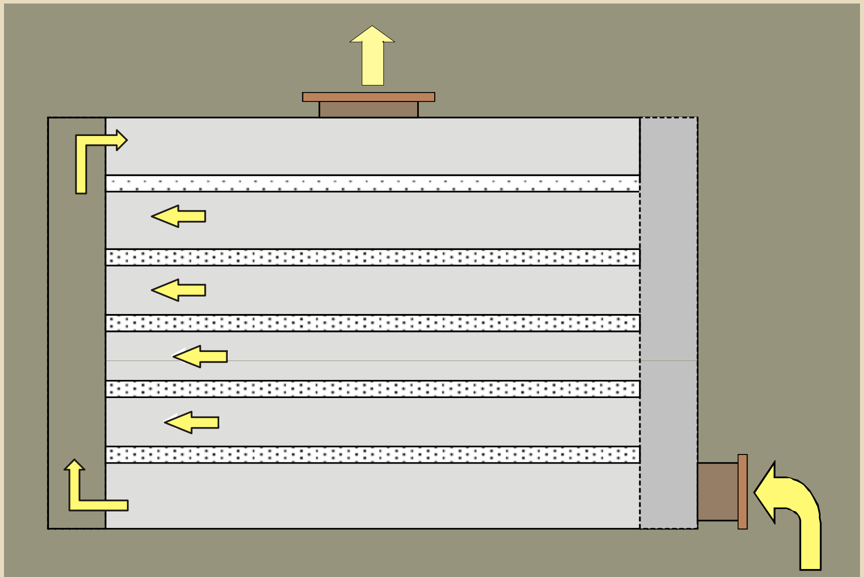
Despcription:
THEORETICAL REMOVAL OF
MERCURY BASED ON VELOCITY

TYPES OF SCRUBBERS

- Deep Bed Scrubbers handle the highest flow rates and mercury concentration. Bed depth is usually 4 feet deep **(depends on mercury concentration)** and have a maximum diameter of 13 feet **(10,000 cfm).**
- Tray scrubbers contain about a quarter of the carbon as a deep bed would for the same flow, these units are used on low grade streams that have high volume, such as e-cells.
- The cylindrical unit can handle high flow rates in a smaller floor area and are used instead of tray units or as back up units to deep bed units. They cost less than deep beds but do not have as high of a loading capacity.
- The units are usually made of stainless steel **(316L).**

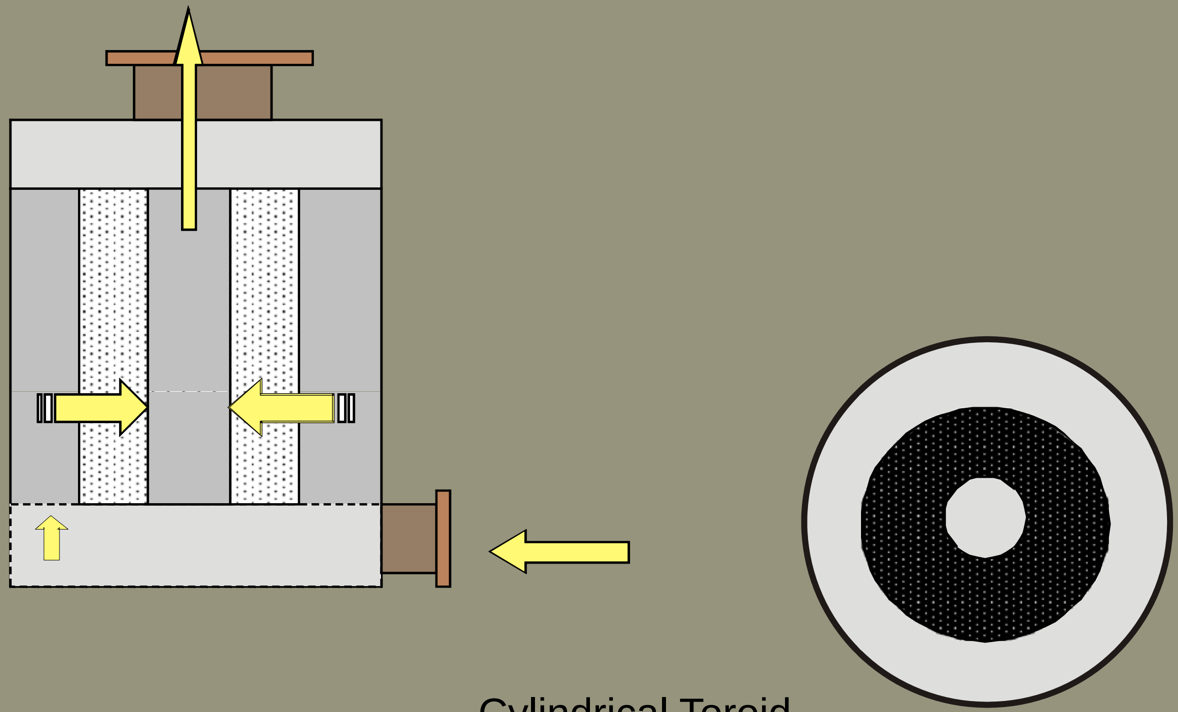
SCRUBBER DESIGN (DEEP BED)





