AQB BACT ANALYSIS

PSD3449-M5 Hobbs Generating Station

PSD applicability:

The original application based the proposed project annual emissions on increases due to the turbine upgrade and increase in operating hours from 8400 hours per year to 8760 hours per year. That PSD applicability analysis showed that the PSD Significant Emission Rates (SER) were exceeded only for particulate emissions (TSP/PM10/PM2.5) and CO2e. However, the 8400 operating hours limit per year was included in permit PSD3449-M2 issued 9-5-2014 to maintain emissions below the PSD Significant Emission Rates (SER) for the project authorized under PSD3449-M2. Relaxing the operating hours restriction therefore triggered a retroactive PSD applicability determination under 20.2.74.300.D NMAC, which states: "If a source or modification becomes a major stationary source or major modification solely due to a relaxation in any enforceable limitation (which limitation was established after August 7, 1980), on the capacity of the source or modification otherwise to emit a pollutant, such as a restriction on hours of operation, then this part shall apply to the source or modification as though construction had not yet commenced."

The retroactive PSD applicability assumed that the 2014 project did not include the operating hours restriction. Without that restriction, the 2014 project would have triggered a BACT review for NOx and SO2 as well as for particulate emissions (TSP/PM10/PM2.5) and CO2e. The applicant submitted a revised BACT that reassessed the BACT for NOX, SO2, particulate emissions (TSP/PM10/PM2.5), and CO2e. The BACT analysis is only for the turbines (HOBB-1 and HOBB-2) and duct burners (DB-1 and DB-2) because these are the only units included in both those projects.

BACT Review Summary

Pollutant	Existing BACT	Proposed BACT	Emission limit
NOx	Dry low NOx burners (turbine)	Dry low NOx burners (turbine)	2.0 ppmvd@15% O2 during normal operations, 96 ppmvd@15% O2 during SSM
	Low NOx burners (duct burner)	Low NOx burners (duct burner)	
	Selective catalytic Reduction	Selective catalytic Reduction	
SO2	Pipeline quality natural gas	Pipeline quality natural gas	none
	Good combustion practices	Good combustion practices	
TSP/PM10/PM2.5	Pipeline quality natural gas	Pipeline quality natural gas	0.0089 lb/MMBtu w/ duct burner, 0.0071 lb/MMBtu w/o duct burners
	Good combustion practices	Good combustion practices	
CO2e	Combined cycle power generation in 2X1 or 1X1 conformation	Combined cycle power generation in 2X1 or 1X1 conformation	none
	Pipeline quality natural gas	Pipeline quality natural gas	

	Efficient turbine and HRSG design and operation practices	Efficient turbine and HRSG design and operation practices	
	Fuel flow meter calibration (40 CFR 75)	Fuel flow meter calibration (40 CFR 75)	

The proposed BACTs for these pollutants match the existing BACTs. AQB reviewed the sources for the proposed BACTs. The California Air Resources Board guidance for Power plant siting was issued in 1999 and updated in 2008, but a 2017 guidance document on NOx limits (Powers Engineering, San Diego, CA) supports similar (2.5 ppm) limits and technology. No alternative technologies to pipeline quality natural gas and combustion practices as BACT for SO2 and particulates were identified. The AQB concluded that the existing BACTs should be retained as the BACTs for these pollutants for these units. The applicant's BACT analysis is attached to this document to show the technologies and sources reviewed.

Lea Power Partners, LLC

Hobbs Generating Station
BACT Analysis

Major Modification to PSD Permit 3449-M4

REV. September 28, 2018

Prepared for:

Lea Power Partners, LLC
98 N. Twombly Lane
Hobbs, NM 88240

Prepared by:

Alliant Environmental, LLC
7804 Pan American Fwy. NE
Albuquerque, NM 87109

Lea Power Partners, LLC
Hobbs Generating Facility F4+ GT Compressor Upgrade
BACT Analysis

INTRODUCTION

Lea Power Partners, LLC (LPP) is the owner of Hobbs Generating Station (HGS) located eight miles west of Hobbs, New Mexico. The facility consists of two natural gas fired Mitsubishi Model M501F gas turbines in a 2x1 configuration with Heat Recovery Steam Generators (HRSGs), Forney duct burners, and a GE D-11 steam turbine. LPP steam is condensed using a 35 cell SPX Air Cooled Condenser and has a maximum net capacity of 604MW.

The site holds both a New Source Review (NSR)/Prevention of Significant Deterioration (PSD) and a Federal Title V Operating permit in the State of New Mexico: PSD3449-M4 and P244-R1/P244-AR2. Emissions for each unit are controlled using carbon monoxide (CO) catalyst and Selective Catalytic Reduction (SCR) with injection of 28% aqueous ammonia.

Mitsubishi Hitachi Power System Americas (MHPSA) proposes to upgrade the two combustion turbines to the F4+ compressor upgrade. The upgrade consists of replacing the Inlet Guide Vanes (IGVs) and first six stages of the compressor, resulting in increased air flow. The expected impact of the upgrade on performance is an increase of 5% in output, no change in heat rate, and a 6.7% increase in turbine exhaust flow.

BACKGROUND

The subject units are three-pressure level reheat HRSG's originally designed for NEPCO in 2000 and then moved to the Hobbs site in 2007. The site consists of two triangular pitch, dual train, outdoor HRSGs. Combustion turbines are Mitsubishi 501F machines fueled by natural gas. The HRSG's supply steam to a single steam turbine and operate in floating pressure mode based on steam turbine conditions.

Each HRSG is triple pressure level with reheat, natural circulation, and equipped with auxiliary heat input via a Forney Corporation duct burner. The duct burner system is located between the secondary and primary stages of superheater and reheater heat transfer sections. The HRSG has been designed for duct firing with gas turbine near full load operation. The heat transfer sections are composed of extended surface, triangular pitched, finned tubes.

PROPOSED PROJECT REVIEW

The proposed project at LPP allows for an upgrade to both combustion turbine generators (CTGs), which is expected to increase power output by approximately 5% and increase the turbine flow rate by 6.7%. This change is expected to result in an increase in fuel consumption, exhaust flow rate, and temperature. The F4+ upgrade project is a completely stand-alone project, not tied in any way to previous projects that required a permit modification, including the permit modifications dated 9-23-2011 and 9-5-2014. It is our understanding that this compressor upgrade package has only been made available for commercial use by MHPSA since 2017.

Due to the increased exhaust flow rate, short term (lb/hr) and/or long term (tpy) emission rates for oxides of nitrogen (NO_x), carbon monoxide (CO), sulfur dioxide (SO_2), volatile organic compounds (VOC), particulate matter (PM_{10} and $PM_{2.5}$), sulfuric acid mist (H_2SO_4 mist), and carbon dioxide equivalent (CO_2e) will increase. However, a review of anticipated emission rate changes shows that the currently permitted short term emission rates for NO_2 and CO will not have to be changed or increased. Stack exhaust NO_x emissions will continue to be controlled to 2 parts per million volume dry basis corrected to 15 percent oxygen (ppmvdc) on a 24-hour average basis, using selective catalytic reduction (SCR) with aqueous ammonia (NH_3). Stack exhaust CO and VOC emissions will continue to be controlled to 2 ppmvdc on a 1-hour average basis and to 1 ppmvdc on a 24-hour average basis, respectively, by means of oxidation catalyst. SO_2 emissions will continue to be controlled using pipeline quality natural gas.

Hobbs, NM is located in Lea County, an area that is classified by the US EPA as in attainment with the National Ambient Air Quality Standards (NAAQS) for all regulated pollutants. The facility is included as one of the 28-named sources under PSD rules and is a major source as defined by the PSD rules under 40 CFR §52.21. The estimated annual emission rate increases and PSD applicability analysis for the proposed compressor upgrade project are summarized in Table 1 below.

Table 1: PSD Applicability Analysis Both Units Combined Proposed Project

Pollutant	Past Actuals (tpy)	Proposed Project Annual w/o SSM (tpy)	Proposed Project Increase (tpy)	PSD SER (tpy)	PSD Review Required?
NO_x	89.9	124.9	35.0	40	No
CO	9.5	76.0	66.5	100	No
VOC	3.9	13.1	9.2	40	No
SO_2	17.2	50.7	33.5	40	No
H_2SO_4 (mist)	2.6	7.77	5.1	7	No
TSP/PM_{10}	48.6	90.5	46.5	15	Yes
$PM_{2.5}$	48.6	90.5	46.5	10	Yes
CO_2e	1,604,421	1,985,998	381,577	75,000	Yes

In addition, LPP is proposing to relax the current federally enforceable operational limits of 8400 hrs/yr operation to 8760 hrs/yr operation. This triggers a retro-active PSD applicability review back to the year 2014, when the operational limits were imposed. Table 2 below shows which pollutants would have triggered a PSD review if no operational limits were imposed. Therefore, in addition to the pollutants already identified in Table 1 above, NO_x and SO_2 are included (retro-actively) in the BACT determination for this permitting action.

Table 2: PSD Applicability Analysis Both Units Retro-Active for 2014 Project

Pollutant	Past Actuals (tpy)	Proposed Project Annual (tpy)	Proposed Project Increase (tpy)	PSD SER (tpy)	PSD Review Required?
NO_x	77.0	120.0	43.0	40	Yes
CO	10.7	73.1	62.4	100	No
VOC	8.8	12.6	3.8	40	No
SO_2	6.7	48.3	41.6	40	Yes
H_2SO_4 (mist)	1.03	7.4	6.4	7	No
TSP/PM_{10}	72.2	85.8	13.6	15	No
$PM_{2.5}$	72.2	85.8	13.6	10	Yes
CO_2e	1,385,260	1,891,328	506,068	75,000	Yes

Since no emission rate decreases occurred during the contemporaneous periods (current or back in 2014), the net emission rate increases are based on the proposed project emission rate increases. The PSD Significant Emission Rate (SER) is exceeded for NO_x, SO_2, TSP/PM_{10}/$PM_{2.5}$ and CO_2e. Therefore, this modification constitutes a major modification of the existing major source and a PSD review is required for the pollutants with significant emissions per 40 CFR §52.21(b)(23)(i) and New Mexico Administrative Code (NMAC) 20.2.74.302. The main reason why a PSD review for NO_x, SO_2, TSP/PM_{10}/$PM_{2.5}$ and CO_2e is being triggered, is because the actual emissions from the past five (5) years are much lower than the permitted emission rates, thus the delta between the post-project allowable and the pre-project actual emission rates are greater than the SER.

PSD regulations call for Best Available Control Technology (BACT) to be used to minimize emissions of pollutants subject to PSD review from a major modification of an existing major source. BACT must be applied to each modified emission unit for the pollutants subject to PSD review and is determined on a case-by-case basis taking into consideration technical feasibility, environmental, economic, and energy impacts.

A BACT analysis is based on "top to bottom" approach as recommended by the US EPA. Five steps are evaluated as follows:

- Step 1: Identify all available control technologies
- Step 2: Eliminate options that are not technically feasible
- Step 3: Rank the remaining control technologies
- Step 4: Evaluate the most effective control technologies
- Step 5: Select BACT

The identification of control technologies is performed through knowledge of the industry and specific facility and previous regulatory requirements for identical or similar sources. A search of EPA's Reasonable Available Control Technology (RACT), BACT, and Lowest Achievable Emission

Rate (LAER) Clearinghouse database, the California Air Resources Board Guidance for Power plant Siting and BACT, and the South Coast Air Quality Management District LAER/BACT Guidelines was performed for natural gas fired combined cycle units. Infeasible alternatives were eliminated and the remaining alternatives are ranked beginning with the most stringent control and creating a control technology grading summary. These technologies were then evaluated for their environmental, energy and economic impact. If the top ranked technology was deemed not achievable, this step was repeated for the remaining, lower ranked control technologies.

It is predicted that the current permitted BACT will continue to be considered BACT after this compressor upgrade. The following BACT analysis for NO_x, CO, VOC, TSP/PM_{10}/$PM_{2.5}$ and CO_2e for this proposed upgrade of the two combustion turbines to the F4+ compressor upgrade was evaluated:

Table 2: Summary of BACT Control Methods for Hobbs CTGs/HRSG Duct Burners

Pollutant	**Proposed BACT**
NO_x	Dry low NO_x burners for the CTGs. Low NO_x burners for the duct burners. SCR
SO_2	Pipeline quality natural gas only. Good combustion practices.
TSP/PM_{10}/$PM_{2.5}$	Use of pipeline quality natural gas only. Follow good combustion practices.
CO_2e	Combined cycle power generation technology. Use of pipeline quality natural gas only. 2x1 configuration with 1x1 and simple cycle options. Efficient CTGs design and practices. Efficient HRSG design and practices. Fuel Flow meter calibration according to 40 CFR 75.

BACT ANALYSIS FOR NO_x

NO_x emissions from turbines and duct burners are the result of either the combination of elemental nitrogen and oxygen in air within the combustion device (thermal NO_x), or the oxidation of the nitrogen contained in the fuel (fuel NO_x). Pipeline quality natural gas fuel does not contain a significant amount of nitrogen; therefore, most of the NO_x emissions from the turbines and the duct burners are the result of thermal NO_x.

Step 1: Identify all available control technologies:

Per the current EPA RACT/BACT/LAER Clearinghouse database, the California Air Resources Board Guidance for Power plant Siting and BACT, and the South Coast Air Quality Management

District LAER/BACT Guidelines, the following are control technologies in order of increased efficiency.

Good Combustion Practices

Suppression of thermal NO_x formation in combustion sources is commercially demonstrated through the adjustment of the air-fuel ratio, combustion air temperature, and combustion zone cooling. Adjustments of these parameters may be accomplished through water injection or dry control technology.

Steam/Water Injection

To reduce combustion temperature, steam or water can be mixed with the air flow. This lowers combustion temperature to below 1,400 F, limiting thermal NO_x generation. However, this technique has the disadvantage of potentially increasing the concentration of CO and unburned hydrocarbons emitted from the turbine.

Low NOx Burners

Low NO_x burners allow for a reduced oxygen level, in comparison to ambient air (approximately 10% versus 21%), resulting in peak flame temperatures less than 3,000 degrees Fahrenheit, and therefore reduce the generation of thermal NO_x.

Lean Pre-Mix, Dry Low NO_x (DLN) Combustion

DLN combustors and pre-mixing fuel and air, minimize flame temperature and therefore the generation of thermal NOx.

XONON

This technology is designed to avoid the high temperatures created in conventional combustors. The XONON combustor operates below 2,700°F at full power generation, which significantly reduces NO_x emissions without raising, and possibly even lowering, emissions of CO and unburned hydrocarbons. XONON uses a proprietary flameless process in which fuel and air react on the surface of a catalyst in the turbine combustor to produce energy in the form of hot gases, which drive the turbine.

EMx ($SCONO_x$)

The EMx (SCONOx) system is based on a multi-pollutant reducing platinum catalyst bed coated with potassium carbonate. The catalyst is designed to reduce NO_x, CO and VOC emissions and is situated downstream of the combustion chamber in a separate reactor vessel and operates in an ideal temperature window of 280 °F to 750 °F. The EMx system does not require a reactant. The $SCONO_x$ catalyst is very susceptible to fouling by sulfur in the flue gas. These catalysts have high frequency maintenance requirements (recoating or washing must be done every 6 months to a year depending on the gas sulfur content).

Selective Catalytic Reduction (SCR)

Ammonia is injected from the SCR system into the turbine and duct burner exhaust gases upstream of a catalyst bed. On the catalyst surface, ammonia reacts with NO_x to form nitrogen and water. Optimal NO_x reduction occurs at catalyst bed temperatures between 575 and 750 degrees Fahrenheit for conventional (typically vanadium or titanium-based) catalyst types. The NO_x removal efficiency depends on the flue gas temperature, amount of catalyst, and the NH_3 to NO_x ratio in the flue gas stream. According to the RBLC database, recent permits have been issued at NO_x emission rates as low as 2.0 ppmvdc, 24-hour average, using SCR technology on natural gas fired combined cycle turbines, with ammonia slip levels in the neighborhood of 7 ppmvdc.

Step 2: Eliminate options that are not technically feasible:

The only options considered to be technically infeasible are XONON and EMx (SCONOx). These technologies have limited commercial validation and have only been applied to commercially to small 1.5 MW Kawasaki M1A-13A gas turbine. Both technologies claim a NO_x exhaust concentration of 2.5 ppmvdc. The scalability and reliability of these technologies remains to be proven. Therefore, due to the differences in the size and the lack of sufficient commercial applications, these options were deemed to be undemonstrated for the proposed facility and technically infeasible.

Step 3: Rank the remaining control technologies:

Technically feasible technologies are therefore, in order of increasingly efficiency, good combustion practices, steam or water injection, low NO_x burners, DLN combustors and SCR. According to the data from the California Air Resources Board Guidance for Power plant Siting and BACT, the combination of good combustion practices and DLN combustors can achieve NO_x exhaust concentrations of 9 ppmvdc. The combination of low NO_x burners and SCR can achieve NO_x exhaust concentrations of 3.5 ppmvdc. The top level control is considered to be the combination of good combustion practices, use of pre-mix DLN combustion, use of low NO_x burners and SCR, shown to achieve NO_x exhaust concentrations of 2 ppmvdc.

Step 4: Evaluate the most effective control technologies:

The most effective control technology listed for units comparable to those at the proposed project is good combustion practices combined with the use of pre-mix DLN combustion, low NO_x burners, and SCR catalyst. These technologies are commonly employed and consistently meet concentration limits in the range of 2 ppmvdc to 2.5ppmvdc. The technologies are robust and proven.

Step 5: Select BACT:

The Hobbs combined cycle units were equipped since construction with SCR in combination with DLN combustors and low NO_x burners to achieve a NO_x emission rate of 2.0 ppmvdc at 15% oxygen over a 24-hour averaging period. These control technologies have been commonly applied as BACT in recent permitting activities [e.g., New Covert Generating Company, LLC (MI), Apex Texas Power, LLC (TX), and CPV Fairview, LLC (PA)]. The California Air Resources Board Guidance for Power Plant Siting and BACT recommends BACT for NO_x emissions from combined-cycle and cogeneration gas turbines be 2.5 ppmvdc at 15 percent oxygen.

