DRAFT
MERCURY MASS BALANCE AND EMISSIONS FACTOR ESTIMATES FOR GOLD ORE PROCESSING FACILITIES

Prepared for

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1.0 Introduction

Toxics Release Inventory reporting by the gold mining industry has shown that these facilities may be large sources of mercury emissions to air. Air emissions of mercury from gold ore processing occur at a maximum rate of thousands of pounds per year, a much higher rate than that observed at coal-fired electric generating plants, which emit an average of 250 pounds per year mercury. In order to identify the specific sources of mercury emissions from gold processing, the range of possible mercury loading and partitioning for each process type with a significant potential has been evaluated. Gold ores are treated by a variety of processes to recover the gold content of the ore. All gold recovery processes rely on leaching relatively low concentration of gold from ores using cyanide solutions. Because gold has a high value, it is economic to recover gold from ores with low concentrations of finely disseminated gold (as low as 0.05 ounces/ton). Ores that contain gold that can be readably extracted by crushing and leaching the ore with cyanide solution are referred to as "oxide" or "free milling" ores (Ref. 1). However, gold recovery from some ores by leaching is not efficient, with as little as 30 percent of the gold content of the ore removed by cyanide leaching. These ores are called refractory ores. Poor gold recovery from refractory ores is caused by the presence of gold in sulfide mineral grains (usually pyrite, iron sulfide) that do not react with the cyanide leach solution, or by adsorption of dissolved gold onto carbonaceous material present in the ore (known as "preg robbing").

Refractory ores can be treated by thermal combustion processes (ore roasting) or in pressure oxidation vessels (autoclaves). These processes oxidize sulfide minerals and carbon, and the gold content of the treated ore can then be extracted by cyanide leaching. Because the gold containing cyanide solution (pregnant leach or liquor) has relatively dilute gold concentrations, gold is concentrated by adsorption onto activated carbon, either in adsorption columns or in carbon added to the leaching process (carbon-in-leach or carbon-in-pulp units). The adsorbed gold is then eluted from the adsorbed carbon by stripping with ammonia, nitric acid, and/or steam processes. The gold is then converted to a solid from the eluate by electrowinning (electroplating of gold onto cathodes) or by precipitation and filtration by adding zinc powder to the concentrated solution. The recovered gold may have significant mercury content, which is separated by retorting, which is a distillation and condensation process. The gold is then further refined in a melting furnace to separate impurities into a slag. The resulting gold is referred to as dore, and may contain significant silver. Dore is then transferred to refineries to be purified into pure gold or bullion.

Mercury is present in many gold ores (typically ranging from 1 to 200 mg/kg), and can be converted to elemental mercury and emitted to the air during these treatment processes because of the physical and chemical properties of mercury (Refs. 2, 3). Mercury in the gold ore is typically present as mercury sulfide (cinnabar) and as an amalgam with the elemental gold. The following processes have mercury present in the feedstock and are performed under chemical and physical conditions that indicate they are potential emission sources of mercury:

Ore Roasters
Ore Autoclaves
Carbon Regeneration Kilns
Electrowinning Units
Mercury Retorts
Dore Furnaces

2.0 Emissions Factors and Mass Balances for Gold Ore Processing Units

2.1 Ore Roasters

Uncontrolled Roaster Emissions

Most roasters are operated with coal as the combustion fuel, although fuel oil or natural gas may be used as fuel, or may be added to the ore-coal feed mixture to provide sufficient heat of combustion to roast the ore. Roasters are typically operated with combustion chamber temperatures of 1,800°F to 2,500°F (1,000°C to 1,400°C), and the ore is heated to a temperature of approximately 1,300°F (700°C) to complete oxidation of ore constituents that interfere with gold extraction. Combustion is usually performed in the roaster by feeding fuel and heated air to the combustion chamber. The ore feed, including any mixed fuel, is fed to the roasting chamber and exposed to the heat produced by fuel combustion through multiple hearth or fluidized bed processes. Roaster feed rates range from less than one ton per hour for small operations that roast ore concentrates, to over 200 tons per hour for large-scale operations that roast lower grade ores.

Because the roasters are operated to oxidize the carbon and sulfide minerals that interfere with gold recovery by cyanide leaching, roasters are designed and operated to effectively burn these constituents. These constituents provide some of the heat of combustion to the roasting process, and ore composition is considered in the design of the roasting process. The carbon and sulfide burned in the roaster produce gaseous combustion products (SO_2 and CO_2) that are emitted from the roaster in the flue gas. Roasters are designed and operated to remove at least 95 percent of the ore sulfide and carbon that interfere with gold recovery (Ref. 4). Effective roaster performance requires nearly complete oxidation of ore sulfide minerals and carbon. Roaster performance for a specific ore depend on the bulk mineralogical composition of the ore, the mode of occurrence of gold in the ore, feed ore grain size distribution and the physical properties of the calcined ore.

The mass balance assumes an ore feedstock mercury concentration of 20 mg/kg, occurring primarily as cinnabar (HgS). Some mercury may also be present as a constituent of disseminated metallic gold present in the ore. Mercury present in cinnabar is converted to metallic mercury during roasting by the chemical reaction:

$$\mathrm{HgS} + \mathrm{O_2}\ ?\ \mathrm{Hg} + \mathrm{SO_2}$$

Because the ore is raised to a temperature of at least 1,300°F (700°C) during the roasting process, virtually all of the mercury produced by oxidation of cinnabar in the ore will be volatilized and entrained in the flue gas (Ref. 2). Elemental mercury produced during roasting is completely volatilized as the roasters heat the ore above the boiling point of mercury (674 EF, 356.58 EC) (Ref. 5). Mercury present as an alloyed constituent in finely disseminated grains of metallic gold or silver in the ore will not be affected by the roasting process and will be retained with the calcined ore. The amount of mercury released to flue gas during roasting of the ore is therefore dependent on the proportion of mercury present in cinnabar and alloyed with metallic gold or silver. Archaeological studies of gold artifacts and gold mines have indicated that unrefined gold can contain 30 weight percent mercury (Ref. 6). Based on the bulk ore compositions presented in the mining and metallurgy literature (gold concentrations from 1.5 mg/kg up to 20 mg/kg, and total mercury concentrations from 1 to 200 mg/kg), it is assumed that most of the mercury present in gold ores is present as cinnabar. This analysis assumes that 80 percent of the mercury present in the ore is in cinnabar, and is released to flue gas during roasting.