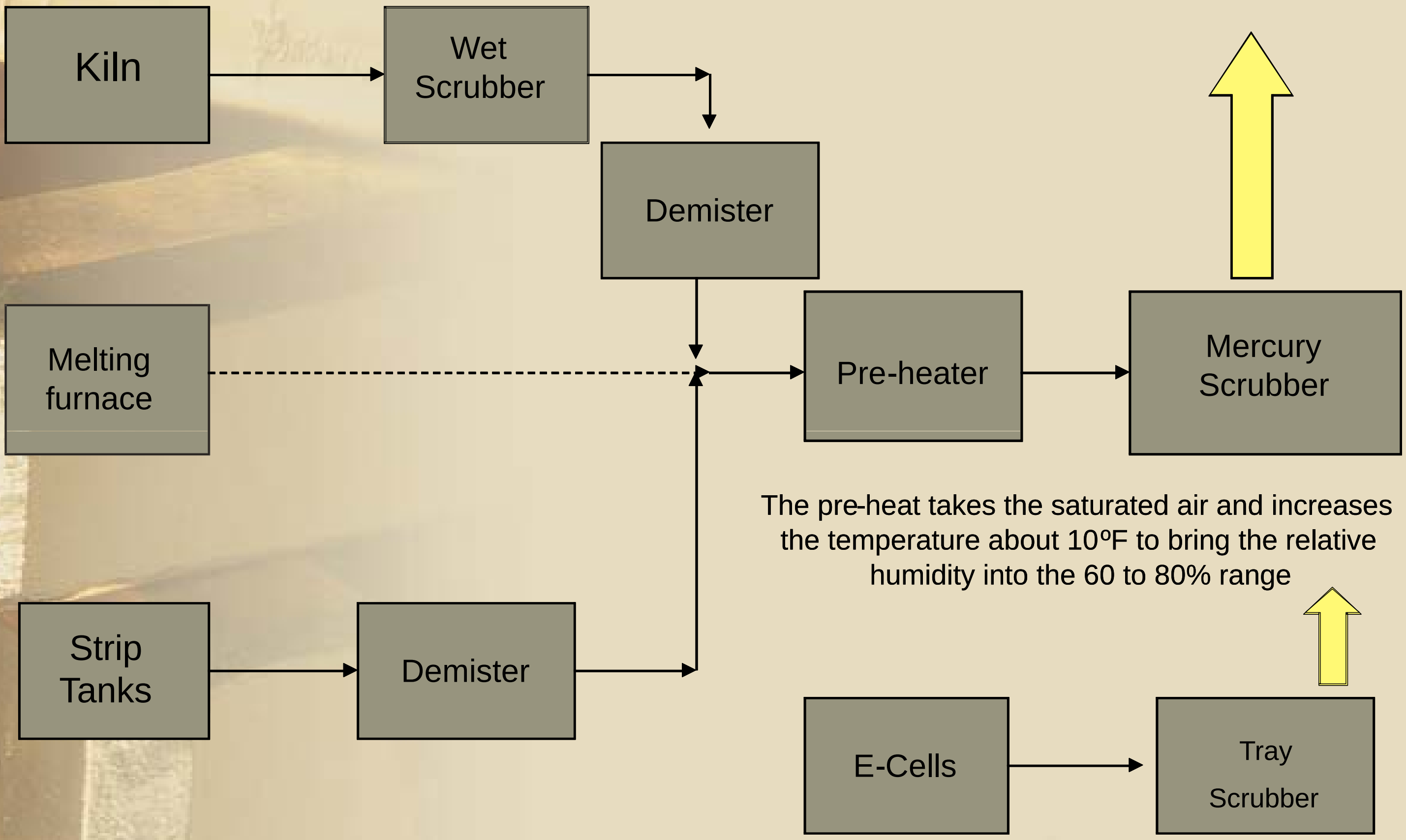
Tray Type Scrubber

CYLINDRICAL TOROID



Cylindrical Toroid

TYPICAL FLOW SHEET



Kiln

Wet Scrubber

Demister

Melting furnace

Pre-heater

Mercury Scrubber

Strip Tanks

Demister

E-Cells

Tray Scrubber

The pre-heat takes the saturated air and increases the temperature about 10ºF to bring the relative humidity into the 60 to 80% range

TYPICAL TREATMENT SCHEME

- The air from the kiln is wet scrubber to remove any particulate matter from gas stream. It passes to a demister to remove any droplets of water. The gas is passed through a pre-heater to bring the relative humidity **(R.H)** down so water doesn't form in the deep bed.
- The air from the preg and barren strip tanks is passed through a demister and then flows into the pre-heater before it passes through the deep bed.
- The air from the melting furnace **(intermittent flow)** passes with the other gases into the deep bed scrubber.
- The air from the E-cells is passed through a tray scrubber.

DESIGN CRITERIA

- Air flow is limited to 75 fpm
- Relative humidity in the gas stream is maintained in the range of 60 to 80% (for maximum reaction rate, as moisture decreases the reaction rate slows and at high humidity the reaction rates slow significantly (1 to 5% of optimum RH%))
- A deep bed scrubber is designed to have the carbon changed two times or less per year. Tray scrubbers are usually designed to be changed 4 times or less per year.
- Air stream temperature is maintained as low as possible, since temperatures above 180°F increase the chances of causing auto-combustion of the sulfur impregnated carbon. Nominal design temperatures are usually below 130°F. Dilution air is usually used to decrease temperatures in the system.