BACT ANALYSIS FOR SO_2

Sulfur dioxide (SO_2) emissions from combustion turbines and duct burners are the result of sulfur compounds contained in the combustion fuel. Total sulfur content in pipeline quality natural gas is inherently low; therefore significantly reducing the amount of SO_2 emissions generated in combustion sources

Step 1: Identify all available control technologies:

Per the current EPA RACT/BACT/LAER Clearinghouse database, the California Air Resources Board Guidance for Power plant Siting and BACT, and the South Coast Air Quality Management District LAER/BACT Guidelines, the following are control technologies in order of increased efficiency.

Good Combustion Practices

Good combustion practices refer to design and operational practices that promote the complete combustion of fuel, leading to lower SO_2 emissions, such as (1) efficient tuning of the air-to-fuel ratio in the combustion zone to allow minimal generation of unburned carbon; (2) proper combustor design that promotes air/fuel mixing and longer combustion chamber residence times, adequate temperature and turbulence; and (3) diligent maintenance and operation according to manufacturer's specifications.

Use of Clean Fuel

Use of natural gas, pipeline quality natural gas, and California Public Utility Commission (PUC) quality natural gas that contain very low amounts of sulfur compounds.

Note:
PUC quality natural gas is any gaseous fuel, gas-containing fuel where the sulfur content is no more than 0.25 grain of hydrogen sulfide per 100 standard cubic feet and no more than 5 grains of total sulfur per 100 standard cubic feet. PUC quality natural gas also means high methane gas of at least 80% methane by volume.)

Step 2: Eliminate options that are not technically feasible:

None of the identified control technology options are technically infeasible.

Step 3: Rank the remaining control technologies:

The top level control is considered to be the combination of good combustion practices and the use of clean fuel.

Step 4: Evaluate the most effective control technologies:

Good combustion practices and use of clean fuels represent the only demonstrated SO_2 control technology for combustion turbines and duct burners firing natural gas. There is no economic penalty associated with these approaches. Good combustion practices and use of clean fuels are employed on combustion turbines throughout the US.

Step 5: Select BACT:

The Hobbs combined cycle units exclusively fire pipeline quality natural gas and will maintain good combustion practices. This fuel type as an SO_2 control technology has been commonly used as BACT in more recent permitting activities [e.g., New Covert Generating Company, LLC (MI), Marshall Energy Center, LLC (MI), and Entergy Texas, Inc. (TX)].

BACT ANALYSIS FOR TSP/PM_{10}/$PM_{2.5}$

Particulate emissions from the turbines and duct burners result primarily from inert solids contained in the fuel, combustion air and water (when water injection is used), and from sulfur compounds and unburned fuel hydrocarbons that agglomerate to form particles. These particles pass through the system and are emitted with the exhaust gas. All particulates emitted by the turbines and duct burners are fine particulate, and essentially all will be less than 2.5 microns in size.

Particulate emissions from gas turbines and duct burners are inherently low when using clean fuels, such as pipeline grade natural gas. In addition, turbines are designed and operated to combust the fuel as completely as possible in order to attain the highest possible thermal efficiency, which maintains particulates at very low levels.

Step 1: Identify all available control technologies:

Per the current EPA RACT/BACT/LAER Clearinghouse database, the California Air Resources Board Guidance for Power plant Siting and BACT, and the South Coast Air Quality Management District LAER/BACT Guidelines, the following are control technologies in order of increased efficiency.

Baghouse/Fabric Filter/Scrubbers

Process exhaust gas passes through a tightly woven or felted fabric arranged in sheets, cartridges, or bags that collect PM via sieving and other mechanisms. The dust cake that accumulates on the filters decreases collection efficiency. Various cleaning techniques include pulse-jet, reverse air flow, and shaker technologies. Operating conditions include: up to 500 ^{o}F (typical); inlet flows of 100 to 100,000 scfm (typical), 100,000 to 1,000,000 scfm (custom); inlet PM concentrations of 0.5 to 10 gr/dscf (typical), 0.05 to 100 gr/dscf (achievable).

This control option is not included in the current EPA RACT/BACT/LAER Clearinghouse database for the control of PM emissions from natural gas-fired combustion turbines. Fabric filters are susceptible to corrosion and blinding by moisture. Appropriate fabrics must be selected for specific process conditions. Natural gas-fired combustion turbines generate low PM emissions and have large flow rates, resulting in very low concentrations of PM. Add-on control devices would not provide any measurable PM emission reduction; therefore, this control technology is deemed not technically feasible. For reference, see attached document “US EPA, Office of Air Quality Planning and Standards, “Air Pollution Control Technology Fact Sheet (Fabric Filter – Pulse-Jet Cleaned Type)”, EPA-452/F-03-025 and (Fabric Filter – Reverse Air Cleaned Type)”, EPA-452/F-03-026.

Electrostatic Precipitators (ESP)

Electrodes stimulate the waste gas and induce an electrical charge in the entrained particles. The resulting electrical field forces char particles to collector walls from which the material may be mechanically dislodged and collected in dry systems or washed with water deluge in wet systems. Operating conditions include: up to 1,300 ^{o}F (dry), lower than 170 to 190 ^{o}F (wet); inlet flow o f1,000 to 100,000 scfm (wire-pipe), 100,000 to 1,000,000 scfm (wire-plate); inlet PM concentration 0.5 to 5 gr/dscf (wire-pipe), 1 to 50 gr/dscf (wire-plate).

Dry ESP efficiency varies significantly with dust resistivity. Air leakage and acid condensation may cause corrosion. This control option is not included in the current EPA RACT/BACT/LAER Clearinghouse database for the control of PM emissions from natural gas-fired combustion turbines. Natural gas-fired combustion turbines generate low PM emissions and have large flow rates, resulting in very low concentrations of PM. Add-on control devices would not provide any measurable PM emission reduction; therefore, this control technology is deemed not technically feasible. For reference, see attached document “US EPA, Office of Air Quality Planning and Standards, “Air Pollution Control Technology Fact Sheet (Dry Electrostatic Precipitator – Wire-Pipe Type)”, EPA-452/F-03-027, “Air Pollution Control Technology Fact Sheet (Dry Electrostatic Precipitator – Wire-Plate Type)”, EPA-452/F-03-028, and “Air Pollution Control Technology Fact Sheet (Dry Electrostatic Precipitator – Wire-Pipe Type)”, EPA-452/F-03-029.

Cyclones/Mini-Cyclones

Centrifugal forces drive particles in the gas stream toward the cyclone walls as waste gas flows through the conical unit. The captured particles are collected in a material hopper below the unit. Operating conditions include: up to 1,000 ^{o}F; inlet flow of 1.1 to 63,500 scfm (single) and up to 106,000 scfm (in parallel); inlet PM concentrations of 0.44 to 7,000 gr/dscf.

Cyclones exhibit lower efficiencies when collecting smaller particles, High-efficiency units may require substantial pressure drop. This control option is not included in the current EPA RACT/BACT/LAER Clearinghouse database for the control of PM emissions from natural gas-fired combustion turbines. Natural gas-fired combustion turbines generate low PM emissions and have large flow rates, resulting in very low concentrations of PM. Add-on control devices would not provide any measurable PM emission reduction; therefore, this control technology is deemed not technically feasible. For reference, see attached document "US EPA, Office of Air Quality Planning and Standards, "Air Pollution Control Technology Fact Sheet (Cyclones)", EPA-452/F-03-005.

Good Combustion Practices:

Good combustion practices refer to design and operational practices that promote the complete combustion of the fuel, leading to lower particulate emissions, such as (1) efficient tuning of the air-to-fuel ratio in the combustion zone to allow minimal generation of unburned carbon; (2) proper combustor design that promotes air/fuel mixing and longer combustion chamber residence times, adequate temperature and turbulence; and (3) diligent maintenance and operation according to manufacturer's specifications.

Use of Clean Fuel:

Use of natural gas, pipeline quality natural gas, and California Public Utility Commission (PUC) quality natural gas that contain very low amounts of sulfur compounds (sulfur content is below 0.25 grain of hydrogen sulfide per 100 standard cubic feet and no more than 5 grains of total sulfur per 100 standard cubic feet, and a minimum of 80% methane by volume).

Step 2: Eliminate options that are not technically feasible:

Baghouses/Filters, Electrostatic Precipitators, and Cyclones are not deemed technical feasible control technologies.

Step 3: Rank the remaining control technologies:

The top level control is considered to be the combination of good combustion practices and the use of clean fuel.

Step 4: Evaluate the most effective control technologies:

Good combustion practices and use of clean fuels represent the only demonstrated particulate control technology for turbines and duct burners firing gaseous fuels. There is no economic penalty associated with these approaches. Good combustion practices and use of clean fuels are employed on combustion turbines throughout the US.

Step 5: Select BACT:

LPP's combined cycle units exclusively fire pipeline quality natural gas and will maintain good combustion practices. This fuel type, as a control technology, has been commonly used as BACT in recent permitting activities (e.g., Entergy Louisiana, LLC St. Charles Power Station (PSD-LA-804_8/31/2016); Southwestern Public Service Company, Gaines County, TX Power Plant (PSD-TX-1470_4/28/2017); Filler City Station LP, Filler City Station (MI-66-17_11/17/2017); Apex Texas Power LLC, Neches Station (PSD-TX-1428_3/24/2016; Decordova II Power Company LLC, Decordova Steam Electric Station (PSD-TX-1432_3/8/2016)).

In addition, attached are statements from the turbine manufacturer and vendor discussing that no other commercially available post combustion PM control technologies exist for these natural gas fired units. In addition, Mitsubishi Hitachi Power System Americas also provided more detailed good combustion practices and design information.

BACT ANALYSIS FOR CO_2e

The combustion of methane and other minor hydrocarbon constituents of the natural gas in the CTGs and duct burners will result in the generation of greenhouse gases (GHG) including carbon dioxide (CO_2) and small quantities of methane (CH_4) and nitrous oxide (N_2O).

Step 1: Identify all available control technologies:

In order of efficiency, the available GHG control technologies listed for natural gas fired combined cycle units in the current EPA RACT/BACT/LAER Clearinghouse database, the California Air Resources Board Guidance for Power plant Siting and BACT, and the South Coast Air Quality Management District LAER/BACT Guidelines include the following technically feasible options for GHG emission mitigation:

- **Use of combined cycle power generation technology:**

  The most efficient way to generate electricity from a natural gas fuel source is the use of a combined cycle design, in which the HRSG is used to recover waste heat that would otherwise be lost to the atmosphere in the turbine exhaust. The recovered heat and produced steam allows generation of additional electric power by a steam turbine. The overall efficiency may be increased from about 30% for a simple cycle (no heat recovery) unit to about 50% for a combined cycle unit.

- **Use of multiple trains combined cycle units:**

  Combustion turbine efficiency is highest at full design load. The use of multiple trains (e.g. 2x1 configurations) allows one or more trains to be shut down while the remaining unit(s) operate(s) at or near full load, where maximum efficiency is achieved, rather than operating a single unit at lower, less efficient loads to meet market demand. Due to the variability of electricity demand, this flexibility helps maintain operational efficiency.

- **Use of natural gas:**

  Natural gas has the lowest carbon intensity among available fossil fuels. According to the comprehensive analysis by the Center of Climate and Energy Solutions “Leveraging Natural Gas to Reduce Greenhouse Gas Emissions”, June 2013, https://www.c2es.org/document/leveraging-natural-gas-to-reduce-greenhouse-gas-emissions/ on average, natural gas combustion releases approximately 50 percent less CO_2 than coal and 33 percent less CO_2 than oil (per unit of useful energy). Therefore, the burning of natural gas only will reduce the carbon footprint when compared to other fossil fuels available.

- **Gas combustion turbine design:**

  State-of-the-art combustion turbines operate at high temperatures due to the heat of compression and the thermal heat of combustion. The higher the operating temperature, the higher the turbine efficiency. To minimize the heat loss from the combustion turbines and protect the personnel and equipment around the units, insulation blankets are applied to the combustion turbine casing. These blankets minimize the heat loss through the combustion turbine shell. Improved design elements (e.g., two-bearing, axial exhaust, cold-end drive designs, etc.) have significantly increased overall combustion efficiency.

- **Fuel Pre-Heating:**

  Thermal efficiency of the turbine can be increased by pre-heating the fuel prior to combustion. This is usually accomplished by heat exchange using steam from the HRSG or hot CTGs compressor bleed air.

- **Inlet evaporative cooling or chillers:**

  Use of inlet evaporative coolers or chillers reduces the inlet air temperature, during high ambient temperature conditions, increasing the air density and hence the mass flow through the combustion turbine increases. As the mass flow through the combustion turbine increases, more power is generated, which increases the turbine efficiency.

- **Periodic maintenance and burner tuning:**

  Regularly scheduled maintenance programs are important for the reliable operation of the unit, as well as to maintain optimal efficiency. A periodic maintenance program consisting of inspection and cleaning of key equipment components and tuning of the combustion system will minimize performance degradation and recover thermal efficiency to the maximum extent possible.

- **Instrumentation and control systems:**

  State-of-the-art combustion turbines have sophisticated instrumentation and control systems to automatically control the operation of the combustion turbine, including the fuel feed and burner operations to achieve low-NOx combustion. The control systems monitor the operation of the unit and modulate the fuel flow and turbine operation to achieve optimal high-efficiency low-emission performance for full load and part load conditions.

- **Minimizing HRSG heat transfer surfaces fouling:**

  Fouling of interior and exterior surfaces of the HRSG heat exchanger tubes hinders the transfer of heat from the combustion turbine hot exhaust gases to the boiler feed water. This fouling occurs from contaminants in the turbine inlet air and in the feed water. Fouling is minimized by turbine inlet air filtration, maintaining proper feed water chemistry, and periodic maintenance, including cleaning the tube surfaces as needed during scheduled equipment outages. By reducing the fouling, the efficiency of the unit is maintained.

- **Steam turbine design:**

  State-of-the-art steam turbines are designed to be highly efficient units. The overall efficiency of the unit is primarily affected by the inlet and outlet steam conditions, the blade ring design, the steam turbine seals and the generator efficiency. New unit designs achieve higher overall performance, reducing startup times significantly and consequently increasing the efficiency of the combined cycle unit as a whole.

- **Periodic steam turbine maintenance:**

Regularly scheduled maintenance programs are important for the reliable operation of the unit, as well as to maintain optimal efficiency. A periodic maintenance program consisting of inspection and cleaning will minimize performance degradation and maintain optimal use of the steam that is delivered from the HRSG.

- **Add-On Controls:**

  CO_2 Capture, Utilization, and Sequestration (CCUS) is an emerging technology that consists of processes to capture (separate) CO_2 from the combustion exhaust gases and then transport and inject it into geologic formations, such as oil and gas reservoirs, un-minable coal seams, and underground saline formations. CCUS could account for up to 90 percent of the emissions mitigation needed to stabilize and ultimately reduce concentrations of CO_2.

Step 2: Eliminate options that are not technically feasible:

All options identified in Step 1 above, with the exception of CCUS, are considered technically feasible for the existing and currently installed combined cycle units and will continue to be technically feasible after the compressor upgrade.

Although CCUS is a promising technology, in order to enable widespread, safe and effective CCUS, large-scale project studies still need to be completed to demonstrate that the capacity required for the purposes of GHG emissions mitigation at a typical power plant is met. The results from the current EPA RACT/BACT/LAER Clearinghouse database, the California Air Resources Board Guidance for Power plant Siting and BACT, and the South Coast Air Quality Management District LAER/BACT Guidelines show no such technology has yet been used for any large commercial natural gas fired combined cycle plant. Each component of CCUS technology (i.e., capture, transport and storage) is discussed in the following paragraphs.

<u>CO_2 Capture:</u>

CCUS could become a viable emission management option as new CO_2 capture technologies are developed. The growth in gas-fired power generation and the shift from coal to gas also means that CCUS technologies are no longer only applicable to coal-fired application. Such carbon capture technologies for natural gas combustion systems have been developed and proven technical feasible with small commercial applications in the energy sector. However, these technologies, which include amine-based solvent systems to separate CO_2 from natural gas generated flue gases at power plants, are too expensive for large scale commercial applications and the capital and operating costs are too expensive.

According to a US Department of Energy (DOE) report from August 2017 "Carbon Capture Opportunities for Natural Gas Fired Power Systems" commercially available CO_2 capture technologies presented that facilities capturing the highest volumes of CO_2 were all associated with gas streams containing relatively high concentrations of CO_2 (25 to 70 percent) such as natural gas processing operations and synthesis gas production. Capturing CO_2 from more dilute streams, such as those generated from power production is less common:

- CO_2 is present at low pressure (15-25 psia) and dilute concentrations (3-4 percent by volume) from the gas-fired turbine exhaust stream. Therefore, a very high volume of gas must be available to achieve CO_2 mass flow necessary to recover CO_2 at a cost efficiency comparable to an application such as natural gas processing.

- Trace impurities (particulate matter, SO_2, NO_x) in the exhaust gas can degrade sorbents and reduce the effectiveness of certain CO_2 capture processes.

Current industrial processes generally involve gas streams that are much lower volumes than that required for the purposes of GHG emissions mitigation at a typical power plant. Scaling up these existing processes represents a significant technical challenge and a potential barrier to widespread commercial deployment in the near term. No references to natural gas fired power plants the size of Lea Power Partners' using CCUS were identified.

The combustion of natural gas at LPP produces an exhaust gas with a maximum CO_2 concentration of less than five volume percent. This low concentration stream will require that a very high volume of gas be treated so that the CO_2 may be captured effectively. However, the CO_2 capture capacities used in current industrial processes are designed for relatively high CO_2 concentration streams (25 percent or higher). As the growth of natural gas use continues, CCUS for gas- power generation will become an important factor in reducing GHG emissions. But continued research and development is needed in order to apply CCUS technologies for full commercial application.

CO_2 Transport:

Even if it is assumed that CO_2 capture could feasibly be achieved at LPP, the high-volume CO_2 stream generated (>63,000 scf/min of CO_2) would need to be transported to a facility capable of storing it. Figure 1 is a map showing the location of current CO_2 pipelines in the Permian Basin (SE New Mexico and West Texas).