For a typical ore with a total mercury concentration of 20 mg/kg, conversion of 80 percent of mercury in the ore to elemental mercury vapor through oxidation of cinnabar results in the following mass balance and emission rates:

Ore Total Mercury Content	20 mg/kg	0.04 lb/ton
Mercury Emitted in Off Gas per Mass of Ore Roasted	16 mg/kg	0.032 lb/ton
Mercury Retained in Calcined Ore	4 mg/kg	0.008 lb/ton

The mass balance and uncontrolled emission rates for the roaster process should be adjusted for the mercury content of ore to develop site-specific emissions estimates. Available data indicate that gold ore mercury concentrations range from 1 mg/kg to 200 mg/kg (Refs. 1, 3, 7).

Mercury emissions from coal-fired boilers have been studied to determine emissions rates and effectiveness of control technologies. Coals typically contain 0.1 mg/kg mercury, and because of the large volumes of coal burned to generate electricity, electric generating plants are a significant source of mercury emissions (Ref. 8). Coal-fired boilers (CFBs) share some basic similarities in processes and operations with ore roasters (Ref. 9). Both operate at similar combustion temperatures and process configurations, including fluidized bed and fixed hearth combustion chambers. Ore roasters with hearth combustion chambers are typically configured with multiple hearths, to ensure complete combustion of ore components. Mercury emissions have also been evaluated for other combustion processes, including municipal waste combustors (WMC) and hazardous waste incinerators (HWI) (Ref. 8).

Factors that differ between CFB and ore roasters include mercury content of the feed and flue gas, flue gas sulfur dioxide concentration, and flue gas mercury speciation. Coals used as boiler fuel have mercury concentrations ranging from 0.03 to 0.24 mg/kg, with an average concentration of 0.1 mg/kg (Ref. 10). Analyses of untreated flue gas from CFB have detected mercury concentrations up to 25 ìg/m^3, with an average concentration of 15 ìg/m^3. Gold ores have measured mercury concentrations from less than 1 mg/kg to 200 mg/kg for ore deposits in the western U.S. Comparison of the ore feed rate and air flow rates for ore roasters at Jerritt Canyon, untreated roaster off gas has an estimated mercury concentration of 1.5 to 15 mg/m^3, up to 1,000 times greater than the typical mercury concentration in CFB flue gas (Ref. 11).

Detailed studies of treatment technologies for mercury removal from CFB emissions have shown that speciation of mercury has a major impact on mercury removals, with some species completely removed and complete pass through for other forms of mercury in certain control types. Important mercury species in combustion gases include elemental mercury vapor (Hg^0), oxidized mercury vapor (Hg^{2+}) and mercury associated with particulate matter (Hg^P). Studies of mercury speciation in CFB flue gas indicate that there is considerable variability in flue gas mercury speciation, ranging from greater than 20 to 80 percent mercury as Hg^0 in flue gas. Most of the remainder of the flue gas mercury is present as Hg^{2+}, with particulate mercury typically less than 10 percent of the total flue gas mercury (Refs. 10, 3, 12). While the mechanisms of coal speciation in CFB flue gas are not completely understood, available information indicates that coal chloride content is positively correlated with the amount of Hg^{2+} in the flue gas, as chloride catalyzes the oxidation of mercury in the gas phase. Thermodynamically, Hg^0 is thermodynamically stable at combustion temperatures, while Hg^{2+} is stable at lower temperatures (Ref. 12). Oxidation of the mercury in cooling flue gas is limited by reaction kinetics where the flue gas has a low chloride content, with greater than 90 per cent of the vapor mercury as Hg^0 in flue gas from combustion of coals with less than 100 mg/kg chloride (Ref. 12).

Speciation of mercury in roaster off gas has not been studied; however, the process for conversion of cinnabar during ore roasting is well understood. The oxidation of the sulfur present in cinnabar produces sulfur dioxide. The stoichiometry of this reaction shows that each atom of sulfur oxidized consumes two atoms of oxygen. Because oxygen is also consumed by burning of the fuel in the roaster, there is not sufficient oxygen present to oxidize the sulfur to sulfate ion. The reaction also releases elemental mercury, which is stable at roasting temperatures. Because roaster off gas may have mercury concentrations up to 1,000 times greater than typical CFB flue gas, oxidation reactions may not contribute as much to the conversion of Hg^0 to Hg^{2+} in roaster off gas, especially prior to gas cooling. Similarly, adsorption onto particulate matter will not be as significant, as particulate matter concentration in roaster off gas should be similar to CFB flue gas, since the source of gas particulate content is fly ash from fuel combustion in both gas streams. The process evaluation for non-ferrous metals smelting estimated that gas emission Mercury speciation is 85 percent Hg^0, 10 percent Hg^{2+} and 5 percent Hg^P (Ref. 8). This speciation estimate for roaster off gas mercury is used to evaluate removal efficiencies and mass balances for treatment options.

Roaster Emissions Data Evaluation

Review of the Nevada DEP Bureau of Air Quality permit files revealed that a number of gold ore roasters have permit limits for mercury emissions; however, emissions test data were available for only one facility, the Jerritt Canyon mine, which has two roasters with a combined operating capacity of 250 tons per hour (Ref. 11). In addition, mercury analyses were performed on the outlet gas after all treatment processes, data on inlet and outlet mercury concentrations for each process were not collected. Total mercury analyses were performed, the speciation of mercury in the treated off gas was not evaluated. The tests were performed in April and May of 2000. The test parameters and emissions data are listed in Table 1.

These data show the potential for variability in roaster emissions that probably reflect the influence of ore content on the mercury emission rates. Retesting of the West Roaster in May 2000 yielded similar results as the previous test, indicating that short-term variations in roaster operating conditions were not the source of the higher emissions at this unit.