TESTING CRITERIA

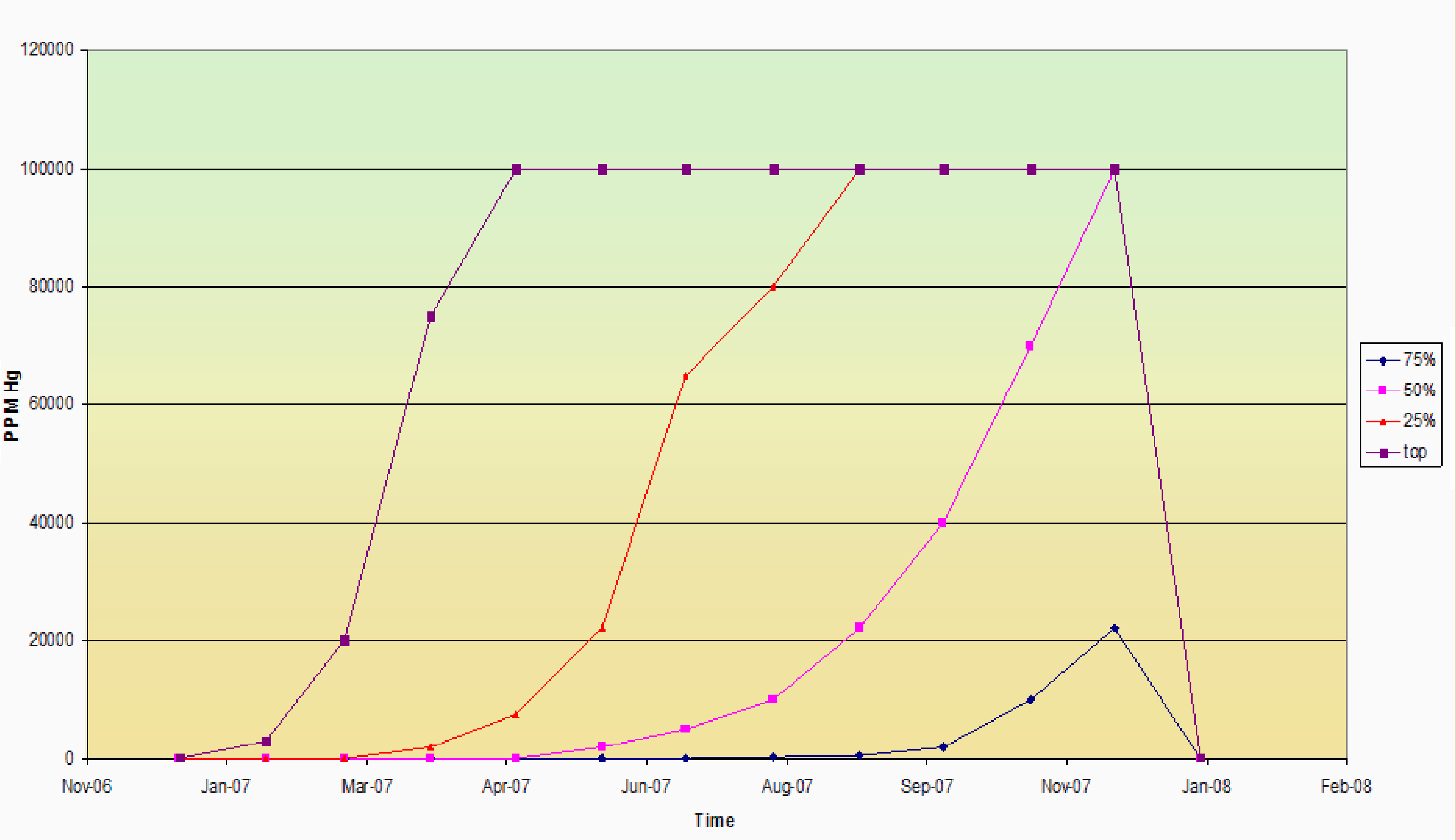
- Gas sampling is not recommended, since even with advanced equipment and trained samplers, reproducibility is not good. Additionally, gas stream sampling is an intricate, long process that doesn’t lend itself to monthly testing.
- Monthly performance testing is a recommended method of testing. This testing involves taking carbon samples monthly from different levels of the deep bed or trays and analyzing the carbon for mercury loading.
- The reason to sample from the various levels of the tank is to watch the progressive increase in the amount of mercury loaded onto the carbon and predict when the carbon needs to be changed prior to breaking through the bed.

S.I.O.N.
Scotia International of Nevada, Inc.

Frqfhqwudwlrq#lq#ssp #Kj

Wlph	Wrs	58(	83(	:8(
Jan 07	0	0	0	0
Feb 07	3000	20	1	0
Mar 07	20000	100	5	1
Apr 07	75000	2000	15	5
May 07	100000	7500	100	8
Jun 07	100000	22000	2000	50
Jul 07	100000	65000	5000	100
Aug 07	100000	80000	10000	200
Sep 07	100000	100000	22000	500
Oct 07	100000	100000	40000	2000
Nov 07	100000	100000	70000	10000
Dec 07	100000	100000	100000	22000
Jan 08	0	0	0	0

Deep Bed Loading Curve



REVIEWING LOADING DATA

- As can be seen from the previous graph the loading is not constant, which is expected from a mine where ore grades are constantly varying.

- The maximum loading for this system appears to be 10% Hg, this concentrate will vary with conditions and carbon source.

- The carbon life is one year.

ADVANTAGES TO PERFORMANCE TESTING

- A skilled sampler is not required. A “grain thief” sampler is all that is required (plus PPE).
- There is little interruption to the process.
- The variability of the ore is addressed by the constant monthly testing.
- The frequent sampling lets the operational group plan when the carbon needs to be changed.
- Carbon analysis for mercury is a well known procedure and most certified labs are capable of performing this analysis.

CONCLUSIONS

- Mercury adsorption from gas streams that are 10,000 cfm or less is best accomplished by sulfur impregnated activated carbon.
- There is no specialized instrumentation or equipment necessary to operate as in the case of wet scrubbers.
- The system is passive and easily monitored.
- The method is economic and within the range of all types of operators **(large and small)**
- The technology is well known and understood.