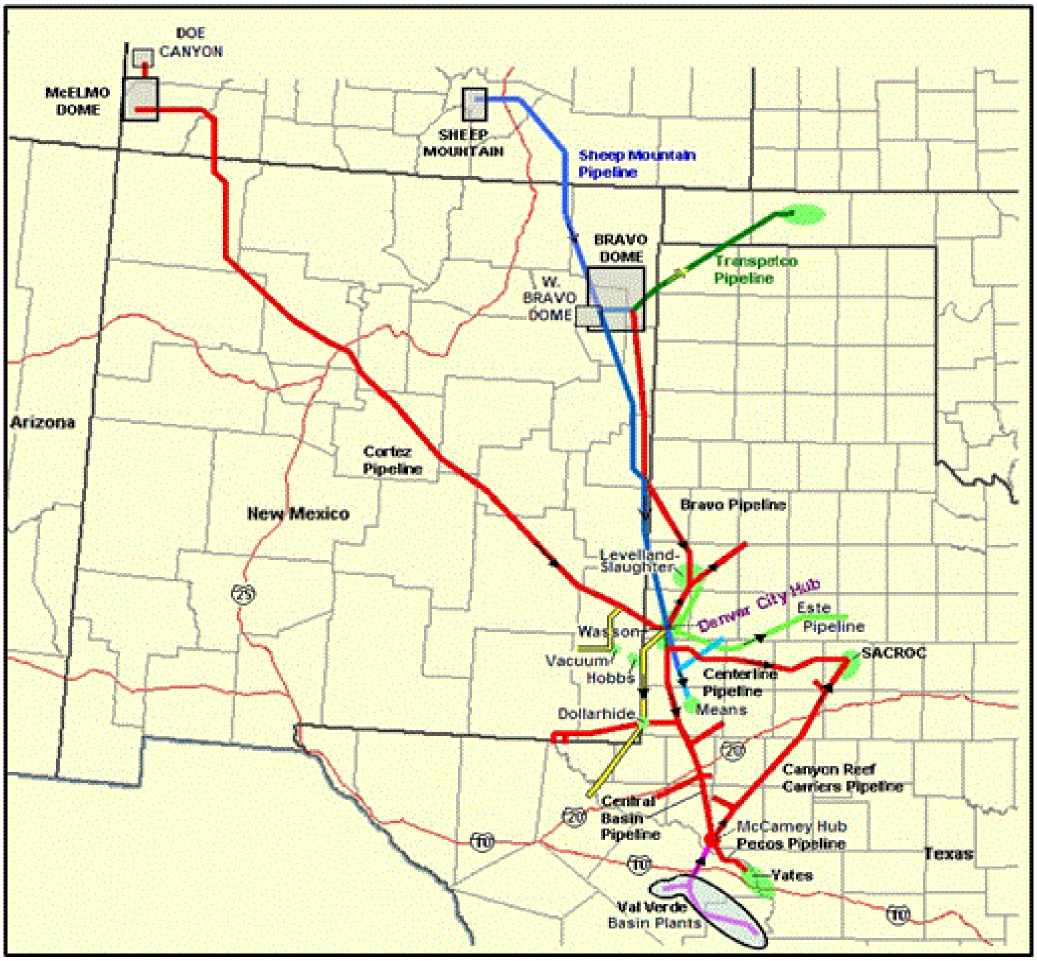
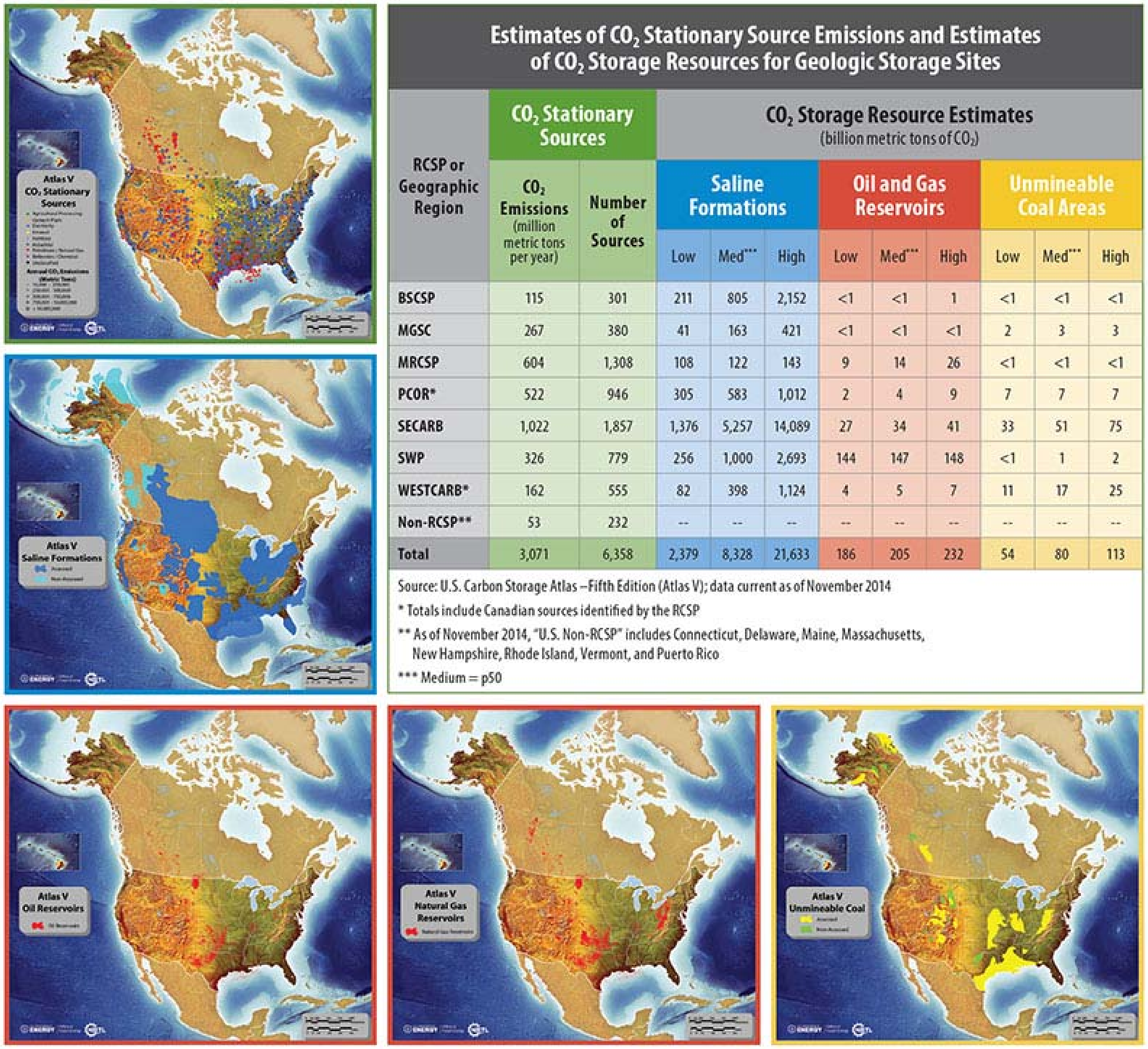


Figure 1: Permian Basin CO_2 Pipeline Infrastructure
[Source: US Department of Energy National Energy Technology Laboratory, Office of Fossil Energy, April 21, 2015]

CO_2 Storage:

As shown on the above map in Figure 1, there are existing pipelines that could potentially transport the CO_2 stream from Hobbs to a storage facility. The largest storage site closest to LPP, with some demonstrated capacity for geological storage of CO_2, is the Scurry Area Canyon Reef Operators (SACROC) oilfield near the eastern edge of the Permian Basin in Scurry County, Texas. This site is over 135 miles away from Hobbs; therefore, a very long and sizable pipeline would be required to transport the large volume of high pressure CO_2 from the plant to the storage facility, which will make CCUS economically infeasible. Several other, much smaller candidate storage reservoirs exist within the Permian Basin; however, none have been confirmed to be viable for large scale CO_2 storage.

Ongoing regional-scale assessments suggest a large resource potential for storage in the United States. According to the DOE's Regional Carbon Sequestration Partnerships (RCSPS) CO_2 storage resources including oil and gas reservoirs, un-minable coal and saline formations in the Southwest Partnership (SWP) area have great potential for large scale CO_2 storage in the future (see Figure 2). The SWP (Southern Wyoming, Utah, Colorado, Kansas, Oklahoma, New Mexico, Arizona, and West Texas) is one of seven regional partnerships established in 2003 by the DOE to study carbon management strategies. Since then, SWP has completed a number of studies.



Estimates of CO_2 Stationary Source Emissions and Estimates of CO_2 Storage Resources for Geologic Storage Sites

RCSP or Geographic Region	CO_2 Stationary Sources		CO_2 Storage Resource Estimates (billion metric tons of CO_2)								
	CO_2 Emissions (million metric tons per year)	Number of Sources	Saline Formations			Oil and Gas Reservoirs			Unmineable Coal Areas		
			Low	Med***	High	Low	Med***	High	Low	Med***	High
BSCSP	115	301	211	805	2,152	<1	<1	1	<1	<1	<1
MGSC	267	380	41	163	421	<1	<1	<1	2	3	3
MRCSP	604	1,308	108	122	143	9	14	26	<1	<1	<1
PCOR*	522	946	305	583	1,012	2	4	9	7	7	7
SECARB	1,022	1,857	1,376	5,257	14,089	27	34	41	33	51	75
SWP	326	779	256	1,000	2,693	144	147	148	<1	1	2
WESTCARB*	162	555	82	398	1,124	4	5	7	11	17	25
Non-RCSP**	53	232	--	--	--	--	--	--	--	--	--
Total	3,071	6,358	2,379	8,328	21,633	186	205	232	54	80	113

Source: U.S. Carbon Storage Atlas – Fifth Edition (Atlas V); data current as of November 2014

* Totals include Canadian sources identified by the RCSP

** As of November 2014, "U.S. Non-RCSP" includes Connecticut, Delaware, Maine, Massachusetts, New Hampshire, Rhode Island, Vermont, and Puerto Rico

*** Medium = p50

Figure 2: Estimates of CO_2 Stationary Source Emissions and Estimates of CO_2 Storage Resources [Source: NETL Carbon Storage Atlas, Fifth Edition (2015)]

According to completed and ongoing studies by the SWP, to enable widespread, safe, and effective CCUS, CO_2 storage should continue to be field-demonstrated for a variety of geologic reservoir classes, with large-scale projects targeted at high-priority reservoir classes and smaller-scale projects covering a wider range of classes that are important regionally.

Small and large-scale field tests in different geological storage classes are being conducted to confirm that CO_2 capture, transportation, and storage can be achieved safely, permanently, and economically. Results from these tests will provide a more thorough understanding of migration and permanent storage of CO_2 within various open and closed depositional systems. The storage types and formations being tested are considered regionally significant and are expected to have the potential to store hundreds of years of CO_2 stationary source emissions.

Accounting that permanent CO_2 storage in geologic formations may not be a viable option for all CO_2 emitters and that this option could result in no environmental benefit at significant cost, the DOE-National Energy Technology Laboratory (NETL) is also researching the development of alternatives that can use captured CO_2 or convert it to a useful product, such as a fuel, chemical, or plastic, with revenue from the CO_2 use offsetting a portion of the CO_2 capture cost.

Based on the reasons provided above, CCUS has only been effectively proven in small scale projects in specific regions, and is therefore considered technically infeasible for this project.

Step 3: Rank the remaining control technologies:

The technically feasible options for GHG emissions mitigation in order of most to least effective include:

- **Use of combined cycle power generation technology;**
- **Use of natural gas;**
- **Instrumentation and control systems;**
- **Gas combustion turbine design;**
- **HRSG design;**
- **Minimizing HRSG heat transfer surfaces fouling;**
- **Inlet evaporative cooling or chillers;**
- **Fuel pre-heating;**
- **Use of multiple trains combined cycle units; and**
- **Periodic maintenance and burner tuning.**

Step 4: Evaluate the most effective control technologies:

All of the technically feasible technologies discussed in Step 1 through Step 3 are being proposed for this project. Therefore, an examination of the energy, environmental, and economic impacts of the efficiency designs is not necessary for this application.

Step 5: Select BACT:

LPP proposes BACT for the combined cycle units the following energy efficiency processes, practices and designs:

- **Use of combined cycle power generation technology;**
- **Use of pipeline quality natural gas only to fire both the CTGs and the HRSG duct burners;**
- **Use of 2x1 configuration, allowing operation with one train full load or two trains full load on demand basis;**
- **Combustion turbines energy efficiency processes, practices and designs, including:**
  - **Efficient design of the turbine compressor, combustor, and blades**
  - **Periodic gas turbine burner tuning, following vendor recommended comprehensive inspection and maintenance programs**

- **Reduction of heat loss**
    - **Instrumentation and controls, including fuel gas flow rate; exhaust gas temperature monitoring; turbine package temperature and pressure monitoring; combustion dynamics monitoring; vibration monitoring; air/fuel ratio monitoring; and HRSG temperature and pressure monitoring**
    - **Inlet chillers**

- **HRSG Energy Efficiency process, Practices, and Designs:**
    - **Efficient heat exchange design**
    - **Insulation of HRSG**
    - **Minimizing fouling of heat exchange surfaces, implementing vendor recommended comprehensive inspection and maintenance program**

- **Calibrate and perform preventive maintenance on the fuel flow meters as required by 40 CFR Part 75, Appendix D, Section 2.1.6 (Quality Assurance)**

Roger Schnabel
Plant Manager, Hobbs
98 North Twombly Lane
Hobbs, NM 88242
Tel: (575) 397-6706
rschnabel@camstex.com

Hobbs – Particulate Matter Controls

Lea Power Partners LLC - Hobbs Generating Station Gas Turbines are equipped with MHPS can-annular dry low NOx combustors. These consist of a pilot nozzle, a main nozzle, and combustor basket to combust natural gas fuel in a lean premix manner to control the formation of nitrogen oxides. The pilot nozzle keeps the flame stable by diffusion combustion using approximately 5% to 7% of the fuel. The remaining fuel is supplied to the main nozzle, which when pre-mixed with air, forms a uniform and low temperature flame. Air enters the pre-mix section in the combustor baskets through turning vanes and metering holes to obtain the proper mixture of air and fuel.

As defined by the US Environmental Protection Agency (EPA) particulate matter (PM) is "a mixture of solid particles and liquid droplets found in the air. Some particles, such as dust, dirt, soot, or smoke, are large or dark enough to be seen with the naked eye. Others are so small they can only be detected using an electron microscope."

Particulate Pollution can be divided into size categories as "PM10" which are inhalable particles, with diameters that are generally 10 micrometers and smaller, and PM2.5 which are fine inhalable particles, with diameters that are generally 2.5 micrometers and smaller. EPA method 5 provides a methodology to determine the Particulate Matter Emissions which includes any material that condenses at or above the filtration temperature, PM10 and PM2.5 emissions, include filterable and condensable emissions coming out of the Gas Turbine. It is well understood across the industry that Gas Turbines using Natural Gas as primary fuel does not produce significant amounts of PM.

The current methods used for filterable and condensable PM can have significant error. Such testing methods were developed for higher-PM generating sources such as coal-fired power plants. These same methods used to measure particulate levels on natural gas often have inaccuracies that are equal to or greater than the amount of PM being generated by combustion.

From a combustion standpoint, there is little soot generated in combustion of natural gas, especially with a lean flame, and there is no ash content in natural gas. Measured PM therefore is primarily associated with to external sources (pollen and dirt in the air) which pass through the inlet air filters, and some oxidation of turbine flow path components. Sulfur contained in the fuel, typically measured in grains per 100 standard cubic feet, which is used to make gas leaks detectible by sense of smell, can result in a condensable form of PM such as Sulfuric Acid Mist As a result the combustion system utilized in this GT is able to control NOx emissions, and have minimal contribution of PM material which places the resulting PM levels near the level of accurate measurement detection.

Thank you,

Timor Abu-Jaber
LTSA Program Manager

Martin Schluep

From:	MELLISH Thaddeus <thaddeus.mellish@cmigroupe.com>
Sent:	Friday, June 08, 2018 9:46 PM
To:	Jacqueline Chester
Cc:	Roger Schnabel; Richard Shaw; Martin Schluep
Subject:	Re: Lea Power Partners, LLC - Hobbs Generating Station PSD Permit No. 3449-M4 Modification Application

Jackie,

CMI confirms that there is no commercially available control technology to lower particulates from combustion turbine power plants with HRSGs.

Thad Mellish
VP Proposals & Aftermarket
CMI Energy

On Jun 8, 2018, at 4:14 PM, Jacqueline Chester <jchester@camsops.com> wrote:

Thank you, Thad. We appreciate your assistance.

Jackie Chester
EH&S and Regulatory Specialist

CAMS New Mexico, LLC
Hobbs Generating Station
98 N. Twombly Lane
Hobbs, NM 88240
Office (575) 397-6731
Cell (575) 263-3105
jchester@camsops.com

From: MELLISH Thaddeus <thaddeus.mellish@cmigroupe.com>
Sent: Friday, June 8, 2018 11:55 AM
To: Jacqueline Chester <jchester@camsops.com>
Cc: Roger Schnabel <rschnabel@camstex.com>; Richard Shaw <rshaw@camstex.com>; Martin Schluep <mschluep@alliantenv.com>
Subject: Re: Lea Power Partners, LLC - Hobbs Generating Station PSD Permit No. 3449-M4 Modification Application

CMI will be able to support your needs. We were just checking internally with our emissions experts.

Best Regards,
Thad

On Jun 8, 2018, at 12:57 PM, Jacqueline Chester <jchester@camsops.com> wrote:

Thad,

If at all possible, we need whatever information you can provide by June 15th. At the latest, we need it the week of June 18th in order to finalize the permit application for submittal.

Thank you,

Jackie Chester
EH&S and Regulatory Specialist

CAMS New Mexico, LLC
Hobbs Generating Station
98 N. Twombly Lane
Hobbs, NM 88240
Office (575) 397-6731
Cell (575) 263-3105
jchester@camsops.com

From: Roger Schnabel
Sent: Thursday, June 7, 2018 7:03 AM
To: MELLISH Thaddeus <thaddeus.mellish@cmigroupe.com>
Cc: Jacqueline Chester <jchester@camsops.com>; Richard Shaw <rshaw@camstex.com>; Martin Schluep <mschluep@alliantenv.com>
Subject: Lea Power Partners, LLC - Hobbs Generating Station PSD Permit No. 3449-M4 Modification Application

Good morning Thad,

We have been working with NMED (New Mexico Environmental Department) to modify our air permit related to the GT Compressor Upgrade that is scheduled to occur in March 2019. NMED has requested that we provide additional information in regards to the F4+ turbine upgrade permit modification application.