The feed rates and controlled emissions data at Jerritt Canyon were compared using the general mass balance and emissions factor relationships previously described. Based on the regional average ore mercury concentration of 20 mg/kg, and a combined roaster feed rate of 215 tons/hr, the assumed loading of mercury in the roaster feed was 8.61 pounds per hour mercury. With 80 percent of the ore mercury partitioned to the roaster off gas, the total untreated emissions rate is estimated at 6.89 pounds per hour of mercury. The combined stack emission rate of 1.31lbs/hr mercury indicates an overall removal rate of 81% by all of the emissions controls in operation at Jerritt Canyon. In order to attribute mercury removals to the individual treatment processes, the mercury speciation and removal efficiency for each process must be evaluated

Table 1. Operating Parameters and Mercury Emissions Rates for Jerritt Canyon Mine Ore Roasters

Unit	Feed Rate	Mercury Emission Rate
East Roaster	107 tons/hr	0.31 lb/hr
West Roaster	104 tons/hr	1.01 lb/hr

Process controls used at Jerritt Canyon include a wet venturi scrubber for gas cooling and some particulate removal, a sodium hydroxide scrubber for sulfur dioxide removal, a sodium oxychloride packed bed scrubber for mercury removal, and a wet electrostatic precipitator (ESP) for final particulates removal. Estimates of mercury speciation in the roaster off gas and removal efficiencies for the individual treatment processes are based on process knowledge for ore roasting and information on mercury removal technology performance derived from studies of coal-fired utility boilers.

Control Efficiencies

Roaster Off-Gas Quench

Quenching of roaster off gasses by water spraying may be performed to reduce the flue gas temperature from approximately 1,000°F to 400°F to allow treatment for control of particulates, sulfur dioxide, and mercury. Roaster off gas quenching is usually performed by spray towers, or by wet venturi scrubbers that also provide some particulate removal. Because quenching is the first treatment step for roaster off gas, influent gas mercury concentrations will typically range from 1.5 to 15 mg/m^3 with 85 percent present as Hg^0 (Ref. 8, 11). Cooling of the roaster off gas will result in some oxidation of Hg^0, but the amount of vapor mercury oxidized is expected to be considerably less than that observed in CFB flue gas, due to the high mercury concentrations relative to the amount of chlorine in the roaster off gas available to catalyze the oxidation reaction. Some mercury may also be adsorbed onto particulates during cooling, as adsorption equilibrium concentrations on the solid phase increase as temperature decreases. Adsorption to solids is also limited by the high mercury concentration in roaster off gas relative to particulates contributed to the gas stream as fly ash. Based on these considerations, roaster off gas quenching is expected to have maximum mercury removal efficiency of **10 percent**, with typical removals of 5 per cent or less. The mass balance relationship for off gas quenching is:

Untreated Hg Emission Rate(lb/hr) = (0.8 x Ore Hg Conc. (lb/ton)) x Ore Feed Rate (ton/hr)

Quench process removal (lb/hr) = 0.1 x Untreated Hg Emission Rate(lb/hr)

Effluent roaster off gas Emission Rate = 0.1 x Untreated Hg Emission Rate(lb/hr)

Based on these emission factors, the Jerritt Canyon roasters processing gold ore containing 20 mg/kg mercury at 215 tons/hr will intake 8.6 pounds of mercury per hour and emit mercury in the untreated roaster off gas at a rate of 6.9 pounds per hour. Wet off gas quenching at Jerritt Canyon is estimated to remove mercury at a rate of 1.7 pounds per hour. Because mercury removal during roaster off gas quench occurs through oxidation and dissolution in the quench solution and entrainment of particulate mercury in the liquid phase, dry gas cooling processes such as dry spray cooling or boiler heat recovery will not result in any mercury removal.

Sulfur Dioxide Scrubbers

Roaster off gas is often treated to remove sulfur dioxide (SO_2) from generated by combustion of sulfur in the fuel and oxidation of sulfide minerals in the ore. The gas stream is fed to spray towers or packed bed towers where the gas flows counter to a sodium hydroxide (NaOH) or milk of lime (CaOH) solution, which reacts with the SO_2 in the gas stream. Studies of CFB flue gas treatment have shown that SO_2 scrubbers can remove up to 90 percent of the Hg^{+2} present in the gas stream as the mercury dissolves into the liquid phase, but does not provide any removal of Hg^0 from the flue gas. Because significant chloride content may be present in the roaster off gas, some conversion of Hg^0 to Hg^{+2} may occur in the cooled gas stream, and the Hg^{+2} component of the roaster off gas could be effectively removed by the SO_2 scrubber solution. Both mercury and chloride content of the gas stream may be variable, depending on the ore composition and coal quality. Based on typical ore and coal chemistry values, an average mercury removal of **25 percent** may be provided by SO_2 scrubbers. Under conditions where coal chloride content is low and ore Mercury content is high, effective mercury removal by SO_2 scrubbers may approach 0 per cent. Based on typical conditions, the expected mass balance relationship for mercury removal by SO_2 scrubbing is:

Inlet Hg Rate(lb/hr) = (0.8 x Ore Hg Concentration (lb/ton))x Ore Feed Rate (ton/hr) x 0.9

SO_2 Scrubber Process Removal Rate (lb/hr) = 0.25 x Inlet Hg Emission Rate(lb/hr)

SO_2 Scrubber Process Outlet Emission Rate = 0.75 x Inlet Hg Emission Rate(lb/hr)

Based on these emission factors, the SO_2 scrubber process at Jerritt Canyon processing gold ore containing 20 mg/kg mercury at 215 tons/hr will intake 6.9 pounds of mercury per hour and emit mercury in the treated roaster off gas at a rate of 5.2 pounds per hour. SO_2 scrubbing at Jerritt Canyon is estimated to remove mercury at a rate of 1.7 pounds per hour.

Particulate Removal Devices

Available control technologies in use for particulate control at gold ore roasters are electrostatic precipitators (ESPs) and baghouses. Baghouses typically provide highly effective control for particulates, but require more maintenance and must be operated under very controlled conditions (gas flow rate, pressure drop) to achieve optimum performance. ESPs provide some advantages in performance over wider operating conditions and may require less maintenance than baghouses. Wet and dry ESPs both function by generating an electric field that imparts an electrostatic charge to particulates in the gas stream (provided the particulates have some electrical conductivity), and then collecting the charged particles on a charged collector plate. Dry ESPs rely on mechanical processes to remove the collected particulate matter from the charged collector plate, while collected particulates are removed from wet ESPs by a film of water flowing over the collector plate. Studies of removal efficiencies for these technologies applied to CFB flue gas show that removal efficiency is strongly correlated with the fraction of Hg^P in the gas stream, with nearly complete removal of Hg^P by both types of devices (Ref. 13). For unscrubbed gas streams, the particulate control devices do not provide any effective removal of Hg^O or Hg^{+2} components in the gas stream.

Based on the performance trends for these devices in CFB flue gas treatment and the expected composition of roaster off gas, the particulate control devices are expected to provide a removal efficiency of up to 9 percent from roaster off gas. Based on typical mercury concentrations in roaster off gas and an average removal efficiency of **5 percent**, the mass balance relationship for Wet ESPs and other particulate control devices can be summarized by the following relationships.