NMED requested the following time sensitive information that we'd like to have CMI provide a statement or response stating that there are no other PM control options post combustion for natural gas powered turbines utilizing HRSGs; or if there are other PM control options offered by CMI please provide that information. I have copied Jackie Chester, our onsite EHS and Regulatory Specialist , Rich Shaw - O&M Supervisor and Martin Schluep (our Environmental Contractor who is preparing the permit application) to streamline the conversation. Please reply to all if you have any additional questions or comments to expedite the response.

1. Please verify with the HRSG manufacturers that there are no other possible post combustion PM controls for natural gas fueled units.

Thank you,

Roger Schnabel
Hobbs Generating Station
98 N Twombly Lane
Hobbs, NM 88240
Office (575) 397-6706
Mobile (801) 360-4189
rschnabel@camsops.com

California Environmental Protection Agency
AIR RESOURCES BOARD

Guidance for Power Plant Siting and Best Available Control Technology

As Approved by the Air Resources Board on July 22, 1999

Stationary Source Division
Issued September 1999

State of California
California Environmental Protection Agency
Air Resources Board

Guidance for Power Plant Siting and Best Available Control Technology

July 22, 1999

Prepared by
Project Assessment Branch
Stationary Source Division

Principal Authors

Grant Chin
Christopher Gallenstein
Robert Giorgis
Stephanie Nakao
Judy Yee

Michael Tollstrup, Manager
Project Support Section

Beverly Werner, Manager
Regulatory Assistance Section

Raymond Menebroker, Chief
Project Assessment Branch

Table of Contents

ACKNOWLEDGMENTS

Contributing Air Resources Board Staff

John DaMassa

Greg Harris

Reviewed by

D. Aron Livingston, Legal Counsel	Office of Legal Affairs Executive Office
Peter Venturini, Chief	Stationary Source Division

the measured value is less than 1 ppmvd at 15 percent oxygen.[14]

d. More Stringent Control Techniques

Staff is not aware of any additional technologically feasible control techniques, existing or under development, designed to limit VOC emissions from gas turbines.

e. BACT Recommendation

Based on VOC emission levels required for simple-cycle gas turbines, the most stringent BACT requirements are in the range of 1 to 2 ppmvd VOC at 15 percent oxygen. Source tests at Carson Energy Group demonstrate VOC emission levels of no more than 2 ppmvd at 15 percent oxygen can be met on a consistent basis. Therefore, staff recommends a BACT emission level for VOC from simple-cycle gas turbines of 2 ppmvd at 15 percent oxygen averaged over 3 hours.

The most stringent VOC BACT requirements for combined-cycle and cogeneration gas turbines have been in the range of 1 to 2 ppmvd VOC at 15 percent oxygen for power plants equipped with oxidation catalysts. Staff recognizes that accuracy of some test methods performed for VOC emissions is uncertain, but available source tests at Crockett Cogeneration and other gas turbine power plants consistently give emission results of no greater than 2.0 ppmvd VOC at 15 percent oxygen averaged over 1 hour with use of an oxidation catalyst. Based on these findings, staff recommends a BACT level of 2.0 ppmvd VOC at 15 percent oxygen averaged over 1 hour (or equivalent limit of 0.0027 lb VOC/MMBtu, higher heating value).

4. Control of PM_{10} Emissions

a. Current SIP Control Measures

Staff is not aware of any control measures designed specifically to limit PM_{10} emissions from gas turbines.

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[14] Personal communications with Ken Lim of the Bay Area Air Quality Management District.

b. Control Techniques Required as BACT

PM_{10} emissions are partially dependent on fuel sulfur and nitrogen content. Natural gas has negligible amounts of fuel-bound nitrogen. As a result, there should be negligible nitrate production from any fuel-bound nitrogen. The production of thermally-induced nitrates and the organic fraction of PM_{10} can best be abated through the use of combustion controls. On new gas turbines with state of the art combustion design, PM_{10} emissions are most effectively reduced through use of fuels with both lower sulfur content and low ash content.

There are no add-on control technologies that can feasibly reduce PM_{10} emissions in gas turbine exhaust. As a result, the lowest PM_{10} emissions are achieved through combustion of low-sulfur natural gas along with combustion design that minimizes NO_X and unburned hydrocarbons. Applicants have the ability to select a low-sulfur fuel, such as natural gas; however, only the gas supplier has the ability to limit fuel sulfur content below PUC-regulated levels.[15] Natural gas utility companies have the ability to specify fuel sulfur content in purchase contracts with gas suppliers. Two major California natural gas utility companies, Pacific Gas & Electric and Southern California Gas, use purchase contracts that specify levels no higher than 1 grain of total sulfur per 100 standard cubic feet (1 gr S/100 scf).

An example of a recent PM_{10} BACT limit on a large combined-cycle gas turbine was applied to the Sutter Power Plant. A PM_{10} limit of 11.5 lb/hr averaged over 24 hours assuming a fuel sulfur content of 0.7 gr S/100 scf and a 10 percent conversion of fuel sulfur to sulfate emissions. Staff's calculations indicate that this limit is equal to an emission concentration of 0.0013 grains per dry standard cubic feet of exhaust gas (gr/dscf) at 3 percent carbon dioxide (CO_2). This determination applied to a Westinghouse 501F gas turbine nominally rated at 170 MW. In this case, the applicant presumed fuel sulfur content is below the 1 gr S/100 scf specified in the local gas utility company purchase contracts.

c. Emission Levels Achieved in Practice

Two consecutive annual source tests at Carson Energy Group in Sacramento County, California, indicate PM_{10} emissions of 0.63 and 0.882 lb/hr (approximately 0.00025 and 0.00035 gr/dscf at 3 percent CO_2) assuming a fuel sulfur content of 1 gr S/100 scf and 6.5 percent conversion of fuel sulfur to sulfate emissions. The results were obtained on a 450 MMBtu/hr General Electric LM6000 simple-cycle gas turbine.

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[15] Under California Public Utilities Commission General Order 58-8, the total sulfur of gas supplied by any gas utility for domestic, commercial, or industrial purposes is limited to 5 grains of total sulfur per 100 standard cubic feet.

5. Control of SO_X Emissions

a. Current SIP Control Measures

Several California districts have SIP control measures limiting sulfur compounds (as sulfur dioxide) from fossil fuel-burning equipment used generally for the production of useful heat or power.[17] The most stringent of these limits restrict sulfur dioxide emissions to no more than 200 pounds per hour. This level of emissions is not approached with gaseous fuel combustion.

b. Control Techniques Required as BACT

SO_X emissions are highly dependent on fuel sulfur content. As a result, the lowest emissions are achieved through the combustion of fuels with the lowest sulfur. Entities regulated by the PUC in California have purchase contracts with an effective maximum total sulfur content for natural gas of 1 gr S/100 scf (equivalent to approximately 17 ppmv sulfur). The most stringent BACT required for a simple-cycle, combined-cycle, or cogeneration gas turbine is firing of low-sulfur natural gas. Natural gas should not contain more than 1 gr S/100 scf if delivered by a California gas utility regulated by the PUC.

The Sutter Power Plant in Sutter County, California, was issued a preconstruction permit for a 170 MW Westinghouse 501F combined-cycle gas turbine. The BACT determination limited SO_2 emissions to no more than 1.0 ppmvd at 15 percent oxygen using 24-hour averaging. This emission level is proposed to be achieved using PUC pipeline quality natural gas for all combustion operations. Staff's calculations indicate that 1.0 ppmvd at 15 percent oxygen is achievable at fuel sulfur contents below 1.8 gr S/100 scf for gaseous fuels assuming full conversion of fuel sulfur to sulfur dioxide.

c. Emission Levels Achieved in Practice

Staff is not aware of any source tests for SO_X conducted on gas turbines that burn natural gas. It appears that source testing is generally not required for gas turbines that burn natural gas exclusively. Because natural gas supplied by a California gas utility regulated by the PUC should not contain more than 1 gr S/100 scf, this represents a limiting factor in SO_X emissions.

d. More Stringent Controls Techniques

SCOSOx is a catalytic sulfur removal system that works in conjunction with the SCONOx system to remove sulfur compounds from combustion exhaust streams. It is nearly identical to

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[17] Such rules may only apply to cogeneration and combined-cycle units. Others may apply more generally and may cover simple-cycle gas turbines.

Two consecutive annual source tests at Sacramento Power Authority (Campbell Soup) in Sacramento County, California, indicate PM_{10} emissions of 1.93 and 2.98 lb/hr (approximately 0.00027 and 0.00042 gr/dscf at 3 percent CO_2) assuming a fuel sulfur content of 1 gr S/100 scf and 6.5 percent conversion of fuel sulfur to sulfate emissions. The results were obtained on a 102 MW combined-cycle Siemens V84.2 gas turbine.

d. More Stringent Control Techniques

Staff is not aware of any additional technologically feasible control techniques, existing or under development, to reduce PM_{10} emissions from gas turbines**.**

5. BACT Recommendation

The lowest PM_{10} emissions from gas turbines are achieved through combustion of low-sulfur natural gas along with combustion design that minimizes NO_X and unburned hydrocarbons. Applicants have the ability to select a low-sulfur fuel, such as natural gas; however, only the gas supplier has the ability to limit fuel sulfur content below Public Utilities Commission (PUC)-regulated levels.[16] Natural gas utility companies have the ability to specify fuel sulfur content in purchase contracts with gas suppliers. Two major California natural gas utility companies, i.e., Pacific Gas & Electric and Southern California Gas, use purchase contracts that specify levels no higher than 1 gr S/100 scf. Staff believe this represents a limiting circumstance in the maximum emission level of the sulfate portion of PM_{10}.

Considering the above, the default PM_{10} BACT requirement for combined-cycle gas turbines is natural gas containing no more than 1 gr S/100 scf. In addition, staff believes that appropriate combustion controls and low sulfur fuel are essential components of a PM_{10} BACT determination for a gas turbine. Any emission limit required for BACT should correspond with a fuel gas sulfur content of 1 gr S/100 scf. Furthermore, there are "housekeeping measures" that can prevent emissions from the lube oil vent, including a lube oil vent coalescer and an associated opacity limit of 5 percent. These latter provisions were required at Badger Creek Limited on a 457.8 MMBtu/hr General Electric LM-5000 gas turbine cogeneration unit with a 48.5 MW capacity.

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[16] Under California Public Utilities Commission General Order 58-8, the total sulfur of gas supplied by any gas utility for domestic, commercial, or industrial purposes is limited to 5 grains of total sulfur per 100 standard cubic feet.

5. Control of SO_X Emissions

a. Current SIP Control Measures

Several California districts have SIP control measures limiting sulfur compounds (as sulfur dioxide) from fossil fuel-burning equipment used generally for the production of useful heat or power.[17] The most stringent of these limits restrict sulfur dioxide emissions to no more than 200 pounds per hour. This level of emissions is not approached with gaseous fuel combustion.

b. Control Techniques Required as BACT

SO_X emissions are highly dependent on fuel sulfur content. As a result, the lowest emissions are achieved through the combustion of fuels with the lowest sulfur. Entities regulated by the PUC in California have purchase contracts with an effective maximum total sulfur content for natural gas of 1 gr S/100 scf (equivalent to approximately 17 ppmv sulfur). The most stringent BACT required for a simple-cycle, combined-cycle, or cogeneration gas turbine is firing of low-sulfur natural gas. Natural gas should not contain more than 1 gr S/100 scf if delivered by a California gas utility regulated by the PUC.

The Sutter Power Plant in Sutter County, California, was issued a preconstruction permit for a 170 MW Westinghouse 501F combined-cycle gas turbine. The BACT determination limited SO_2 emissions to no more than 1.0 ppmvd at 15 percent oxygen using 24-hour averaging. This emission level is proposed to be achieved using PUC pipeline quality natural gas for all combustion operations. Staff's calculations indicate that 1.0 ppmvd at 15 percent oxygen is achievable at fuel sulfur contents below 1.8 gr S/100 scf for gaseous fuels assuming full conversion of fuel sulfur to sulfur dioxide.

c. Emission Levels Achieved in Practice

Staff is not aware of any source tests for SO_X conducted on gas turbines that burn natural gas. It appears that source testing is generally not required for gas turbines that burn natural gas exclusively. Because natural gas supplied by a California gas utility regulated by the PUC should not contain more than 1 gr S/100 scf, this represents a limiting factor in SO_X emissions.

d. More Stringent Controls Techniques

SCOSOx is a catalytic sulfur removal system that works in conjunction with the SCONOx system to remove sulfur compounds from combustion exhaust streams. It is nearly identical to

---

[17] Such rules may only apply to cogeneration and combined-cycle units. Others may apply more generally and may cover simple-cycle gas turbines.

the SCONOx catalyst for NO_X removal except that it favors sulfur compound absorption and is installed upstream of the SCONOx catalyst. SCOSOx was installed in early 1999 at the Genetics Institute in Andover, Massachusetts in conjunction with SCONOx. The 5 MW cogeneration plant consists of a 65 MMBtu/hr Solar Taurus Model 60 gas turbine with auxiliary-fired HRSG. The SCOSOx system was installed as a "guard bed" for the SCONOx system to enhance the control effectiveness of the NO_X catalyst. In this case, no attempt was made to determine SO_X removal. Therefore, there is no opportunity to assess any SO_X emissions reductions associated with SCOSOx at this time. Goal Line Environmental Technologies is now supplying the SCOSOx catalyst automatically with the SCONOx technology.

5. BACT Recommendation

SO_X emissions result from the oxidation of fuel sulfur during combustion. Staff is unaware of combustion or add-on controls feasible for controlling SO_X emissions from gas turbines. Therefore, staff recommends a SO_X BACT limit equivalent to emissions caused by combusting gaseous fuel with a sulfur content of 1 gr S/100 scf. Based on mass balance calculations and assuming no fuel sulfur conversion to sulfate, a gas turbine firing on natural gas with this level of sulfur content will emit a maximum 0.55 ppmvd at 15 percent oxygen. The district determination may also wish to require as BACT compliance with a fuel sulfur content limit, especially if the content limit is below purchase specification used by the gas utility. In addition, staff suggests that a an emission concentration limit corresponding to the assumed fuel sulfur content, i.e., 0.55 ppmvd at 15 percent oxygen or lower, may be appropriate.

6. Considerations in Controlling Emissions from Startup and Shutdown

Due to deregulation of the electric utility industry in California, many new power plants will be operating under merchant mode. Recent applications for power plant certifications indicate these plants will operate under varying loads with numerous startups and shutdowns to handle changing electricity demands. Gas turbines generally have higher emissions during periods of startup and shutdown. In fact, startup and shutdown emission may substantially contribute to the total project emissions. Therefore, the BACT decision should consider control of emissions during such periods of operation.

Gas turbines are designed to run online near rated capacity. Optimal combustion in a gas turbine tends to occur at full load. In addition, emission control systems, especially those dependent on feedback systems, operate best at steady-state. In this post deregulation period, gas turbine~~s~~ power plants may spend a significant amount of time in other modes of operation. Derated operation can be associated with less efficient combustion. Startup, shutdown, and load changes will cause variations of flue gas flows and temperature. Periods of disequilibrium may be frequent and long. For example, cold startups for combined cycle units may require up to four hours.

To the extent possible, emissions should be controlled where possible, including during

EPA-452/F-03-005

Air Pollution Control Technology Fact Sheet

Name of Technology: Cyclones

This type of technology is a part of the group of air pollution controls collectively referred to as "precleaners," because they are oftentimes used to reduce the inlet loading of particulate matter (PM) to downstream collection devices by removing larger, abrasive particles. Cyclones are also referred to as cyclone collectors, cyclone separators, centrifugal separators, and inertial separators. In applications where many small cyclones are operating in parallel, the entire system is called a multiple tube cyclone, multicyclone, or multiclone.

Type of Technology: Removal of PM by centrifugal and inertial forces, induced by forcing particulate-laden gas to change direction.

Applicable Pollutants:

Cyclones are used to control PM, and primarily PM greater than 10 micrometers (µm) in aerodynamic diameter. However, there are high efficiency cyclones designed to be effective for PM less than or equal to 10 µm and less than or equal to 2.5 µm in aerodynamic diameter (PM_{10} and $PM_{2.5}$). Although cyclones may be used to collect particles larger than 200 µm, gravity settling chambers or simple momentum separators are usually satisfactory and less subject to abrasion (Wark, 1981; Perry, 1984).

Achievable Emission Limits/Reductions:

The collection efficiency of cyclones varies as a function of particle size and cyclone design. Cyclone efficiency generally increases with (1) particle size and/or density, (2) inlet duct velocity, (3) cyclone body length, (4) number of gas revolutions in the cyclone, (5) ratio of cyclone body diameter to gas exit diameter, (6) dust loading, and (7) smoothness of the cyclone inner wall. Cyclone efficiency will decrease with increases in (1) gas viscosity, (2) body diameter, (3) gas exit diameter, (4) gas inlet duct area, and (5) gas density. A common factor contributing to decreased control efficiencies in cyclones is leakage of air into the dust outlet (EPA, 1998).

Control efficiency ranges for single cyclones are often based on three classifications of cyclone, i.e., conventional, high-efficiency, and high-throughput. The control efficiency range for conventional single cyclones is estimated to be 70 to 90 percent for PM, 30 to 90 percent for PM_{10}, and 0 to 40 percent for $PM_{2.5}$.

High efficiency single cyclones are designed to achieve higher control of smaller particles than conventional cyclones. According to Cooper (1994), high efficiency single cyclones can remove 5 µm particles at up to 90 percent efficiency, with higher efficiencies achievable for larger particles. The control efficiency ranges for high efficiency single cyclones are 80 to 99 percent for PM, 60 to 95 percent for PM_{10}, and 20 to 70 percent for $PM_{2.5}$. Higher efficiency cyclones come with higher pressure drops, which require higher energy costs to move the waste gas through the cyclone. Cyclone design is generally driven by a specified pressure-drop limitation, rather than by meeting a specified control efficiency (Andriola, 1999; Perry, 1994).

According to Vatavuk (1990), high throughput cyclones are only guaranteed to remove particles greater than 20 µm, although collection of smaller particles does occur to some extent. The control efficiency ranges for high-throughput cyclones are 80 to 99 percent for PM, 10 to 40 percent for PM_{10}, and 0 to 10 percent for $PM_{2.5}$.

Multicyclones are reported to achieve from 80 to 95 percent collection efficiency for 5 µm particles (EPA, 1998).

Applicable Source Type: Point

Typical Industrial Applications:

Cyclones are designed for many applications. Cyclones themselves are generally not adequate to meet stringent air pollution regulations, but they serve an important purpose as precleaners for more expensive final control devices such as fabric filters or electrostatic precipitators (ESPs). In addition to use for pollution control work, cyclones are used in many process applications, for example, they are used for recovering and recycling food products and process materials such as catalysts (Cooper, 1994).