Based on 90 percent pass through from off gas quenching and 25 percent pass through from SO_2 scrubbing, multiplying these pass through rates gives the inlet loading factor: 0.9 x 0.75 =0.675.

$$\text{Inlet Hg Rate(lb/hr)} = (0.8 \times \text{Ore Hg Concentration (lb/ton)}) \times \text{Ore Feed Rate (ton/hr)} \times 0.675$$

$$\text{Particulate Process Removal Rate (lb/hr)} = 0.05 \times \text{Inlet Hg Emission Rate(lb/hr)}$$

$$SO_2 \text{ Scrubber Process Outlet Emission Rate} = 0.95 \times \text{Inlet Hg Emission Rate(lb/hr)}$$

Because the effectiveness of the mercury removal by particulate control devices is dependent on the fraction of Hg^P, particulate removal by ESP prior to gas cooling (known as hot side ESP) may not provide significant mercury removal. This configuration is used at some CFBs, but is not typically used for particulate control in roaster emissions. Based on these emission factors, the particulate process at Jerritt Canyon processing gold ore containing 20 mg/kg mercury at 215 tons/hr will intake 5.2 pounds of mercury per hour and emit mercury at a rate of 4.94 pounds per hour. Particulate removal for the Jerritt Canyon loading rate is estimated to remove mercury at a rate of 0.26 pounds per hour.

Carbon Adsorption

Fixed bed carbon adsorption units have been used to control mercury emissions at municipal waste combustors and hazardous waste incinerators in the U.S. and Europe, and their performance is well understood (Ref. 8). Effective performance of the units require that the influent gas stream is sufficiently cooled so that mercury can be effectively adsorbed on the carbon, and to prevent oxidation losses of the carbon matrix (Ref. 13). Typically, gases are cooled below 300ºC for effective mercury removal by carbon adsorption. Factors affecting carbon bed adsorption performance include residence time of the gas phase in the carbon bed, bed temperature, and carbon particle size. Longer residence times, smaller carbon particle sizes and lower temperature ranges can result in mercury removal efficiencies of nearly 100 percent. As mercury is adsorbed in the fixed bed, the carbon will eventually approach is adsorptive capacity and will allow some mercury to pass through the filter. The adsorptive capacity of the carbon can be increased by impregnating the carbon with elemental sulfur. Mercury adsorbed by the carbon then reacts with the sulfur to produce HgS, which has a much lower vapor pressure than elemental mercury and will not be desorbed from the filter under normal operating conditions. Carbon filters can be regenerated by chemical stripping or retorting of the adsorbed mercury, and the mercury can be recovered from the regeneration process.

Mercury adsorption from gas phases has been reported at 50 to greater than 95 percent recovery. Lower recovery efficiencies by carbon adsorption are attributed to the presence of Hg^{+2} in the vapor phase, elevated temperature of the inlet gas, or insufficient residence time. Properly designed and operated carbon adsorption filters can achieve mercury removals of **90 percent**, especially for gas streams where Hg^{+2} has already been removed through scrubbing processes. Mercury removal by carbon adsorption under appropriate operating conditions provided below.

Based on 90 percent pass through from off gas quenching, 25 percent pass through from SO_2 scrubbing, and 95 per cent pass through by particulate removal, multiplying these pass through rates gives the inlet loading factor: 0.9 x 0.75 x 0.95=0.641.

Inlet Hg Rate(lb/hr) = (0.8 x Ore Hg Concentration (lb/ton))x Ore Feed Rate (ton/hr) x 0.641

Carbon Adsorption Process Removal Rate (lb/hr) = 0.9 x Inlet Hg Emission Rate(lb/hr)

Carbon Adsorption Process Outlet Emission Rate = 0.1 x Inlet Hg Emission Rate(lb/hr)

Based on these emission factors, the carbon adsorption process at Jerritt Canyon feed rates, processing gold ore containing 20 mg/kg mercury at 215 tons/hr, will intake 4.94 pounds of mercury per hour and emit mercury at a rate of 0.446 pounds per hour. Particulate removal for the Jerritt Canyon loading rate is estimated to remove mercury at a rate of 4.446 pounds per hour.

Large volume ore roasters have gas flow rates that may exceed 10,000 ft^3/m. Therefore, carbon filters used for this gas stream will have to be designed to allow sufficient flow and residence time for mercury removal, and may require management of significant volumes of carbon material.

Other Mercury Removal Technologies

Several other technologies are available for mercury removal from roaster off gas, including mercury scrubber technologies and selenium adsorption filters. Mercury scrubbing is achieved by sodium oxychloride packed bed scrubbers, and sulfuric acid scrubbers, including the Bolkem and Outokumpu processes. Mercury can also be removed from gasses by the Boliden_Norzink process, which reacts mercurous chloride with mercury to form mercuric chloride, which is then removed from the stripper solution.

A sodium oxychloride packed bed scrubber is used for mercury removal at Jerritt Canyon. Roaster off gas testing data indicates that with 25 percent removal of mercury by sulfur dioxide scrubbing, the estimated performance of the sodium oxychloride packed bed scrubber is 56 percent, averaged across the two units. While this is a significant amount of mercury removal, the large ore feed and gas flow rates for these units result in significant mercury emissions (1.31 lb/hr, total) even with the mercury scrubber in operation. These data indicate that mercury removal processes will have to perform at high removal efficiencies to achieve acceptable mercury emissions for large volume roasters that are used to process mercury rich gold ores.

Other available control technologies rely on scrubbing of mercury from roaster off gas by reaction of the Hg^O in the gas phase with a scrubber solution that oxidizes the Hg to Hg^{+2}, which is dissolved into the scrubber solution. These technologies all require removal of mercury solids or regeneration of scrubber solutions that includes generation of solid or liquid mercury bearing residual streams. The most commonly used mercury scrubbing process is the Boliden-Norzink process, which reacts mercurous chloride solution with vapor mercury to produce mercuric chloride, by the following reaction:

$$HgCl_2 + Hg \ ? \ 2HgCl$$

The scrubber solution is regenerated by reaction with chlorine gas, with period removal of mercury by precipitation and settling or filtration. The $HgCl_2$ solution is fed to a packed bed tower and reacts the roaster off gas, flowing counter to the solution flow in the tower. This treatment process is typically used where SO_2 will be recovered to generate sulfuric acid, and mercury content in the acid will restrict use of the acid as a commercial product. Reported mercury removal efficiencies for this process are greater than 90 per cent.

The Bolkem and Outokumpu processes both remove mercury from the gas stream by reaction with a sulfuric acid scrubber solution. In the Bolkem process, roaster off gas is scrubbed with a concentrated sulfuric acid solution in a series of two drying towers. The reaction produces Hg_2S0_4, which is removed from the scrubber solution by reaction with sodium thiosulfate, which produces a precipitate of HgS that is removed in a thickener or filter. In the Outokumpu process, roaster off gas is scrubbed in concentrated sulfuric acid at 150°C to 180°C, producing $HgSO_4$, which precipitates and is filtered from the scrubber solution. Mercury containing solids from these processes can be recovered by retorting.

Selenium filters are used to control mercury emissions at two non-ferrous metals smelters currently operating in Sweden (Refs. 14, 15). 90 per cent removal efficiencies have been reported for this process. The gas stream is passed through a fixed bed filter of amorphous selenium, which reacts to form HgSe, which remains in the filter. The filter material reaches its adsorptive capacity as the selenium is reacted with vapor Hg, and can be regenerated by retorting or chemical processing. The gas stream must also be sufficiently cooled, (less than 400°C) to prevent thermal decomposition of HgSe in the filter.

Mercury can also be removed by scrubbing with a selenium solution in 20 to 40 percent sulfuric acid solution, and this technology has reported removal efficiencies of 90 to 95 per cent (Ref. 14).

Mercury scrubber technologies require that the units are operated under proper conditions, including maintenance of scrubber solution chemistry, maintenance of scrubber towers and management of mercury containing treatment residuals and hazardous treatment chemicals (sulfuric acid, chlorine gas, selenium, HgSe). Generally, these technologies have been used where roasting of sulfide ores produces SO_2 bearing off gases that can be treated to produce sulfuric acid as an economic product. While gold ores may contain sulfide minerals, the ores typically do not contain as much sulfide as ore concentrates of other metals, which have been treated to remove non-sulfide metals. These technologies can be used to treat mercuric roaster off gases produced by roasting gold ores, but may have to be adapted to gas streams that typically contain lower SO_2 concentrations.

2.2 Autoclaves

Sulfide minerals that interfere with gold recovery through cyanide leaching process can also be treated in autoclaves. Autoclave treatment of ores is a wet process, water is added to crushed ore to form a slurry or pulp that is acidified and then oxidized under elevated pressure and temperature conditions. Autoclaving is not used for treatment of ores containing high concentrations of carbonate minerals, as the carbonates require high levels of sulfuric acid addition to lower the pH to the desired range for the pulp. Autoclaves are also not used for treatment of ores that have poor gold recovery due to the carbon content of the ore. Sulfuric acid is added to the pulp to lower the pH of the feed material to 1 or lower, as this promotes the oxidation of sulfide minerals. The acidified pulp is pumped into the pressurized reaction chamber, where the material is heated to 180°C to 220 °C, and is pressurized to 345 pounds per square inch in an oxygen atmosphere (Ref. 16). The pulp is agitated in the reaction chamber, and the high temperature and oxygen pressure cause rapid oxidation of sulfide minerals. The strongly oxidizing conditions promote complete oxidation of sulfur in the sulfide minerals to sulfate. For cinnabar, which contains most of the mercury in the ore, the reaction is:

$$HgS + 2O_2 \quad ? \quad HgSO_4$$

Because of the controlled conditions that promote oxidation, greater than 90 per cent of the mercury present in the pulp is converted to oxidized mercury. The sulfide content of the ore is completely oxidized to allow gold recovery from the treated ore of 90 percent or more through cyanide leaching (Refs. 1, 16). At the discharge from the pressurized reaction chamber in the autoclave, the pulp is transferred to a flash chamber, where pressure is relieved and the pulp liquid is converted to steam. Steam may be recovered and returned to the pressurized reaction compartment to reduce heat loss from the process. Off gas from the flash chamber is treated in a venturi to remove acid mist and cool the gas stream, and additional mist and particulate removal may be performed in a cyclone or similar unit.

Autoclave emission testing has been performed at Twin Creeks, where two autoclave units are operated in series to oxidize sulfide ore minerals. The testing was performed at a feed rate of approximately 204 tons per hour, and the ore has a mercury content 198 mg/kg (Ref. 17). The mercury feed rate to the autoclave process for the test is estimated at 80.78 pounds of mercury per hour. The measured emission rate downstream of the venturi and cyclone during the test was 0.0153 pounds of mercury per hour. This indicates that the controlled mercury emission rate was 0.02 per cent of the process. The venturi and cyclone control system is a wet cooling and cleaning process, the effective removal rate of mercury is 90 percent for the Hg^{2+} component of the gas stream, and zero per cent removal for the Hg^o in the autoclave off gas. The completeness of the oxidation of sulfide minerals for ore treatment is typically 95 percent, and a similar degree of oxidation of mercury will occur in the autoclave. The removal efficiencies and speciation of the untreated off gas provide the following relationship between the untreated and treated gas streams. The removal efficiences for each species of mercury in the control device show that:

Total Treated Mercury Discharge Rate = 1 x Untreated Hg^o + 0.10 x Untreated Hg^{2+}

While the oxidation performance of the autoclave process results in 95 percent oxidation of mercury:

Total Treated Mercury Discharge Rate = 1 x Untreated Hg^o + (0.10 x 19 x Untreated Hg^0)

Total Treated Mercury Discharge Rate = 3 x Untreated Hg^o

Combining these relationships, the combined generation, removal and treated emission rates are as follows:

Total Untreated Mercury Emission Rate: 0.122 pounds of mercury per hour

Total Mercury Removal Rate:0.107 pounds of mercury per hour

Total Mercury Emission Rate = 0.1 x Hg^{2+}

The ore feed concentration and emission rates measured at the Twin Creeks autoclave test indicate that the mercury emission rates and removals are as follows:

Uncontrolled emission rate = 0.13 per cent of autoclave mercury feed rate
(ore feed rate times mercury fraction in ore)

Removal Efficiency for Venturi/Cyclone system: 85 per cent

(90 percent removal of 95 per cent of mercury as Hg^{2+})

Controlled Emission Rate = 0.02 per cent of autoclave mercury feed rate

The process information and test data show that large scale autoclaves can be used to treat mercury rich ores with mercury emission rates well below one per cent of the mercury feed rate in the autoclave. Low mercury emission rates in autoclaves are attributed to the process conditions, including high oxygen pressure that promotes wet reaction oxidation of ore sulfide minerals, and operating temperatures that thermodynamically favor formation of Hg^{2+}. The oxidized mercury is less volatile and is more effective controlled in wet gas stream treatment processes.