Cyclones are used extensively after spray drying operations in the food and chemical industries, and after crushing, grinding and calcining operations in the mineral and chemical industries to collect salable or useful material. In the ferrous and nonferrous metallurgical industries, cyclones are often used as a first stage in the control of PM emissions from sinter plants, roasters, kilns, and furnaces. PM from the fluid-cracking process are removed by cyclones to facilitate catalyst recycling. Fossil-fuel and wood-waste fired industrial and commercial fuel combustion units commonly use multiple cyclones (generally upstream of a wet scrubber, ESP, or fabric filter) which collect fine PM (< 2.5 µm) with greater efficiency than a single cyclone. In some cases, collected fly ash is reinjected into the combustion unit to improve PM control efficiency (AWMA, 1992; Avallone, 1996; STAPPA/ALAPCO, 1996; EPA, 1998).

Emission Stream Characteristics:

a. **Air Flow:** Typical gas flow rates for a single cyclone unit are 0.5 to 12 standard cubic meters per second (sm^3/sec) (1,060 to 25,400 standard cubic feet per minute (scfm)). Flows at the high end of this range and higher (up to approximately 50 sm^3/sec or 106,000 scfm) use multiple cyclones in parallel (Cooper, 1994). There are single cyclone units employed for specialized applications which have flow rates of up to approximately 30 sm^3/sec (63,500 scfm) and as low as 0.0005 sm^3/sec (1.1 scfm) (Wark, 1981; Andriola, 1999).

b. **Temperature:** Inlet gas temperatures are only limited by the materials of construction of the cyclone, and have been operated at temperatures as high as 540°C (1000°F) (Wark, 1981; Perry, 1994).

c. **Pollutant Loading:** Waste gas pollutant loadings typically range from 2.3 to 230 grams per standard cubic meter (g/sm^3) (1.0 to 100 grains per standard cubic foot (gr/scf)) (Wark, 1981). For specialized applications, loadings can be as high as 16,000 g/sm^3 (7,000 gr/scf), and as low as I g/sm^3 (0.44 gr/scf) (Avallone, 1996; Andriola, 1999).

d. **Other Considerations:** Cyclones perform more efficiently with higher pollutant loadings, provided that the device does not become choked. Higher pollutant loadings are generally associated with higher flow designs (Andriola, 1999).

Emission Stream Pretreatment Requirements:

No pretreatment is necessary for cyclones.

Cost Information:

The following are cost ranges (expressed in 2002 dollars) for a single conventional cyclone under typical operating conditions, developed using an EPA cost-estimating spreadsheet (EPA, 1996), and referenced to the volumetric flow rate of the waste stream treated. Flow rates higher than approximately 10 sm^3/sec (21,200 scfm) usually employ multiple cyclones operating in parallel. For purposes of calculating the example cost effectiveness, flow rates are assumed to be between 0.5 and 50 sm^3/sec (1,060 and 106,000 scfm), the PM inlet loading is assumed to be approximately 2.3 and 230 g/sm^3 (1.0 to 100 gr/scf) and the control efficiency is assumed to be 90 percent. The costs do not include costs for disposal or transport of collected material. Capital costs can be higher than in the ranges shown for applications which require expensive materials. As a rule, smaller units controlling a waste stream with a low PM concentration will be more expensive (per unit volumetric flow rate and per quantity of pollutant controlled) than a large unit controlling a waste stream with a high PM concentration.

a. **Capital Cost:** \$4,600 to \$7,400 per sm^3/sec (\$2.20 to \$3.50 per scfm)

b. **O & M Cost:** \$1,500 to \$18,000 per sm^3/sec (\$0.70 to \$8.50 per scfm), annually

c. **Annualized Cost:** \$2,800 to \$29,000 per sm^3/sec (\$1.30 to \$13.50 per scfm), annually

d. **Cost Effectiveness:** \$0.47 to \$440 per metric ton (\$0.43 to \$400 per short ton), annualized cost per ton per year of pollutant controlled

Flow rates higher than approximately 10 sm^3/sec (21,200 scfm), and up to approximately 50 sm^3/sec (106,000 scfm), usually employ multiple cyclones operating in parallel. Assuming the same range of pollutant loading and an efficiency of 90 percent, the following cost ranges (expressed in third quarter 1995 dollars) were developed for multiple cyclones, using an EPA cost-estimating spreadsheet (EPA, 1996), and referenced to the volumetric flow rate of the waste stream treated.

Theory of Operation:

Cyclones use inertia to remove particles from the gas stream. The cyclone imparts centrifugal force on the gas stream, usually within a conical shaped chamber. Cyclones operate by creating a double vortex inside the cyclone body. The incoming gas is forced into circular motion down the cyclone near the inner surface of the cyclone tube. At the bottom of the cyclone, the gas turns and spirals up through the center of the tube and out of the top of the cyclone (AWMA, 1992).

Particles in the gas stream are forced toward the cyclone walls by the centrifugal force of the spinning gas but are opposed by the fluid drag force of the gas traveling through and out of the cyclone. For large particles, inertial momentum overcomes the fluid drag force so that the particles reach the cyclone walls and are collected. For small particles, the fluid drag force overwhelms the inertial momentum and causes these particles to leave the cyclone with the exiting gas. Gravity also causes the larger particles that reach the cyclone walls to travel down into a bottom hopper. While they rely on the same separation mechanism as momentum separators, cyclones are more effective because they have a more complex gas flow pattern (AWMA, 1992).

Cyclones are generally classified into four types, depending on how the gas stream is introduced into the device and how the collected dust is discharged. The four types include tangential inlet, axial discharge; axial inlet, axial discharge; tangential inlet, peripheral discharge; and axial inlet, peripheral discharge. The first two types are the most common (AWMA, 1992).

Pressure drop is an important parameter because it relates directly to operating costs and control efficiency. Higher control efficiencies for a given cyclone can be obtained by higher inlet velocities, but this also increases the pressure drop. In general, 18.3 meters per second (60 feet per second) is considered the best operating velocity. Common ranges of pressure drops for cyclones are 0.5 to 1 kilopascals (kPa) (2 to 4 in. H_2O) for low-efficiency units (high throughput), 1 to 1.5 kPa (4 to 6 in. H_2O) for medium-efficiency units (conventional), and 2 to 2.5 kPa (8 to 10 in. H_2O) for high-efficiency units (AWMA, 1992).

When high-efficiency (which requires small cyclone diameter) and large throughput are both desired, a number of cyclones can be operated in parallel. In a multiple tube cyclone, the housing contains a large number of tubes that have a common gas inlet and outlet in the chamber. The gas enters the tubes through axial inlet vanes which impart a circular motion (AWMA, 1992). Another high-efficiency unit, the wet cyclonic separator, uses a combination of centrifugal force and water spray to enhance control efficiency.

Advantages:

Advantages of cyclones include (AWMA, 1992; Cooper, 1994; and EPA, 1998):

1. Low capital cost;
2. No moving parts, therefore, few maintenance requirements and low operating costs;
3. Relatively low pressure drop (2 to 6 inches water column), compared to amount of PM removed;
4. Temperature and pressure limitations are only dependent on the materials of construction;
5. Dry collection and disposal; and
6. Relatively small space requirements.

Disadvantages:

Disadvantages of cyclones include (AWMA, 1992; Cooper, 1994; and EPA, 1998):

1. Relatively low PM collection efficiencies, particularly for PM less than 10 μm in size;
2. Unable to handle sticky or tacky materials; and
3. High efficiency units may experience high pressure drops.

Other Considerations:

Using multiple cyclones, either in parallel or in series, to treat a large volume of gas results in higher efficiencies, but at the cost of a significant increase in pressure drop. Higher pressure drops translate to higher energy usage and operating costs. Several designs should be considered to achieve the optimum combination of collection efficiency and pressure drop (Cooper, 1994).

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EPA-452/F-03-025

Air Pollution Control Technology Fact Sheet

Name of Technology: Fabric Filter - Pulse-Jet Cleaned Type
(also referred to as Baghouses)

Type of Technology: Control Device - Capture/Disposal

Applicable Pollutants: Particulate Matter (PM), including particulate matter less than or equal to 10 micrometers (µm) in aerodynamic diameter (PM_{10}), particulate matter less than or equal to 2.5 µm in aerodynamic diameter ($PM_{2.5}$), and hazardous air pollutants (HAPs) that are in particulate form, such as most metals (mercury is the notable exception, as a significant portion of emissions are in the form of elemental vapor).

Achievable Emission Limits/Reductions:

Typical new equipment design efficiencies are between 99 and 99.9%. Older existing equipment have a range of actual operating efficiencies of 95 to 99.9%. Several factors determine fabric filter collection efficiency. These include gas filtration velocity, particle characteristics, fabric characteristics, and cleaning mechanism. In general, collection efficiency increases with increasing filtration velocity and particle size.

For a given combination of filter design and dust, the effluent particle concentration from a fabric filter is nearly constant, whereas the overall efficiency is more likely to vary with particulate loading. For this reason, fabric filters can be considered to be constant outlet devices rather than constant efficiency devices. Constant effluent concentration is achieved because at any given time, part of the fabric filter is being cleaned. As a result of the cleaning mechanisms used in fabric filters, the collection efficiency is constantly changing. Each cleaning cycle removes at least some of the filter cake and loosens particles which remain on the filter. When filtration resumes, the filtering capability has been reduced because of the lost filter cake and loose particles are pushed through the filter by the flow of gas. As particles are captured, the efficiency increases until the next cleaning cycle. Average collection efficiencies for fabric filters are usually determined from tests that cover a number of cleaning cycles at a constant inlet loading. (EPA, 1998a)

Applicable Source Type: Point

Typical Industrial Applications:

Fabric filters can perform very effectively in many different applications. Common applications of fabric filter systems with pulse-jet cleaning are presented in Table 1, however, fabric filters can be used in most any process where dust is generated and can be collected and ducted to a central location.

Table 1. Typical Industrial Applications of Pulse-Jet Cleaned Fabric Filters (EPA 1997; EPA, 1998a)

Application	Source Category Code (SCC)
Utility Boilers (Coal)	1-01-002...003
Industrial Boilers (Coal, Wood)	1-02-001...003, 1-02-009
Commercial/Institutional Boilers (Coal, Wood)	1-03-001...003, 1-03-009
Ferrous Metals Processing:	
Iron and Steel Production	3-03-008...009
Steel Foundries	3-04-007,-009
Mineral Products:	
Cement Manufacturing	3-05-006...007
Coal Cleaning	3-05-010
Stone Quarrying and Processing	3-05-020
Other	3-05-003...999
Asphalt Manufacture	3-05-001...002
Grain Milling	3-02-007

Emission Stream Characteristics:

a. **Air Flow:** Baghouses are separated into two groups, standard and custom, which are further separated into low, medium, and high capacity. Standard baghouses are factory-built, off the shelf units. They may handle from less than 0.10 to more than 50 standard cubic meters per second (sm^3/sec) ((“hundreds” to more than 100,000 standard cubic feet per minute (scfm)). Custom baghouses are designed for specific applications and are built to the specifications prescribed by the customer. These units are generally much larger than standard units, i.e., from 50 to over 500 sm^3/sec (100,000 to over 1,000,000 scfm). (EPA, 1998b)

b. **Temperature:** Typically, gas temperatures up to about 260°C (500°F), with surges to about 290°C (550°F) can be accommodated routinely, with the appropriate fabric material. Spray coolers or dilution air can be used to lower the temperature of the pollutant stream. This prevents the temperature limits of the fabric from being exceeded. Lowering the temperature, however, increases the humidity of the pollutant stream. Therefore, the minimum temperature of the pollutant stream must remain above the dew point of any condensable in the stream. The baghouse and associated ductwork should be insulated and possibly heated if condensation may occur. (EPA, 1998b)

c. **Pollutant Loading:** Typical inlet concentrations to baghouses are 1 to 23 grams per cubic meter (g/m^3) (0.5 to 10 grains per cubic foot (gr/ft^3)), but in extreme cases, inlet conditions may vary between 0.1 to more than 230 g/m^3 (0.05 to more than 100 gr/ft^3). (EPA, 1998b)

d. **Other Considerations:** Moisture and corrosives content are the major gas stream characteristics requiring design consideration. Standard fabric filters can be used in pressure or vacuum service, but only within the range of about ± 640 millimeters of water column (25 inches of water column). Well-designed and operated baghouses have been shown to be capable of reducing overall particulate emissions to less than 0.05 g/m^3 (0.010 gr/ft^3), and in a number of cases, to as low as 0.002 to 0.011 g/m^3 (0.001 to 0.005 gr/ft^3). (AWMA, 1992)

Emission Stream Pretreatment Requirements:

Because of the wide variety of filter types available to the designer, it is not usually required to pretreat a waste stream's inlet temperature. However, in some high temperature applications, the cost of high temperature-resistant bags must be weighed against the cost of cooling the inlet temperature with spray coolers or dilution air (EPA, 1998b). When much of the pollutant loading consists of relatively large particles, mechanical collectors such as cyclones may be used to reduce the load on the fabric filter, especially at high inlet concentrations (EPA, 1998b).

Cost Information:

Cost estimates are presented below for pulse-jet cleaned fabric filters. The costs are expressed in 2002 dollars. The cost estimates assume a conventional design under typical operating conditions and do not include auxiliary equipment such as fans and ductwork. The costs for pulse-jet cleaned systems are generated using EPA's cost-estimating spreadsheet for fabric filters (EPA, 1998b).

Costs are primarily driven by the waste stream volumetric flow rate and pollutant loading. In general, a small unit controlling a low pollutant loading will not be as cost effective as a large unit controlling a high pollutant loading. The costs presented are for flow rates of 470 m^3/sec (1,000,000 scfm) and 1.0 m^3/sec (2,000 scfm), respectively, and a pollutant loading of 9 g/m^3 (4.0 gr/ft^3).

Pollutants that require an unusually high level of control or that require the fabric filter bags or the unit itself to be constructed of special materials, such as Gore-Tex or stainless steel, will increase the costs of the system (EPA, 1998b). The additional costs for controlling more complex waste streams are not reflected in the estimates given below. For these types of systems, the capital cost could increase by as much as 75% and the operational and maintenance (O&M) cost could increase by as much as 20%.

a. **Capital Cost:** \$13,000 to \$55,000 per sm^3/s (\$6 to \$26 per scfm)

b. **O & M Cost:** \$11,000 to \$50,000 per sm^3/s (\$5 to \$24 per scfm), annually

c. **Annualized Cost:** \$13,000 to \$83,000 per sm^3/s (\$6 to \$39 per scfm), annually

d. **Cost Effectiveness:** \$46 to \$293 per metric ton (\$42 to \$266 per short ton)

Theory of Operation:

In a fabric filter, flue gas is passed through a tightly woven or felted fabric, causing PM in the flue gas to be collected on the fabric by sieving and other mechanisms. Fabric filters may be in the form of sheets, cartridges, or bags, with a number of the individual fabric filter units housed together in a group. Bags are most common type of fabric filter. The dust cake that forms on the filter from the collected PM can significantly increase collection efficiency. Fabric filters are frequently referred to as baghouses because the fabric is usually configured in cylindrical bags. Bags may be 6 to 9 m (20 to 30 ft) long and 12.7 to 30.5 centimeters (cm) (5 to 12 inches) in diameter. Groups of bags are placed in isolable compartments to allow cleaning of the bags or replacement of some of the bags without shutting down the entire fabric filter. (STAPPA/ALAPCO, 1996)

Operating conditions are important determinants of the choice of fabric. Some fabrics (e.g., polyolefins, nylons, acrylics, polyesters) are useful only at relatively low temperatures of 95 to 150•C (200 to 300•F). For high-temperature flue gas streams, more thermally stable fabrics such as fiberglass, Teflon®, or Nomex® must be used (STAPPA/ALAPCO, 1996).

Practical application of fabric filters requires the use of a large fabric area in order to avoid an unacceptable pressure drop across the fabric. Baghouse size for a particular unit is determined by the choice of air-to-cloth ratio, or the ratio of volumetric air flow to cloth area. The selection of air-to-cloth ratio depends on the particulate loading and characteristics, and the cleaning method used. A high particulate loading will require the use of a larger baghouse in order to avoid forming too heavy a dust cake, which would result in an excessive pressure drop As an example, a baghouse for a 250 MW utility boiler may have 5,000 separate bags with a total fabric area approaching 46,500 m^2 (500,000 square feet). (ICAC, 1999)

Determinants of baghouse performance include the fabric chosen, the cleaning frequency and methods, and the particulate characteristics. Fabrics can be chosen which will intercept a greater fraction of particulate, and some fabrics are coated with a membrane with very fine openings for enhanced removal of submicron particulate. Such fabrics tend to be more expensive.

Pulse-jet cleaning of fabric filters is relatively new compared to other types of fabric filters, since they have only been used for the past 30 years. This cleaning mechanism has consistently grown in popularity because it can treat high dust loadings, operate at constant pressure drop, and occupy less space than other types of fabric filters. Pulse-jet cleaned fabric filters can only operate as external cake collection devices. The bags are closed at the bottom, open at the top, and supported by internal retainers, called cages. Particulate-laden gas flows into the bag, with diffusers often used to prevent oversized particles from damaging the bags. The gas flows from the outside to the inside of the bags, and then out the gas exhaust. The particles are collected on the outside of the bags and drop into a hopper below the fabric filter. (EPA, 1998a)

During pulse-jet cleaning, a short burst, 0.03 to 0.1 seconds in duration, of high pressure [415 to 830 kiloPascals (kPa) (60 to 120 pounds per square inch gage (psig))] air is injected into the bags (EPA, 1998a; AWMA, 1992). The pulse is blown through a venturi nozzle at the top of the bags and establishes a shock wave that continues onto the bottom of the bag. The wave flexes the fabric, pushing it away from the cage, and then snaps it back dislodging the dust cake. The cleaning cycle is regulated by a remote timer connected to a solenoid valve. The burst of air is controlled by the solenoid valve and is released into blow pipes that have nozzles located above the bags. The bags are usually cleaned row by row (EPA, 1998a).

There are several unique attributes of pulse-jet cleaning. Because the cleaning pulse is very brief, the flow of dusty gas does not have to be stopped during cleaning. The other bags continue to filter, taking on extra duty because of he bags being cleaned. In general, there is no change in fabric filter pressure drop or performance as a result of pulse-jet cleaning. This enables the pulse-jet fabric filters to operate on a continuous basis with solenoid valves as the only significant moving parts. Pulse-jet cleaning is also more intense and occurs with greater frequency than the other fabric filter cleaning methods. This intense cleaning dislodges nearly all of the dust cake each time the bag is pulsed. As a result, pulse-jet filters do not rely on a dust cake to provide filtration. Felted (non-woven) fabrics are used in pulse-jet fabric filters because they do not require a dust cake to achieve high collection efficiencies. It has been found that woven fabrics used with pulse-jet fabric filters leak a great deal of dust after they are cleaned. (EPA, 1998a)

Since bags cleaned by the pulse-jet method do not need to be isolated for cleaning, pulse-jet cleaned fabric filters do not need extra compartments to maintain adequate filtration during cleaning. Also, because of the intense and frequent nature of the cleaning, they can treat higher gas flow rates with higher dust loadings. Consequently, fabric filters cleaned by the pulse-jet method can be smaller than other types of fabric filters in the treatment of the same amount of gas and dust, making higher gas-to-cloth ratios achievable. (EPA, 1998a)

Advantages:

Fabric filters in general provide high collection efficiencies on both coarse and fine (submicron) particulates. They are relatively insensitive to fluctuations in gas stream conditions. Efficiency and pressure drop are relatively unaffected by large changes in inlet dust loadings for continuously cleaned filters. Filter outlet air is very clean and may be recirculated within the plant in many cases (for energy conservation). Collected material is collected dry for subsequent processing or disposal. Corrosion and rusting of components are usually not problems. Operation is relatively simple. Unlike electrostatic precipitators, fabric filter systems do not require the use of high voltage, therefore, maintenance is simplified and flammable dust may be collected with proper care. The use of selected fibrous or granular filter aids (precoating) permits the high-efficiency collection of submicron smokes and gaseous contaminants. Filter collectors are available in a large number of configurations, resulting in a range of dimensions and inlet and outlet flange locations to suit installation requirements. (AWMA, 1992)

Disadvantages:

Temperatures much in excess of 290•C (550•F) require special refractory mineral or metallic fabrics, which can be expensive. Certain dusts may require fabric treatments to reduce dust seepage, or in other cases, assist in the removal of the collected dust. Concentrations of some dusts in the collector, approximately 50 g/m^3 (22 gr/ft^3), may represent a fire or explosion hazard if a spark or flame is accidentally admitted. Fabrics can burn if readily oxidizable dust is being collected. Fabric filters have relatively high maintenance requirements (e.g., periodic bag replacement). Fabric life may be shortened at elevated temperatures and in the presence of acid or alkaline particulate or gas constituents. They cannot be operated in moist environments; hygroscopic materials, condensation of moisture, or tarry adhesive components may cause crusty caking or plugging of the fabric or require special additives. Respiratory protection for maintenance personnel may be required when replacing fabric. Medium pressure drop is required, typically in the range of 100 to 250 mm of water column (4 to 10 inches of water column). (AWMA, 1992)

A specific disadvantage of pulse-jet units that use very high gas velocities is that the dust from the cleaned bags can be drawn immediately to the other bags. If this occurs, little of the dust falls into the hopper and the dust layer on the bags becomes too thick. To prevent this, pulse-jet fabric filters can be designed with separate compartments that can be isolated for cleaning. (EPA, 1998a)

Other Considerations:

Fabric filters are useful for collecting particles with resistivities either too low or too high for collection with electrostatic precipitators. Fabric filters therefore may be good candidates for collecting fly ash from low-sulfur coals or fly ash containing high unburned carbon levels, which respectively have high and low resistivities, and thus are relatively difficult to collect with electrostatic precipitators. (STAPPA/ALAPCO, 1996)

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EPA-452/F-03-026

Air Pollution Control Technology
Fact Sheet

Name of Technology: Fabric Filter - Reverse-Air Cleaned Type
- Reverse-Air Cleaned Type with Sonic Horn Enhancement
- Reverse-Jet Cleaned Type
(also referred to as Baghouses)

Type of Technology: Control Device - Capture/Disposal

Applicable Pollutants: Particulate Matter (PM), including particulate matter less than or equal to 10 micrometers (•m) in aerodynamic diameter (PM_{10}), particulate matter less than or equal to 2.5 •m in aerodynamic diameter ($PM_{2.5}$), and hazardous air pollutants (HAPs) that are in particulate form, such as most metals (mercury is the notable exception, as a significant portion of emissions are in the form of elemental vapor).

Achievable Emission Limits/Reductions:

Typical new equipment design efficiencies are between 99 and 99.9%. Older existing equipment have a range of actual operating efficiencies of 95 to 99.9%. Several factors determine fabric filter collection efficiency. These include gas filtration velocity, particle characteristics, fabric characteristics, and cleaning mechanism. In general, collection efficiency increases with increasing filtration velocity and particle size.

For a given combination of filter design and dust, the effluent particle concentration from a fabric filter is nearly constant, whereas the overall efficiency is more likely to vary with particulate loading. For this reason, fabric filters can be considered to be constant outlet devices rather than constant efficiency devices. Constant effluent concentration is achieved because at any given time, part of the fabric filter is being cleaned. As a result of the cleaning mechanisms used in fabric filters, the collection efficiency is constantly changing. Each cleaning cycle removes at least some of the filter cake and loosens particles which remain on the filter. When filtration resumes, the filtering capability has been reduced because of the lost filter cake and loose particles are pushed through the filter by the flow of gas. As particles are captured, the efficiency increases until the next cleaning cycle. Average collection efficiencies for fabric filters are usually determined from tests that cover a number of cleaning cycles at a constant inlet loading. (EPA, 1998a)

Applicable Source Type: Point

Typical Industrial Applications:

Fabric filters can perform very effectively in many different applications. Common applications of fabric filter systems with reverse-air cleaning are presented in Table 1, however, fabric filters can be used in most any process where dust is generated and can be collected and ducted to a central location. Other cleaning-types may also be used in these applications. Sonic horn enhancement of mechanical shaker cleaning is generally used for applications with dense particulates such as utility boilers, metal processing, and mineral products.

Table 1. Typical Industrial Applications of Reverse-Air -Cleaned Fabric Filters
(EPA, 1997; EPA, 1998a)

Application	Source Category Code (SCC)
Utility Boilers (Coal)	1-01-002...003
Industrial Boilers (Coal, Wood)	1-02-001...003, 1-02-009
Commercial/Institutional Boilers (Coal, Wood)	1-03-001...003, 1-03-009
Non-Ferrous Metals Processing (Primary and Secondary):	
Copper	3-03-005, 3-04-002
Lead	3-03-010, 3-04-004
Zinc	3-03-030, 3-04-008
Aluminum	3-03-000...002 3-04-001
Other metals production	3-03-011...014 3-04-005...006 3-04-010...022
Ferrous Metals Processing:	
Coke	3-03-003...004
Ferroalloy Production	3-03-006...007
Iron and Steel Production	3-03-008...009
Gray Iron Foundries	3-04-003
Steel Foundries	3-04-007,-009
Mineral Products:	
Cement Manufacturing	3-05-006...007
Coal Cleaning	3-05-010
Stone Quarrying and Processing	3-05-020
Other	3-05-003...999
Asphalt Manufacture	3-05-001...002
Grain Milling	3-02-007

Emission Stream Characteristics:

a. **Air Flow:** Baghouses are separated into two groups, standard and custom, which are further separated into low, medium, and high capacity. Standard baghouses are factory-built, off the shelf units. They may handle from less than 0.10 to more than 50 standard cubic meters per second (sm^3/sec) (“hundreds” to more than 100,000 standard cubic feet per minute (scfm)). Custom baghouses are designed for specific applications and are built to the specifications prescribed by the customer. These units are generally much larger than standard units, i.e., from 50 to over 500 sm^3/sec (100,000 to over 1,000,000 scfm). (EPA, 1998b)

b. **Temperature:** Typically, gas temperatures up to about 260°C (500°F), with surges to about 290°C (550°F) can be accommodated routinely, with the appropriate fabric material. Spray coolers or dilution air can be used to lower the temperature of the pollutant stream. This prevents the temperature limits of the fabric from being exceeded. Lowering the temperature, however, increases the humidity of the pollutant stream. Therefore, the minimum temperature of the pollutant stream must remain above the dew point of any condensable in the stream. The baghouse and associated ductwork should be insulated and possibly heated if condensation may occur. (EPA, 1998b)

c. **Pollutant Loading:** Typical inlet concentrations to baghouses are 1 to 23 grams per cubic meter (g/m^3) (0.5 to 10 grains per cubic foot (gr/ft^3)), but in extreme cases, inlet conditions may vary between 0.1 to more than 230 g/m^3 (0.05 to more than 100 gr/ft^3). (EPA, 1998b)

d. **Other Considerations:** Moisture and corrosives content are the major gas stream characteristics requiring design consideration. Standard fabric filters can be used in pressure or vacuum service, but only within the range of about ± 640 millimeters of water column (25 inches of water column). Well-designed and operated baghouses have been shown to be capable of reducing overall particulate emissions to less than 0.05 g/m^3 (0.010 gr/ft^3), and in a number of cases, to as low as 0.002 to 0.011 g/dsm^3 (0.001 to 0.005 gr/dscf). (AWMA, 1992)

Emission Stream Pretreatment Requirements:

Because of the wide variety of filter types available to the designer, it is not usually required to pretreat a waste stream's inlet temperature. However, in some high temperature applications, the cost of high temperature-resistant bags must be weighed against the cost of cooling the inlet temperature with spray coolers or dilution air (EPA, 1998b). When much of the pollutant loading consists of relatively large particles, mechanical collectors such as cyclones may be used to reduce the load on the fabric filter, especially at high inlet concentrations (EPA, 1998b).

Cost Information:

Cost estimates are presented below for reverse-air cleaned fabric filters, for sonic horn enhancement, and for reverse-jet cleaned fabric filters. The costs are expressed in 2002 dollars for reverse-air cleaned and sonic horn enhancement. The cost estimates assume a conventional design under typical operating conditions. The costs do not include auxiliary equipment such as fans and ductwork.

The costs for reverse-air cleaned systems are generated using EPA's cost-estimating spreadsheet for fabric filters (EPA, 1998b). The cost estimate for sonic horn enhancement is obtained from the manufacturer quote given in the OAQPS Control Cost Manual (EPA, 1998b). Sonic horns are presented as an incremental cost to the capital cost for a shaker-cleaned system. The operational and maintenance (O&M) cost for shaker-cleaned systems are reduced by 1% to 3% with the sonic horn enhancement. The capital cost for the reverse-jet cleaned fabric baghouse is based on a manufacturer quote (Carrington, 2000). This quote includes only the baghouse purchased equipment cost. O&M costs, annualized costs, and cost effectiveness were not estimated for reverse-jet. In general, reverse-jet has higher capital costs and O&M costs than reverse-air due to its complexity (see Section 10, Theory of Operation).

Costs are primarily driven by the waste stream volumetric flow rate and pollutant loading. In general, a small unit controlling a low pollutant loading will not be as cost effective as a large unit controlling a high pollutant loading. The costs presented are for flow rates of 470 m^3/sec (1,000,000 scfm) and 1.0 m^3/sec (2,000 scfm), respectively, and a pollutant loading of 9 g/m^3 (4.0 gr/ft^3) . For reverse-jet, the capital cost presented is for a baghouse of 378,000 m^3/sec (800,000 scfm).

Pollutants that require an unusually high level of control or that require the fabric filter bags or the unit itself to be constructed of special materials, such as Gore-Tex or stainless steel, will increase the costs of the system (EPA, 1998b). The additional costs for controlling more complex waste streams are not reflected in the estimates given below. For these types of systems, the capital cost could increase by as much as 40% and the O&M cost could increase by as much as 5%.

a. **Capital Cost:** \$19,000 to \$180,000 per sm^3/s (\$9 to \$85 per scfm), reverse-air
   \$1,000 to \$1,300 per m^3/sec (\$ 0.51 to \$0.61 per scfm), additional cost for sonic horns
   \$2,000 to \$4,200 per m^3/sec (\$1 to \$2 per scfm), reverse-jet purchased equipment cost

b. **O & M Cost:** \$14,000 to \$58,000 per sm^3/s (\$6 to \$27 per scfm), annually

c. **Annualized Cost:** \$17,000 to \$106,000 per sm^3/s (\$8 to \$50 per scfm), annually

d. **Cost Effectiveness:** \$58 to \$372 per metric ton (\$53 to \$337 per short ton)

Theory of Operation:

In a fabric filter, flue gas is passed through a tightly woven or felted fabric, causing PM in the flue gas to be collected on the fabric by sieving and other mechanisms. Fabric filters may be in the form of sheets, cartridges, or bags, with a number of the individual fabric filter units housed together in a group. Bags are most common type of fabric filter. The dust cake that forms on the filter from the collected PM can significantly increase collection efficiency. Fabric filters are frequently referred to as baghouses because the fabric is usually configured in cylindrical bags. Bags may be 6 to 9 m (20 to 30 ft) long and 12.7 to 30.5 centimeters (cm) (5 to 12 inches) in diameter. Groups of bags are placed in isolable compartments to allow cleaning of the bags or replacement of some of the bags without shutting down the entire fabric filter. (STAPPA/ALAPCO, 1996)

Operating conditions are important determinants of the choice of fabric. Some fabrics (e.g., polyolefins, nylons, acrylics, polyesters) are useful only at relatively low temperatures of 95 to 150•C (200 to 300•F). For high-temperature flue gas streams, more thermally stable fabrics such as fiberglass, Teflon®, or Nomex® must be used (STAPPA/ALAPCO, 1996).

Practical application of fabric filters requires the use of a large fabric area in order to avoid an unacceptable pressure drop across the fabric. Baghouse size for a particular unit is determined by the choice of air-to-cloth ratio, or the ratio of volumetric air flow to cloth area. The selection of air-to-cloth ratio depends on the particulate loading and characteristics, and the cleaning method used. A high particulate loading will require the use of a larger baghouse in order to avoid forming too heavy a dust cake, which would result in an excessive pressure drop As an example, a baghouse for a 250 megawatt (MW) utility boiler may have 5,000 separate bags with a total fabric area approaching 46,500 m^2 (500,000 square feet). (ICAC, 1999)

Determinants of baghouse performance include the fabric chosen, the cleaning frequency and methods, and the particulate characteristics. Fabrics can be chosen which will intercept a greater fraction of particulate, and some fabrics are coated with a membrane with very fine openings for enhanced removal of submicron particulate. Such fabrics tend to be more expensive. Cleaning intensity and frequency are important variables in determining removal efficiency. Because the dust cake can provide a significant fraction of the fine particulate removal capability of a fabric, cleaning which is too frequent or too intense will lower the removal efficiency. On the other hand, if removal is too infrequent or too ineffective, then the baghouse pressure drop will become too high. (ICAC, 1999)

Reverse-air cleaning is a popular fabric filter cleaning method that has been used extensively and improved over the years. It is a gentler but sometimes less effective clearing mechanism than mechanical shaking.

Most reverse-air fabric filters operate in a manner similar to shaker-cleaned fabric filters. Typically, the bags are open on the bottom, closed on top and the gas flows from the inside to the outside of the bags with dust being captured on the inside. However, some reverse-air designs collect dust on the outside of the bags. In either design, reverse-air cleaning is performed by forcing clean air through the filters in the opposite direction of the dusty gas flow. The change in direction of the gas flow causes the bag to flex and crack the filter cake. In internal cake collection, the bags are allowed to collapse to some extent during reverse-air cleaning. The bags are usually prevented from collapsing entirely by some kind of support, such as rings that are sewn into the bags. The support enables the dust cake to fall off the bags and into the hopper. Cake release is also aided by the reverse flow of the gas. Because felted fabrics retain dust more than woven fabrics and thus, are more difficult to clean, felts are usually not used in reverse-air systems. (EPA, 1998a)

There are several methods of reversing the flow through the filters. As with mechanical shaker-cleaned fabric filters, the most common approach is to have separate compartments within the fabric filter so that each compartment can be isolated and cleaned separately while the other compartments continue to treat the dusty gas. One method of providing the reverse flow air is by the use of a secondary fan or cleaned gas from the other compartments. Reverse-air cleaning alone is used only in cases where the dust releases easily from the fabric. In many instances, reverse-air is used in conjunction with shaking, pulsing or sonic horns. (EPA, 1998a)

Sonic horns are increasingly being used to enhance the collection efficiency of mechanical shaker and reverse-air fabric filters (AWMA, 1992). Sonic horns utilize compressed air to vibrate a metal diaphragm, producing a low frequency sound wave from the horn bell. The number of horns required is determined by fabric area and the number of baghouse compartments. Typically, 1 to 4 horns per compartment operating at 150 to 200 hertz are required. Compressed air to power the horns is supplied at 275 to 620 kiloPascals (kPa) (40 to 90 pounds per square inch gage (psig)). Sonic horns activate for approximately 10 to 30 seconds during each cleaning cycle (Carr, 1984) .

Sonic horn cleaning significantly reduces the residual dust load on the bags. This decreases the pressure drop across the filter fabric by 20 to 60%. It also lessens the mechanical stress on the bags, resulting in longer operational life (Carr, 1984). As stated previously, this can decrease the O&M cost by 1 to 3%, annually. Baghouse compartments are easily retrofitted with sonic horns. Sonic assistance is frequently used with fabric filters at coal-burning utilities (EPA, 1998a).

Reverse-jet is a cleaning method developed in the 1950's to provide better removal of residual dusts. In this method, the reverse air is piped to a ring around the bag with a narrow slot in it. The air flows through the slot, creating a high velocity air stream that flexes the bag at that point. The ring is mounted on a carriage, driven by a motor and cable system, that travels up and down the bag. This method provides excellent cleaning of residual dust. Due to its complexity, however, maintenance requirements are high. In addition, air impingement on the bags results in increased wear (Billings, 1970). The application of reverse-jet cleaning has been declining (EPA, 1998a).