2.3 Carbon Regeneration Kilns

Carbon used to collect dissolved gold from cyanide solutions is stripped by one of several wet chemical processes to generate a concentrated gold solution. The stripped carbon is then regenerated to restore its ability to adsorp gold before being returned to gold recovery processes. The most common regeneration technique is thermal treatment in rotary kilns. In order to prevent oxidation of the carbon in the kiln, steam is introduced to maintain a reducing environment. The elevated temperatures and reducing environment in the kiln chamber promotes volatilization of adsorbed mercury into the kiln off gas as Hg^{o}. The feed rates for carbon regeneration kilns varies from less than 0.25 to 1.5 tons per hour. Higher volumes of carbon adsorbent must be regenerated at facilities that use carbon in direct contact with the leach system, such as carbon in leach and carbon in pulp systems. The range of mercury emission rates is dependent on the mercury content of the carbon feed, since the kiln operation will ensure greater than 90 per cent volatilization of the mercury present in the kiln feed (Ref. 1).

Design studies for gold recovery processes have shown that the mass loading of mercury to carbon adsorption media is dependent on the ore mercury concentration in the leaching process, the cyanide concentration of the leach solution, and the use of additives in the leaching process to suppress mercury dissolution into the leach solution. Roasted ores and ores with low mercury content prior to any treatment will result in lower mercury concentrations in the leach solution, resulting in lower mercury loading to carbon. Leaching studies have shown that the proportion of mercury leached from the ore is also related to the cyanide concentration of the leach solution (Ref. 1). Cyanide solutions with 150 mg/l sodium cyanide were found to dissolve very little mercury, while sodium cyanide solution at a concentration of 2,000 mg/l was found to leach 80 percent of the mercury from the ore. Regional studies of Nevada ores have found that at typical ore concentrations of 20 mg/kg mercury, 20 percent of the ore mercury is leached into the cyanide solution, resulting in gold to mercury concentration ratios of nearly 1:1 in the leach solution (Ref. 1). Addition of sodium sulfide (Na_2S) or sodium bisulfide (NaHS) has been shown to suppress mercury dissolution into the cyanide leach solution, and this method has been successfully used to minimize mercury control requirements in gold processing operations at Jerritt Canyon and at mines in Australia (Ref 1). Once the carbon has been loaded with gold and mercury from the adsorption process, the gold is recovered by circulating a concentrated caustic cyanide solution through the carbon to desorb the gold into the strip solution (Ref. 1). Target gold concentrations are reported to be on the order of 150 ounces per ton gold on loaded carbon, and less than 5 ounces per ton gold on carbon after stripping has been completed (Ref. 1).

The amount of mercury retained on the carbon after gold recovery is dependent on the type of mercury cyanide complex present in the cyanide solution and carbon strip process used to remove the adsorbed gold (Ref. 1). Gold stripping from carbon under atmospheric generally removes less mercury from the carbon that stripping operations performed at elevated pressures and temperatures. Based on results of stripping studies, mercury concentrations on stripped carbon range from 2,000 mg/kg to 200 mg/kg at facilities where mercury-bearing ores are processed. Lower mercury concentrations in stripped carbon are produced where additives are used to suppress mercury dissolution into leach cyanide solutions (through addition of mercury suppressants such as Na_2S), or where the stripped carbon has been treated with a nitric acid solution prior to kiln regeneration. Emissions testing of kiln off gas at the Smoky Valley mine detected mercury emissions at 0.01 lb/hr, reflecting low mercury loading in the stripped carbon at this facility (Ref. 18). Using a midpoint of potential mercury concentrations in stripped carbon, a value of 1,100 mg/kg mercury is used for this mass balance evaluation.

At this concentration the emission factor for regeneration kilns is derived as follows:

Mercury Emission Rate (lbs/hr) = Kiln Feed Rate (tons/hr) x 2,000 (lbs/ton) x 0.0011

For a kiln with a feed rate of 0.5 tons/hr, the resulting uncontrolled mercury emission rate is 1.1 lb/hr mercury. This shows that regeneration kilns may be significant sources of mercury emissions.

Because the regeneration kilns operate in a steam environment, the mercury will desorb from the carbon in the kiln chamber as Hg^o. Particulate control devices such as baghouses and venturi scrubbers do not provide any effective control of vapor phase Hg^o (Refs. 8, 12). Some Hg^o present in the off gas from the kilns may be adsorbed onto particulate carbon entrained in the gas, and this component of the mercury present in the off gas will be removed by the control devices. Only a minor fraction of the carbon will be entrained into the off gas, and the Hg^o: particulate ratio will not be near the ratio of 10,000 needed for effective adsorption of mercury in the off gas (Ref 3). At most 10 per cent of the mercury will be adsorbed by entrained carbon in the off gas and removed by particulate control devices.

At 10 per cent removal efficiency for particulate control devices for the kiln off gas, the controlled emission rate for the expected mercury loading to the kiln is:

Controlled Emission Rate (lbs/hr) = Uncontrolled Emission Rate (lbs/hr) x 0.9

This indicates kiln off gases treated for particulate removal under expected mercury loading rates is 0.99 pounds per hour.

Carbon adsorption filters can be used to effectively treat kiln emissions for removal of mercury. Once the off gas has been sufficiently cooled, treatment of the off gas can be performed to result in an effective removal efficiency of 90 per cent or greater. The emission factor for kiln off gas treated by the carbon adsorption process is:

Controlled Emission Rate (lbs/hr) = Uncontrolled Emission Rate (lbs/hr) x 0.1

For a carbon with 1,100 mg/kg adsorbed mercury and a feed rate of 0.5 tons per hour, the precited emission rate for the carbon adsorption treated stream is 0.1 lb/hr mercury.

2.4 Electrowinning Cell Rooms

The gold bearing solution produced by the carbon stripping process is piped to gold recovery processes. The two major processes used for gold recovery are electrowinning and the Merrill Crowe process. In electrowinning, the concentrated gold solution produced by carbon stripping is pumped to an electrolytic cell where gold is plated onto the cathode as the solution flows through the electrowinning cell. In the Merrill Crowe process, the solution is placed in a pressure reaction vessel, and zinc powder is added to the solution, forming zinc cyanide solution and precipitating gold, silver and mercury from solution. The precipitated metals are then recovered in a filter press.