Advantages:

Fabric filters in general provide high collection efficiencies on both coarse and fine (submicron) particulates. They are relatively insensitive to fluctuations in gas stream conditions. Efficiency and pressure drop are relatively unaffected by large changes in inlet dust loadings for continuously cleaned filters. Filter outlet air is very clean and may be recirculated within the plant in many cases (for energy conservation). Collected material is collected dry for subsequent processing or disposal. Corrosion and rusting of components are usually not problems. Operation is relatively simple. Unlike electrostatic precipitators, fabric filter systems do not require the use of high voltage, therefore, maintenance is simplified and flammable dust may be collected with proper care. The use of selected fibrous or granular filter aids (precoating) permits the high-efficiency collection of submicron smokes and gaseous contaminants. Filter collectors are available in a large number of configurations, resulting in a range of dimensions and inlet and outlet flange locations to suit installation requirements. (AWMA, 1992)

Disadvantages:

Temperatures much in excess of 290•C (550•F) require special refractory mineral or metallic fabrics, which can be expensive. Certain dusts may require fabric treatments to reduce dust seepage, or in other cases, assist in the removal of the collected dust. Concentrations of some dusts in the collector, approximately 50 g/m^3 (22 gr/ft^3), may represent a fire or explosion hazard if a spark or flame is accidentally admitted. Fabrics can burn if readily oxidizable dust is being collected. Fabric filters have relatively high maintenance requirements (e.g., periodic bag replacement). Fabric life may be shortened at elevated temperatures and in the presence of acid or alkaline particulate or gas constituents. They cannot be operated in moist environments; hygroscopic materials, condensation of moisture, or tarry adhesive components may cause crusty caking or plugging of the fabric or require special additives. Respiratory protection for maintenance personnel may be required when replacing fabric. Medium pressure drop is required, typically in the range of 100 to 250 mm of water column (4 to 10 inches of water column). (AWMA, 1992)

Other Considerations:

Fabric filters are useful for collecting particles with resistivities either too low or too high for collection with electrostatic precipitators. Fabric filters therefore may be good candidates for collecting fly ash from low-sulfur coals or fly ash containing high unburned carbon levels, which respectively have high and low resistivities, and thus are relatively difficult to collect with electrostatic precipitators. (STAPPA/ALAPCO, 1996)

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EPA-452/F-03-027

Air Pollution Control Technology
Fact Sheet

Name of Technology: Dry Electrostatic Precipitator (ESP)- Wire-Pipe Type

Type of Technology: Control Device - Capture/Disposal

Applicable Pollutants:

Particulate Matter (PM), including particulate matter less than or equal to 10 micrometers (µm) in aerodynamic diameter (PM_{10}), particulate matter less than or equal to 2.5 µm in aerodynamic diameter ($PM_{2.5}$), and hazardous air pollutants (HAPs) that are in particulate form, such as most metals (mercury is the notable exception, as a significant portion of emissions are in the form of elemental vapor).

Achievable Emission Limits/Reductions:

Typical new equipment design efficiencies are between 99 and 99.9%. Older existing equipment have a range of actual operating efficiencies of 90 to 99.9%. While several factors determine ESP collection efficiency, ESP size is most important. Size determines treatment time; the longer a particle spends in the ESP, the greater its chance of being collected. Maximizing electric field strength will maximize ESP collection efficiency (STAPPA/ALAPCO, 1996). Collection efficiency is also affected by dust resistivity, gas temperature, chemical composition (of the dust and the gas), and particle size distribution.

Applicable Source Type: Point

Typical Industrial Applications:

Many older ESPs are of the wire-pipe design, consisting of a single tube placed on top of a smokestack (EPA, 1998). Dry pipe-type ESPs are occasionally used by the textile industry, pulp and paper facilities, the metallurgical industry, including coke ovens, hazardous waste incinerators, and sulfuric acid manufacturing plants, among others, though other ESP types are employed as well. Wet wire-pipe ESPs are used much more frequently than dry wire-pipe ESPs, which are used only in cases in which wet cleaning is undesirable, such as high temperature streams or wastewater restrictions (EPA, 1998; Flynn, 1999).

Emission Stream Characteristics:

a. **Air Flow:** Typical gas flow rates for dry wire-pipe ESPs are 0.5 to 50 standard cubic meters per second (sm^3/sec) (1,000 to 100,000 standard cubic feet per minute (scfm)) (Flynn, 1999).

b. **Temperature:** Dry wire-pipe ESPs can operate at very high temperatures, up to 700°C (1300°F) (AWMA, 1992). Operating gas temperature and chemical composition of the dust are key factors influencing dust resistivity and must be carefully considered in the design of an ESP.

c. **Pollutant Loading:** Typical inlet concentrations to a wire-pipe ESP are 1 to 10 g/m^3 (0.5 to 5 gr/scf). It is common to pretreat a waste stream, usually with a wet spray or scrubber, to bring the stream temperature and pollutant loading into a manageable range. Highly toxic flows with concentrations well below 1 g/m^3 (0.5 gr/scf) are also sometimes controlled with ESPs (Flynn, 1999).

d. **Other Considerations:** In general, dry ESPs operate most efficiently with dust resistivities between 5×10^3 and 2×10^{10} ohm-cm. In general, the most difficult particles to collect are those with aerodynamic diameters between 0.1 and 1.0 µm. Particles between 0.2 and 0.4 µm usually show the most penetration. This is most likely a result of the transition region between field and diffusion charging (EPA, 1998).

Emission Stream Pretreatment Requirements:

When much of the pollutant loading consists of relatively large particles, mechanical collectors, such as cyclones or spray coolers may be used to reduce the load on the ESP, especially at high inlet concentrations. Gas conditioning equipment to improve ESP performance by changing dust resistivity is occasionally used as part of the original design, but more frequently it is used to upgrade existing ESPs. The equipment injects an agent into the gas stream ahead of the ESP. Usually, the agent mixes with the particles and alters their resistivity to promote higher migration velocity, and thus higher collection efficiency. Conditioning agents that are used include SO_3, H_2SO_4, sodium compounds, ammonia, and water; the conditioning agent most used is SO_3 (AWMA, 1992).

Cost Information:

The following are cost ranges (expressed in 2002 dollars) for dry wire-pipe ESPs of conventional design under typical operating conditions, developed using EPA cost-estimating spreadsheets (EPA, 1996). Costs can be substantially higher than in the ranges shown for pollutants which require an unusually high level of control, or which require the ESP to be constructed of special materials such as stainless steel or titanium. In general, smaller units controlling a low concentration waste stream will not be as cost effective as a large unit cleaning a high pollutant load flow.

a. **Capital Cost:** \$42,000 to \$260,000 per sm^3/sec (\$20 to \$125 per scfm)

b. **O & M Cost:** \$8,500 to \$19,000 per sm^3/sec (\$4 to \$9 per scfm), annually

c. **Annualized Cost:** \$19,000 to \$55,000 per sm^3/sec (\$9 to \$26 per scfm), annually

d. **Cost Effectiveness:** \$47 to \$710 per metric ton (\$43 to \$640 per short ton)

Theory of Operation:

An ESP is a particulate control device that uses electrical forces to move particles entrained within an exhaust stream onto collection surfaces. The entrained particles are given an electrical charge when they pass through a corona, a region where gaseous ions flow. Electrodes in the center of the flow lane are maintained at high voltage and generate the electrical field that forces the particles to the collector walls. In dry ESPs, the collectors are knocked, or "rapped", by various mechanical means to dislodge the particulate, which slides downward into a hopper where they are collected. Recently, dry wire-pipe ESPs are being cleaned acoustically with sonic horns (Flynn, 1999). The horns, typically cast metal horn bells, are usually powered by compressed air, and acoustic vibration is introduced by a vibrating metal plate that periodically interrupts the airflow (AWMA, 1992). As with a rapping system, the collected particulate slides downward into the hopper. The hopper is evacuated periodically, as it becomes full. Dust is removed through a valve into a dust-handling system, such as a pneumatic conveyor, and is then disposed of in an appropriate manner.

In a wire-pipe ESP, also called a tubular ESP, the exhaust gas flows vertically through conductive tubes, generally with many tubes operating in parallel. The tubes may be formed as a circular, square, or hexagonal honeycomb. Square and hexagonal pipes can be packed closer together than cylindrical pipes, reducing wasted space. Pipes are generally 7 to 30 cm (3 to 12 inches (in.)) in diameter and 1 to 4 meters (3 to 12 feet) in length. The high voltage electrodes are long wires or rigid "masts" suspended from a frame in the upper part of the ESP that run through the axis of each tube. Rigid electrodes are generally supported by both an upper and lower frame. In modern designs, sharp points are added to the electrodes, either at the entrance to a tube or along the entire length in the form of stars, to provide additional ionization sites (EPA, 1998; Flynn, 1999).

The power supplies for the ESP convert the industrial AC voltage (220 to 480 volts) to pulsating DC voltage in the range of 20,000 to 100,000 volts as needed. The voltage applied to the electrodes causes the gas between the electrodes to break down electrically, an action known as a "corona." The electrodes are usually given a negative polarity because a negative corona supports a higher voltage than does a positive corona before sparking occurs. The ions generated in the corona follow electric field lines from the electrode to the collection surfaces. Therefore, each electrode-pipe combination establishes a charging zone through which the particles must pass. As larger particles (>10 µm diameter) absorb many times more ions than small particles (>1 µm diameter), the electrical forces are much stronger on the large particles (EPA, 1996).

Due to necessary clearances needed for nonelectrified internal components at the top of wire-plate ESPs, part of the gas is able to flow around the charging zones. This is called "sneakage" and places an upper limit on the collection efficiency. Wire-pipe ESPs provide no sneakage paths around the collecting region, but field nonuniformities may allow some particles to avoid charging for a considerable fraction of the tube length. Dry wire-pipe ESPs are, however, subject to reentrainment of the collected material after cleaning the collectors with a rapping or acoustic mechanism, though the closed nature of the pipes increases chances for recollection (AWMA, 1992).

Another major factor in the performance is the resistivity of the collected material. Because the particles form a continuous layer on the ESP pipes, all the ion current must pass through the layer to reach the ground. This current creates an electric field in the layer, and it can become large enough to cause local electrical breakdown. When this occurs, new ions of the wrong polarity are injected into the wire-pipe gap where they reduce the charge on the particles and may cause sparking. This breakdown condition is called "back corona." Back corona is prevalent when the resistivity of the layer is high, usually above 2×10^{11} ohm-cm. Above this level, the collection ability of the unit is reduced considerably because the sever back corona causes difficulties in charging the particles. Low resistivities will also cause problems. At resistivities below 10^{8} ohm-cm, the particles are held on the collecting surface so loosely that general reentrainment, as well as that associated with collector cleaning, become much more severe. Hence, care must be taken in measuring or estimating resistivity because it is strongly affected by such variables as temperature, moisture, gas composition, particle composition, and surface characteristics (AWMA, 1992).

Advantages:

Dry wire-pipe ESPs and other ESPs in general, because they act only on the particulate to be removed, and only minimally hinder flue gas flow, have very low pressure drops (typically less than 13 millimeters (mm) (0.5 in.) water column). As a result, energy requirements and operating costs tend to be low. They are capable of very high efficiencies, even for very small particles. They can be designed for a wide range of gas temperatures, and can handle high temperatures, up to 700°C (1300°F). Dry collection and disposal allows for easier handling. Operating costs are relatively low. ESPs are capable of operating under high pressure (to 1,030 kPa (150 psi)) or vacuum conditions. Relatively large gas flow rates can be effectively handled, though are uncommon in wire-pipe ESPs (AWMA, 1992).

Disadvantages:

ESPs generally have high capital costs. Wire discharge electrodes (approximately 2.5 mm (0.01 in.) in diameter) are high-maintenance items. Corrosion can occur near the top of the wires because of air leakage and acid condensation. Also, long weighted wires tend to oscillate - the middle of the wire can approach the pipe, causing increased sparking and wear. Newer ESP designs are tending toward rigid electrodes, or "masts" which largely eliminate the drawbacks of using wire electrodes (Cooper and Alley, 1994; Flynn, 1999).

ESPs in general are not suited for use in processes which are highly variable because they are very sensitive to fluctuations in gas stream conditions (flow rates, temperatures, particulate and gas composition, and particulate loadings). ESPs are also difficult to install in sites which have limited space since ESPs must be relatively large to obtain the low gas velocities necessary for efficient PM collection (Cooper and Alley, 1994). Certain particulates are difficult to collect due to extremely high or low resistivity characteristics. There can be an explosion hazard when treating combustible gases and/or collecting combustible particulates. Relatively sophisticated maintenance personnel are required, as well as special precautions to safeguard personnel from the high voltage. Dry ESPs are not recommended for removing sticky or moist particles. Ozone is produced by the negatively charged electrode during gas ionization (AWMA, 1992).

Other Considerations:

Dusts with very high resistivities (greater than 10^{10} ohm-cm) are also not well-suited for collection in dry ESPs. These particles are not easily charged, and thus are not easily collected. High-resistivity particles also form ash layers with very high voltage gradients on the collecting electrodes. Electrical breakdowns in these ash layers lead to injection of positively charged ions into the space between the discharge and collecting electrodes (back corona), thus reducing the charge on particles in this space and lowering collection efficiency. Fly ash from the combustion of low-sulfur coal typically has a high resistivity, and thus is difficult to collect (ICAC, 1999).

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EPA-452/F-03-028

Air Pollution Control Technology Fact Sheet

Name of Technology: Dry Electrostatic Precipitator (ESP) - Wire-Plate Type

Type of Technology: Control Device - Capture/Disposal

Applicable Pollutants: Particulate Matter (PM), including particulate matter less than or equal to 10 micrometers (•m) in aerodynamic diameter (PM_{10}), particulate matter less than or equal to 2.5 •m in aerodynamic diameter ($PM_{2.5}$), and hazardous air pollutants (HAPs) that are in particulate form, such as most metals (mercury is the notable exception, as a significant portion of emissions are in the form of elemental vapor).

Achievable Emission Limits/Reductions:

Typical new equipment design efficiencies are between 99 and 99.9%. Older existing equipment have a range of actual operating efficiencies of 90 to 99.9%. While several factors determine ESP collection efficiency, ESP size is most important. Size determines treatment time; the longer a particle spends in the ESP, the greater its chance of being collected. Maximizing electric field strength will maximize ESP collection efficiency (STAPPA/ALAPCO, 1996). Collection efficiency is also affected by dust resistivity, gas temperature, chemical composition (of the dust and the gas), and particle size distribution. Cumulative collection efficiencies of PM, PM_{10}, and $PM_{2.5}$ for actual operating ESPs in various types of applications are presented in Table 1.

Table 1. Cumulative PM, PM_{10}, and $PM_{2.5}$ Collection Efficiencies for Dry ESPs (EPA, 1998; EPA, 1997)

	Collection Efficiency (%)		
Application	Total PM (EPA, 1997)	PM_{10} (EPA, 1998)	$PM_{2.5}$ (EPA, 1998)
Coal-Fired Boilers			
Dry bottom (bituminous)	99.2	97.7	96.0
Spreader stoker (bituminous)	99.2	99.4	97.7
Primary Copper Production			
Multiple hearth roaster	99.0	99.0	99.1
Reverbatory smelter	99.0	97.1	97.4
Iron and Steel Production			
Open hearth furnace	99.2	99.2	99.2

Applicable Source Type: Point

Typical Industrial Applications:

Approximately 80% of all ESPs in the U.S. are used in the electric utility industry. ESPs are also used in pulp and paper (7%), cement and other minerals (3%), and nonferrous metals industries (1%) (EPA, 1998). Common applications of dry wire-plate ESPs are presented in Table 2.

Table 2. Typical Industrial Applications of Dry Wire-Plate ESPs (EPA, 1998)

Application	Source Category Code (SCC)	Are Other ESP Types Also Typically Used for this Application?
Utility Boilers (Coal, Oil)	1-01-002...004	No
Industrial Boilers (Coal, Oil, Wood, Liquid Waste)	1-02-001...005 1-02-009,-013	No
Commercial/Institutional Boilers (Coal, Oil, Wood)	1-03-001...005 1-03-009	No
Chemical Manufacture	Site specific	Yes
Non-Ferrous Metals Processing (Primary and Secondary):		
Copper	3-03-005 3-04-002	Yes
Lead	3-03-010 3-04-004	Yes
Zinc	3-03-030 3-04-008	Yes
Aluminum	3-03-000...002 3-04-001	Yes
Other metals production	3-03-011...014 3-04-005...006 3-04-010...022	Yes
Ferrous Metals Processing:		
Ferroalloy Production	3-03-006...007	No
Iron and Steel Production	3-03-008...009	Yes
Gray Iron Foundries	3-04-003	No
Steel Foundries	3-04-007,-009	Yes
Petroleum Refineries and Related Industries	3-06-001...999	No
Mineral Products:		
Cement Manufacturing	3-05-006...007	No
Stone Quarrying and Processing	3-05-020	Yes
Other	3-05-003...999	Yes
Wood, Pulp, and Paper	3-07-001	Yes
Incineration (Municipal Waste)	5-01-001	Yes

Emission Stream Characteristics:

a. **Air Flow:** Typical gas flow rates for wire-plate ESPs are 100 to 500 standard cubic meters per second (sm^3/sec) (200,000 to 1,000,000 standard cubic feet per minute (scfm)). Most smaller plate-type ESPs (50 sm^3/sec to 100 sm^3/sec, or 100,000 to 200,000 scfm) use flat plates instead of wires for the high-voltage electrodes (AWMA, 1992).

b. **Temperature:** Wire-plate ESPs can operate at very high temperatures, up to 700°C (1300°F) (AWMA, 1992). Operating gas temperature and chemical composition of the dust are key factors influencing dust resistivity and must be carefully considered in the design of an ESP.

c. **Pollutant Loading:** Typical inlet concentrations to a wire-plate ESP are 2 to 110 g/m^3 (1 to 50 grains per cubic foot (gr/ft^3)). It is common to pretreat a waste stream, usually with a mechanical collector or cyclone, to bring the pollutant loading into this range. Highly toxic flows with concentrations below 1 g/m^3 (0.5 gr/ft^3) are also sometimes controlled with ESPs (Bradburn, 1999; Boyer, 1999; Brown, 1999).

d. **Other Considerations:** In general, dry ESPs operate most efficiently with dust resistivities between 5×10^3 and 2×10^{10} ohm-cm. In general, the most difficult particles to collect are those with aerodynamic diameters between 0.1 and 1.0 μm. Particles between 0.2 and 0.4 μm usually show the most penetration. This is most likely a result of the transition region between field and diffusion charging (EPA, 1998).

Emission Stream Pretreatment Requirements:

When much of the pollutant loading consists of relatively large particles, mechanical collectors such as cyclones or spray coolers may be used to reduce the load on the ESP, especially at high inlet concentrations. Gas conditioning equipment to improve ESP performance by changing dust resistivity is occasionally used as part of the original design, but more frequently it is used to upgrade existing ESPs. The equipment injects an agent into the gas stream ahead of the ESP. Usually, the agent mixes with the particles and alters their resistivity to promote higher migration velocity, and thus higher collection efficiency. Conditioning agents that are used include SO_3, H_2SO_4, sodium compounds, ammonia, and water; the conditioning agent most used is SO_3 (AWMA, 1992).

Cost Information:

The following are cost ranges (expressed in 2002 dollars) for wire-plate ESPs of conventional design under typical operating conditions, developed using EPA cost-estimating spreadsheets (EPA, 1996). Costs can be substantially higher than in the ranges shown for pollutants which require an unusually high level of control, or which require the ESP to be constructed of special materials such as stainless steel or titanium. In general, smaller units controlling a low concentration waste stream will not be as cost effective as a large unit cleaning a high pollutant load flow.

a. **Capital Cost:** \$21,000 to \$70,000 per sm^3/sec (\$10 to \$33 per scfm)

b. **O & M Cost:** \$6,400 to \$74,000 per sm^3/sec (\$3 to \$35 per scfm), annually

c. **Annualized Cost:** \$9,100 to \$81,000 per sm^3/sec (\$4 to \$38 per scfm), annually

d. **Cost Effectiveness:** \$38 to \$260 per metric ton (\$35 to \$236 per short ton)

Theory of Operation:

An ESP is a particulate control device that uses electrical forces to move particles entrained within an exhaust stream onto collector plates. The entrained particles are given an electrical charge when they pass through a corona, a region where gaseous ions flow. Electrodes in the center of the flow lane are maintained at high voltage and generate the electrical field that forces the particles to the collector walls. In dry ESPs, the collectors are knocked, or "rapped", by various mechanical means to dislodge the particulate, which slides downward into a hopper where they are collected. The hopper is evacuated periodically, as it becomes full. Dust is removed through a valve into a dust-handling system, such as a pneumatic conveyor, and is then disposed of in an appropriate manner.

In the wire-plate ESP, the exhaust gas flows horizontally and parallel to vertical plates of sheet metal. Plate spacing is typically between 19 to 38 cm (9 in. and 18 in.) (AWMA, 1992). The high voltage electrodes are long wires that are weighted and hang between the plates. Some later designs use rigid electrodes (hollow pipes approximately 25 mm to 40 mm in diameter) in place of wire (Cooper and Alley, 1994). Within each flow path, gas flow must pass each wire in sequence as it flows through the unit. The flow areas between the plates are called ducts. Duct heights are typically 6 to 14 m (20 to 45 feet) (EPA, 1998).

The power supplies for the ESP convert the industrial AC voltage (220 to 480 volts) to pulsating DC voltage in the range of 20,000 to 100,000 volts as needed. The voltage applied to the electrodes causes the gas between the electrodes to break down electrically, an action known as a "corona." The electrodes are usually given a negative polarity because a negative corona supports a higher voltage than does a positive corona before sparking occurs. The ions generated in the corona follow electric field lines from the wires to the collecting plates. Therefore, each wire establishes a charging zone through which the particles must pass. As larger particles (>10 μm diameter) absorb many times more ions than small particles (>1 μm diameter), the electrical forces are much stronger on the large particles (EPA, 1996).

Certain types of losses affect control efficiency. The rapping that dislodges the accumulated layer also project some of the particles (typically 12% for coal fly ash) back into the gas stream. These reentrained particles are then processed again by later sections, but the particles reentrained in the last section of the ESP have no chance to be recaptured and so escape the unit. Due to necessary clearances needed for nonelectrified internal components at the top of the ESP, part of the gas may flow around the charging zones. This is called "sneakage" and places an upper limit on the collection efficiency. Anti-sneakage baffles are placed to force the sneakage flow to mix with the main gas stream for collection in later sections (EPA, 1998).

Another major factor in the performance is the resistivity of the collected material. Because the particles form a continuous layer on the ESP plates, all the ion current must pass through the layer to reach the ground plates. This current creates an electric field in the layer, and it can become large enough to cause local electrical breakdown. When this occurs, new ions of the wrong polarity are injected into the wire-plate gap where they reduce the charge on the particles and may cause sparking. This breakdown condition is called "back corona." Back corona is prevalent when the resistivity of the layer is high, usually above 2×10^{11} ohm-cm. Above this level, the collection ability of the unit is reduced considerably because the sever back corona causes difficulties in charging the particles. Low resistivities will also cause problems. At resistivities below 10^8 ohm-cm, the particles are held on the plates so loosely that rapping and nonrapping reentrainment become much more severe. Hence, care must be taken in measuring or estimating resistivity because it is strongly affected by such variables as temperature, moisture, gas composition, particle composition, and surface characteristics (AWMA, 1992).

Precipitator size is related to many design parameters. One of the main parameters is the specific collection area (SCA), which is defined as the ratio of the surface area of the collection electrodes to the gas flow. Higher collection areas lead to better removal efficiencies. Collection areas normally are in the range of 40 to 160 m^2 per sm^3/second of gas flow (200-800 ft^2/1000 scfm), with typical values of 80 (400) (AWMA, 1992).

Advantages:

Dry wire-plate ESPs and other ESPs in general, because they act only on the particulate to be removed, and only minimally hinder flue gas flow, have very low pressure drops (typically less than 13 mm (0.5 in.) water column). As a result, energy requirements and operating costs tend to be low. They are capable of very high efficiencies, even for very small particles. They can be designed for a wide range of gas temperatures, and can handle high temperatures, up to 700°C (1300°F). Dry collection and disposal allows for easier handling. Operating costs are relatively low. ESPs are capable of operating under high pressure (to 1,030 kPa (150 psi)) or vacuum conditions. Relatively large gas flow rates can be effectively handled. (AWMA, 1992)

Disadvantages:

ESPs generally have high capital costs. The wire discharge electrodes (approximately 2.5 mm (0.01 in.) in diameter) are high-maintenance items. Corrosion can occur near the top of the wires because of air leakage and acid condensation. Also, long weighted wires tend to oscillate - the middle of the wire can approach the plate, causing increased sparking and wear. Newer ESP designs are tending toward rigid electrodes (Cooper and Alley, 1994).

ESPs in general are not suited for use in processes which are highly variable because they are very sensitive to fluctuations in gas stream conditions (flow rates, temperatures, particulate and gas composition, and particulate loadings). ESPs are also difficult to install in sites which have limited space since ESPs must be relatively large to obtain the low gas velocities necessary for efficient PM collection (Cooper and Alley, 1994). Certain particulates are difficult to collect due to extremely high or low resistivity characteristics. There can be an explosion hazard when treating combustible gases and/or collecting combustible particulates. Relatively sophisticated maintenance personnel are required, as well as special precautions to safeguard personnel from the high voltage. Dry ESPs are not recommended for removing sticky or moist particles. Ozone is produced by the negatively charged electrode during gas ionization (AWMA, 1992).

Other Considerations:

Dusts with very high resistivities (greater than 10^{10} ohm-cm) are also not well-suited for collection in dry ESPs. These particles are not easily charged, and thus are not easily collected. High-resistivity particles also form ash layers with very high voltage gradients on the collecting electrodes. Electrical breakdowns in these ash layers lead to injection of positively charged ions into the space between the discharge and collecting electrodes (back corona), thus reducing the charge on particles in this space and lowering collection efficiency. Fly ash from the combustion of low-sulfur coal typically has a high resistivity, and thus is difficult to collect (ICAC, 1999).

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EPA-452/F-03-029

Air Pollution Control Technology
Fact Sheet

Name of Technology: Wet Electrostatic Precipitator (ESP)- Wire-Pipe Type

Type of Technology: Control Device - Capture/Disposal

Applicable Pollutants: Particulate Matter (PM), including particulate matter less than or equal to 10 micrometers (μm) in aerodynamic diameter (PM_{10}), particulate matter less than or equal to 2.5 μm in aerodynamic diameter ($PM_{2.5}$), and hazardous air pollutants (HAPs) that are in particulate form, such as most metals (mercury is the notable exception, as a significant portion of emissions are in the form of elemental vapor). Wet ESPs are often used to control acid mists and can provide incidental control of volatile organic compounds.

Achievable Emission Limits/Reductions:

Typical new equipment design efficiencies are between 99 and 99.9%. Older existing equipment have a range of actual operating efficiencies of 90 to 99.9%. While several factors determine ESP collection efficiency, ESP size is most important. Size determines treatment time; the longer a particle spends in the ESP, the greater its chance of being collected. Maximizing electric field strength will maximize ESP collection efficiency (STAPPA/ALAPCO, 1996). Collection efficiency is also affected to some extent by dust resistivity, gas temperature, chemical composition (of the dust and the gas), and particle size distribution.

Applicable Source Type: Point

Typical Industrial Applications:

Wet ESPs are used in situations for which dry ESPs are not suited, such as when the material to be collected is wet, sticky, flammable, explosive, or has a high resistivity. Also, as higher collection efficiencies have become more desirable, wet ESP applications have been increasing. Many older ESPs are of the wire-pipe design, consisting of a single tube placed on top of a smokestack (EPA, 1998). Wet pipe-type ESPs are commonly used by the textile industry, pulp and paper facilities, the metalurgical industry, including coke ovens, hazardous waste incinerators, and sulfuric acid manufacturing plants, among others, though other ESP types are employed as well (EPA, 1998; Flynn, 1999).

Emission Stream Characteristics:

a. **Air Flow:** Typical gas flow rates for wet wire-pipe ESPs are 0.5 to 50 standard cubic meters per second (sm^3/sec) (1,000 to 100,000 standard cubic feet per minute (scfm)) (Flynn, 1999).

b. **Temperature:** Wet wire-pipe ESPs are limited to operating at temperatures lower than approximately 80 to 90•C (170 to 190•F) (EPA, 1998; Flynn, 1999).

c. **Pollutant Loading:** Typical inlet concentrations to a wire-pipe ESP are 1 to 10 grams per cubic meter (g/m^3) (0.5 to 5 gr/ft^3). It is common to pretreat a waste stream, usually with a wet spray or scrubber, to bring the stream temperature and pollutant loading into a manageable range. Highly toxic flows with concentrations well below 1 g/m^3 (0.5 gr/ft^3) are also sometimes controlled with ESPs (Flynn, 1999).

d. **Other Considerations:** Dust resistivity is not a factor for wet ESPs, because of the high humidity atmosphere which lowers the resistivity of most materials. Particle size is much less of a factor for wet ESPs, compared to dry ESPs. Much smaller particles can be efficiently collected by wet ESPs due to the lack of resistivity concerns and the reduced reentrainment (Flynn, 1999).

Emission Stream Pretreatment Requirements:

When the pollutant loading is exceptionally high or consists of relatively large particles (> 2 µm), venturi scrubbers or spray chambers may be used to reduce the load on the ESP. Much larger particles (> 10 µm), are controlled with mechanical collectors such as cyclones. Gas conditioning equipment to reduce both inlet concentration and gas temperature is occasionally used as part of the original design of a wet ESPs (AWMA, 1992; Flynn, 1999).

Cost Information:

The following are cost ranges (expressed in 2002 dollars) for wire-pipe ESPs of conventional design under typical operating conditions, developed using EPA cost-estimating spreadsheets for dry wire-plate ESPs with adjustments made to reflect wet wire-pipe ESPs (EPA, 1996). Costs can be substantially higher than in the ranges shown for pollutants which require an unusually high level of control, or which require the ESP to be constructed of special materials such as titanium. Capital and operating costs are generally higher due to noncorrosive materials requirements, increased water usage, and treatment and disposal of wet effluent. In most cases, smaller units controlling a low concentration waste stream will not be as cost effective as a large unit cleaning a high pollutant load flow (EPA, 1998).

a. **Capital Cost:** $85,000 to $424,000 per s$m^3$/sec ($40 to $200 per scfm)

b. **O & M Cost:** $12,000 to $21,000 per s$m^3$/sec ($6 to $10 per scfm), annually

c. **Annualized Cost:** $25,000 to $97,000 per s$m^3$/s ($12 to $46 per scfm), annually

d. **Cost Effectiveness:** $73 to $720 per metric ton ($65 to $660 per ton)

Theory of Operation:

An ESP is a particulate control device that uses electrical forces to move particles entrained within an exhaust stream onto collection surfaces. The entrained particles are given an electrical charge when they pass through a corona, a region where gaseous ions flow. Electrodes in the center of the flow lane are maintained at high voltage and generate the electrical field that forces the particles to the collector walls. In wet ESPs, the collectors are either intermittently or continuously washed by a spray of liquid, usually water. The collection hoppers used by dry ESPs are replaced with a drainage system. The wet effluent is collected, and often treated on-site (EPA, 1998).

In a wire-pipe ESP, also called a tubular ESP, the exhaust gas flows vertically through conductive tubes, generally with many tubes operating in parallel. The tubes may be formed as a circular, square, or hexagonal honeycomb. Square and hexagonal pipes can be packed closer together than cylindrical pipes, reducing wasted space. Pipes are generally 7 to 30 cm (3 to 12 inches (in.)) in diameter and 1 to 4 m (3 to 12 feet) in length. The high voltage electrodes are long wires or rigid “masts” suspended from a frame in the upper part of the ESP that run through the axis of each tube. Rigid electrodes are generally supported by both an upper and lower frame. In modern designs, sharp points are added to the electrodes, either at the entrance to a tube or along the entire length in the form of stars, to provide additional ionization sites (EPA, 1998; Flynn, 1999).

The power supplies for the ESP convert the industrial AC voltage (220 to 480 volts) to pulsating DC voltage in the range of 20,000 to 100,000 volts as needed. The voltage applied to the electrodes causes the gas between the electrodes to break down electrically, an action known as a “corona.” The electrodes are usually given a negative polarity because a negative corona supports a higher voltage than does a positive corona before sparking occurs. The ions generated in the corona follow electric field lines from the electrode to the collecting pipe. Therefore, each electrode-pipe combination establishes a charging zone through which the particles must pass. As larger particles (>10 •m diameter) absorb many times more ions than small particles (>1 •m diameter), the electrical forces are much stronger on the large particles (EPA, 1996).

Due to necessary clearances needed for nonelectrified internal components at the top of wire-plate ESPs, part of the gas is able to flow around the charging zones. This is called “sneakage” and places an upper limit on the collection efficiency. Wire-pipe ESPs provide no sneakage paths around the collecting region, but field nonuniformities may allow some particles to avoid charging for a considerable fraction of the tube length (AWMA, 1992).

Wet ESPs require a source of wash water to be injected or sprayed near the top of the collector pipes either continuously or at timed intervals. This wash system replaces the rapping mechanism usually used by dry ESPs. The water flows with the collected particles into a sump from which the fluid is pumped or drained. A portion of the fluid may be recycled to reduce the total amount of water required. The remainder is pumped into a settling pond or passed through a dewatering stage, with subsequent disposal of the sludge (AWMA, 1992).

Unlike dry ESPs, resistivity of the collected material is generally not a major factor in performance. Because of the high humidity in a wet ESP, the resistivity of particles is lowered, eliminating the “back corona” condition. The frequent washing of the pipes also limits particle buildup on the collectors (EPA, 1998).

Advantages:

Wet wire-pipe ESPs and other ESPs in general, because they act only on the particulate to be removed, and only minimally hinder flue gas flow, have very low pressure drops (typically less than 13 millimeters (mm) (0.5 in.) water column). As a result, energy requirements and operating costs tend to be low. They are capable of very high efficiencies, even for very small particles. Operating costs are relatively low. ESPs are capable of operating under high pressure (to 1,030 kPa (150 psi)) or vacuum conditions, and relatively large gas flow rates can be effectively handled (AWMA, 1992).

Wet ESPs can collect sticky particles and mists, as well as highly resistive or explosive dusts. The continuous or intermittent washing with a liquid eliminates the reentrainment of particles due to rapping which dry ESPs are subject to. The humid atmosphere that results from the washing in a wet ESP enables them to collect high resistivity particles, absorb gases or cause pollutants to condense, and cools and conditions the gas stream. Liquid particles or aerosols present in the gas stream are collected along with particles and provide another means of rinsing the collection electrodes (EPA, 1998). Wet wire-pipe ESPs have the additional advantages of reducing “sneakage” by passing the entire gas stream through the collection field, and the ability to be tightly sealed to prevent leaks of materia, especially valuable or hazardous materials (AWMA, 1992).

Disadvantages:

ESPs generally have high capital costs. Wire discharge electrodes (approximately 2.5 mm (0.01 in.) in diameter) are high-maintenance items. Corrosion can occur near the top of the wires because of air leakage and acid condensation. Also, long weighted wires tend to oscillate - the middle of the wire can approach the pipe, causing increased sparking and wear. Newer ESP designs are tending toward rigid electrodes, or “masts” which largely eliminate the drawbacks of using wire electrodes (Cooper and Alley, 1994; Flynn, 1999).

ESPs in general are not suited for use in processes which are highly variable because they are very sensitive to fluctuations in gas stream conditions (flow rates, temperatures, particulate and gas composition, and particulate loadings). ESPs are also difficult to install in sites which have limited space since ESPs must be relatively large to obtain the low gas velocities necessary for efficient PM collection (Cooper and Alley, 1994). Relatively sophisticated maintenance personnel are required, as well as special precautions to safeguard personnel from the high voltage. Ozone is produced by the negatively charged electrode during gas ionization (AWMA, 1992). Wet ESPs add the complexity of a wash system, and the fact that the resulting slurry must be handled more carefully than a dry product, and in many cases requires treatment, especially if the dust can be sold or recycled. Wet ESPs are limited to operating at stream temperatures under approximately 80 to 90•C (170 to 190•F), and generally must be constructed of noncorrosive materials (EPA, 1998; Flynn, 1999).

Other Considerations:

For wet ESPs, consideration must be given to handling wastewaters. For simple systems with innocuous dusts, water with particles collected by the ESP may be discharged from the ESP system to a solids-removing clarifier (either dedicated to the ESP or part of the plant wastewater treatment system) and then to final disposal. More complicated systems may require skimming and sludge removal, clarification in dedicated wequipment, pH adjustment, and/or treatment to remove dissolved solids. Spray water from an ESP preconditioner may be treated separately from the water used to wash the ESP collecting pipes so that the cleaner of the two treated water streams may be returned to the ESP. Recirculation of treated water to the ESP may approach 100 percent (AWMA, 1992).

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