Metals emissions have from a variety of electroplating processes have been evaluated, with misting of electroplating solution by off gassing of the gas produced at the anodes. The mist entrains dissolved metal to produce emissions (Ref. 19). Mercury is volatile and will be emitted from the electrowinning process even when mist from the process is controlled. Mercury is more electropositive than gold, and selectively plates onto the cathodes in the electrowinning cell before gold and silver plate out onto the cathode. Because elemental mercury is a liquid, it may weep from the cathode and collect in a pool in the bottom of the electrowinning cell vessel. Gas forming on the cathode (primarily ammonia formed by reduction of cyanide anion) acts as a stripping gas promoting mercury volatilization. The aqueous solution does not provide a barrier to mercury volatilization (MSHA guidance). Based on the vapor pressure of mercury and volatilization rates from metallic mercury, the emission rate for mercury from electrowinning cells is:

Emission Rate (lb/hr) = Cathode Area (ft^2) x Mercury Fraction in plated metal x 0.02 (lbs/ft^2/hr)

(Refs. 1, 20).

For a typical electrowinning unit configuration, the cathode area is 115 ft^2. For an electroplate composition that is 40 percent mercury, 50 percent gold and 10 percent silver, the mercury fraction would be 0.4. This would result in an emission rate of 0.92 pounds per hour. The mercury emission rate will be directly proportion to the mercury content of the electrolyte solution, and mercury precipitation prior to electrowinning through Na_2S may reduce the mercury concentration by more than 95 percent (Ref. 1). Mist control through scrubbing will not provide any mercury removal, as the mercury has been reduced to Hg^o through the electrowinning process. Carbon adsorption of the vented gas stream from the electrowinning cells can provide removal of 90 percent or more of the vapor phase mercury, resulting in a controlled emission factor of:

Emission Rate (lb/hr) = Cathode Area (ft^2) x Cathode Mercury Fraction x 0.02 (lbs/ft^2/hr) x 0.1

With the example configuration described above, the mercury emission rate after carbon adsorption treatment is expected to be 0.092 pounds per hour.

After the electrowinning process has been completed, the cathodes are removed from the cells. The cathodes are typically steel wool, and the plated steel wool is removed from the drained electrowinning cells and is placed in charge pots for retorting. The charge pots should be covered when the cathode material is not being placed into them, and ventilation should be provided in the work area to prevent worker exposure. Ventilation exhaust will contain Hg^o due to volatilzation of mercury from the cathodes. The emission rate will depend on the surface area of the exposed mercury and the amount of time the material is exposed in the electrowinning cell room. Ventilation exhaust should be treated in a carbon adsorption filter prior to discharge.

2.5 Retorts

Retorts are used to separate mercury from the gold recovered by electrowinning or zinc precipitation. Depending on the composition of the gold solution, the recovered metal may contain from trace amounts to more than 50 wieght percent mercury. Based on reported production rates, most facilities in Nevada that produce commercial mercury indicate that typical mercury production rates are 15 per cent of the gold rates (Ref. 22). In the retorting process, the recovered gold, mercury and silver mixture is placed into the charge pot and loaded into the retort.

Retorting is usually done for 12 to 24 hours at 600°C to 700°C, to remove around 99 per cent of the mercury. The charge is heated under a partial vacuum, and the mercury vaporizes and is recovered in a water-cooled condenser. The liquid mercury that is bled from the condenser tube is piped into a collection vessel. The remaining gold and silver at the end of the retorting process typically contains about 1,000 to 8,000 mg/kg mercury (Ref. 1). The condenser allows some mercury to discharge in the off gas, and loss of 0.4 to 0.7 per cent of the mercury from the condenser has been reported (. 23). Based on this relationship, the emission factor for mercury from the gas discharge after condenser recovery is:

Mercury Discharge (lbs/hr) = Charge Weight (lbs) x Mercury Fraction x 0.0055

For a retort charge of 1,000 pounds with a mercury composition of 15 per cent, the total emission of mercury from the condenser during a retort cycle would be 0.825 pounds of mercury. Some facilities operate a carbon adsorption filter between the condenser and the vacuum pump. The cooled gas downstream of the condenser is expected to allow 95 per cent removal efficiency for a properly maintained carbon adsorption filter, resulting in a treated mercury discharge rate of:

Mercury Discharge (lbs/hr) = Charge Weight (lbs) x Mercury Fraction x 0.0055 x 0.05

For the example mass and composition retort charge considered above, this would result in a batch emission amount of 0.04 pounds of mercury.

2.6 Dore Furnaces

After the ore has been removed from the retort, it is melted in a refinery furnace to produce a commercial mixture of gold and silver known as dore. The gold is heated to approximately 1,500^{o}C with a flux material that preferentially absorbs impurities, such as base and metallic metals. Most of the remaining mercury is volatilized in the dore furnace. The dore melt is poured into bars, and any flux slag that hardens on the bars is removed with a mechanical chipper. The cleaned bars are then further processed to produce gold bullion (99.5 percent pure gold). Studies of retort efficiencies have shown that the retorted gold contains 1,000to 8,000 mg/kg mercury. The largest refinery furnaces have a throughput of 5 tons per hour, with most units processing 0.25 to 0.4 tons per hour. The mercury emission rate for dore furnaces is derived as follows:

Mercury Discharge (lbs/hr) = Charge Rate (pounds/hr) x 0.0045 Mercury content of Feed

For a furnace feed rate of 600 pounds per hour, the mercury emission rate is 2.7 pounds per hour. Because the furnace melt contains gold, silver and mercury in their metallic forms, the mercury emitted will be present as metallic mercury. Because current controls on the furnaces are particulate controls such as baghouses and wet scrubbers, little control of the mercury emissions is expected. Most furnaces heat the dore by electrical induction. Because there is no combustion process associated with this heating method, relatively low volumes of fume gas are collected by the exhaust system for the furnaces. These gas streams could be cooled and treated by carbon adsorption filters, with an expected mercury removal efficiency of 90 per cent or greater. It should also be noted that the melting and refining of gold and silver mixtures that have not been retorted may result in higher emission rates than presented in this analyses. Site-specific information on the compostion of furnace feed materials would be needed to estimate emission rates for these conditions. Furnace emissions with carbon filter controls have emission rates estimated by:

Hg Emission Rate (lbs/hr) = Charge Rate (pounds/hr) x 0.0045 Hg Content of Feed x 0.1

3.0 Summary and Conclusions

Emissions factors and mass balance evaluations of gold ore processes and control technologies have been estimated based on source testing data, process engineering information on mercury concentrations and behavior in the processes and control technologies, and estimates derived from mercury emissions and controls from other industrial processes with similar emission types. The mercury feed rate for the processes may differ significantly among facilities and at individual sites over the life of a mine because of the variable mercury content of gold ores and the different methods used for ore processing and gold recovery. Gold and mercury have some similarities in their geochemical behavior, and both are associated with mineral districts where gold deposition has occurred through hydrothermal and volcanic processes, including deposits in Nevada, the leading gold producing state, California, and other mineral districts. Lower mercury concentrations are possible in gold ores associated with copper porphyry mineralization and gold deposits that have been subjected to geologic metamorphism (elevated temperature and pressure conditions) after gold deposition. Deposits of these types are found in Washington, Arizona, South Dakota, Montana, Idaho and South Carolina. Development of representative, site-specific emissions factors and mass balance evaluations will require assessment of ore mercury concentration, ore mineral composition, ore treatment methods, and gold extraction and recovery processes.

The emissions factors and control efficiencies for the processes with significant potential for mercury emissions are listed in Table 2. Where site-specific process configurations or mercury concentrations in ore are present, actual emissions may vary significantly from the estimated emissions factors. For example, facilities where gold recovered from electrowinning or zinc precipitation processes is not retorted prior to furnace smelting may have higher emission rates from the refinery furnace than facilities where retorting is used to separate mercury from the furnace feed material. Because gold ore processing and recovery uses physical and chemical processes that also concentrate mercury in its elemental form, most mercury emitted from the individual processes is expected to occur as elemental mercury vapor. Mercury removal by wet chemical scrubbing processes has been shown to be of limited effectiveness for elemental mercury data in extensive speciation and removal efficiency studies performed on coal-fired boiler emissions. Measurement of mercury concentrations in industrial gas streams also presents some difficulties, and individual site evaluations should include mass balance evaluations that measure mercury concentrations in the solid phases (process input and output streams) and treatment residuals (adsorption media and scrubber solutions). Statistical methods should also be employed in the development of sampling and analysis schemes to account for temporal and spatial variability in the mercury concentration in gold ore feedstocks at individual facilities.

Based on the information reviewed for this evaluation, the following aspects of mercury emissions from gold mines should be considered in development of any emissions control and pollution prevention strategies:

- The overall potential for mercury emissions is related to mercury content of ores, and the mercury concentrations in ore may vary on a short-term or long term basis as the ore is excavated and processed.

- Removal efficiencies of mercury control technologies is highly dependent on mercury speciation. Many gold ore processes convert mercury to its elemental form, which exhibits poor recovery in many control technologies.

- Available information indicates that autoclave treatment of gold ores produces much lower mercury emissions than roasting; however, the mercury retained in the solid phase after autoclaving may result in higher emissions in downstream processes, such as carbon regeneration kilns, electrowinning cells and furnaces.

- The site-specific configuration of processes may have a large impact on emissions from an individual process. For example, gold recovered by electrowinning or zinc precipitation that is not retorted prior to smelting may result in higher mercury emissions at the smelter furnace.

- Control technologies that reduce air emissions may transfer mercury to other media that require treatment or management, including scrubber solutions, processed tailings and spent adsorption or filtration media. Control techniques that remove mercury as the sulfide compound are most stable, with lower vapor pressure than metallic mercury and lower aqueous solubility than mercury salts. Mecury sulfide should be stable as long as it is not managed in an oxidizing environment in a medium with sufficient sulfide content to produce acid generating conditions.

Table 2. Process Emission Factors and Control Efficiencies

Process Unit	Emission Control	Emissions Factor (lb/hr)	Comments

Ore Roasters	Untreated	(0.8xOre Hg Conc. (lb/ton)) x Ore Feed Rate (ton/hr)	80 percent Hg volatilized
	Quench	(0.8 xOre Hg Conc. (lb/ton)) x Ore Feed Rate (ton/hr) x 0.9	No removal with dry process
	SO_2 Scrubber	(0.8xOre Hg Conc. (lb/ton)) x Ore Feed Rate (ton/hr) x 0.675	Not used where ore sulfide
	Particulate Control	(0.8xOre Hg Conc. (lb/ton)) x Ore Feed Rate (ton/hr) x 0.641	Baghouse, wet or dry ESP,
	Carbon Filter	(0.8xOre Hg Conc. (lb/ton)) x Ore Feed Rate (ton/hr)x0.064	Effective for cooled gas
Autoclaves	Untreated	Ore Hg Conc. (lb/ton) x Ore Feed Rate (ton/hr) x 0.0013	Hg oxidized form
	Venturi/Cyclone	Ore Hg Conc. (lb/ton) x Ore Feed Rate (ton/hr) x 0.0002	Wet Scrubbing effective for
Carbon Regeneration Kilns	Venturi/Cyclone	Kiln Feed Rate (tons/hr) x 2,000 (lbs/ton) x 0.0011	Strip process may offload Hg prior to regeneration
	Carbon Filter	Kiln Feed Rate (tons/hr) x 2,000 (lbs/ton) x 0.0011x0.1	
Electrowinning Units	Untreated	Cathode Area(ft^2) x Hg metal fraction x 0.02(lbs/ft^2/hr)	Hg recovery from solution prior to electrowinning will reduce emissions
	Carbon Filter	Cathode Area(ft^2) x Hg Fractionx0.02(lbs/ft^2/hr)x0.1	Ventilation discharge will be at suitable temperature for carbon filter
Retorts	Condenser	Charge Weight (lbs) x Mercury Fractionx0.0055	Loss rate from condenser assumes covered collection container for liquid Hg
	Carbon Filter	Charge Weight (lbs) x Mercury Fraction x 0.0055 x 0.05	Effective for gas flow rate and
Dore Furnaces	Particulate Control	Charge Rate (lbs/hr) x 0.0045 Hg content of Feed	
	Carbon Filter	Charge Rate (lbs/hr) x 0.0045 Hg content of Feed x 0.1	Gas may require precooling
	Carbon Filter	Charge Rate (lbs/hr) x 0.0045 Hg content of Feed x 0.1	Gas stream may require

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