Prepared for
Canadian Energy Partnership for Environmental Innovation and
Petroleum Technology Alliance Canada

Prepared by
Ramboll Environ,
Irvine, California

Document type
Final (Revision 0)

Date
8 July, 2016

CEPEI PM2.5 EMISSION FACTOR DEVELOPMENT

UPDATE: ALTERNATIVE PM2.5 EMISSION FACTORS FOR NATURAL GAS-FIRED ENGINES

RAMBOLL ENVIRON

REVISION HISTORY

Revision No.	Date	Approved By	Comment
Draft A	16 February 2016	Glenn England	For review
Draft B	4 March 2016	Glenn England	Revised – for review
Revision 0	8 July 2016	Glenn England	Final. Revised in response to CEPEI comments and final test data. Misc. corrections and revisions.

Distribution

Jasmine Urisk (CEPEI)

Glenn England (Ramboll Environ)

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

T5EmissionFactorReport-R0.docx

ACRONYMS AND ABBREVIATIONS

%	percent
%vol	percent volume
°C	degrees Centigrade
°F	degrees Fahrenheit
°R	degrees Rankine
µg	microgram
2SLB	two-stroke lean burn
4SLB	four-stroke lean burn
4SRB	four-stroke rich burn
A/F	air-fuel ratio controller
Ag	silver
Al	aluminum
API	American Petroleum Institute
Au	gold
Ba	barium
BC	British Columbia
Br	bromine
Btu	British thermal unit
Btu/scf	British thermal units per standard cubic foot
Ca	calcium
Cd	cadmium
Ce	cerium
CEPEI	Canadian Energy Partnership for Environmental Innovation
cfm	cubic feet per minute
Cl	chlorine
Cl^-	chloride ion
CO Cat	CO oxidation catalyst
CO	carbon monoxide
Co	cobalt
CO_2	carbon dioxide
cPM	condensable particulate matter
Cr	chromium

Cs	cesium
CTM 39	U.S. EPA Conditional Test Method 039
Cu	copper
DB	duct burner
DR	dilution ratio
dscf	dry standard cubic foot (unless otherwise noted, standard reference conditions are 528°R, 29.92 in. Hg)
dscfm	dry standard cubic feet per minute
dscm	dry standard cubic meter
EC	elemental carbon
Eu	europium
Fe	iron
fPM	filterable particulate matter
g	gram
GJ/hr	gigajoules per hour
gr	grain (= 1/7000 pound)
GTCC/C	gas turbine combined cycle cogeneration unit
Hg	mercury
HHV	higher (gross) heating value
hp	horsepower
hr	hour
In	indium
K	potassium
kg/GJ	kilograms per gigajoule
kg/s	kilograms per second
La	lanthanum
lb	pound
LPC	lean premix combustor
Mg	magnesium
mg	milligram
MMBtu	million British thermal units
MMBtu/hr	million British thermal units per hour
Mn	manganese
Mo	molybdenum

MW	megawatt
Na	sodium
Na^+	sodium ion
NH_4^+	ammonium ion
Ni	nickel
NO_3^-	nitrate ion
NO_X	nitrogen oxides
NSCR	non-selective catalytic reduction
O_2	oxygen (molecular)
OC	organic carbon
P	phosphorus
PAH	polycyclic aromatic hydrocarbons
Pb	lead
PCC	pre-combustion chamber
PM	particulate matter
PM10	particulate matter with aerodynamic diameter of 10 micrometers and smaller
PM2.5	particulate matter with aerodynamic diameter of 2.5 micrometers and smaller
psia	pound per square inch absolute
Q-Q	quantile-quantile (graph)
Rb	rubidium
RICE	reciprocating internal combustion engine
RPM	revolutions per minute
S	sulfur
Sb	antimony
scf	standard cubic foot
scfd	standard cubic feet per day
SCR	selective catalytic reduction
Si	silicon
Sm	samarium
Sn	tin
SO_2	sulfur dioxide
SO_4^{2-}	sulfate ion
$SO_4^=$	sulfate ion
Sr	strontium

STP	standard temperature and pressure
SVOC	semivolatile organic compounds
Tb	terbium
Ti	titanium
Tl	thallium
TMF	Teflon® membrane filter
U	uranium
UPL	upper prediction limit
U.S. EPA	U.S. Environmental Protection Agency
U.S.	United States
V	vanadium
W	tungsten
Y	yttrium
Zn	zinc
Zr	zirconium

1. EXECUTIVE SUMMARY

In 2012, the Canadian Energy Partnership for Environmental Innovation (CEPEI) published a technical memorandum[1] providing alternative PM2.5 (particles with aerodynamic diameter of 2.5 micrometers and smaller) air emission factors and species profiles for natural gas-fired boilers, process heaters, a diesel engine and gas turbine combined cycle/cogeneration power plants. This document provides updated emission factors for natural gas-fired gas turbines/combined cycle/cogeneration units and new emission factors for natural gas-fired spark-ignited reciprocating engines.

Previously reported PM2.5 emission factors and species profiles[2] are based on tests conducted in the United States (U.S.) from 1998 to 2003 during an industry-government collaboration led by GE Energy and Environmental Research Corporation (GE EER) using a dilution sampling methodology. Dilution sampling is thought to provide more accurate measurements of PM2.5 from gas combustion than traditional hot filter/cooled impinger test methods. The California Energy Commission, New York State Energy and Research Development Authority and U.S. Department of Energy co-sponsored the work along with the American Petroleum Institute (API) and Gas Research Institute. The U.S. Environmental Protection Agency (U.S. EPA) served as external peer reviewers during the study, contributing to the study design and results review, eventually adopting PM2.5 and PM10 emission factors for natural gas combustion derived from the results for use in its tri-annual air pollutant National Emission Inventories (NEIs). Those tests included two natural gas-fired heavy duty gas turbine combined cycle power generation units with lean premix combustors and a refinery gas-fired aeroderivative gas turbine cogeneration system, all three with supplementary firing capability and with post-combustion emission controls (oxidation catalyst and selective catalytic reduction, SCR). No natural gas-fired reciprocating engines were included in those collaborative tests. API separately sponsored tests of three natural gas-fired spark-ignited reciprocating engines operating as natural gas production compressor drives in 2003[3]. In 2008, GE Energy subsequently conducted method evaluation tests on a natural gas-fired combined cycle power generation unit with SCR using a similar dilution methodology based on modified U.S. EPA Conditional Test Method 39 (CTM 39), with external peer review participation from U.S. EPA, California Air Resources Board and the South Coast Air Quality Management District. In 2014, the Utah Department of Environmental Quality (in consultation with U.S. EPA) approved PM10 tests using modified CTM 39 to demonstrate compliance with PM10 emission limits based on U.S. EPA's NEI PM10 emission factor. Thus, modified CTM 39 has been applied with consent of regulatory agencies for PM2.5/10 emission factor development and for regulatory compliance demonstration.

In 2015, CEPEI and the Petroleum Technology Alliance of Canada (PTAC), including the British Columbia Oil and Gas Research and Innovation Society (BC OGRIS), sponsored new tests on two natural gas-fired engines in Canada: a gas turbine engine and a spark-ignited reciprocating engine, both operating as natural gas pipeline compressor drives and with no post-combustion controls. The engines are typical of Canadian natural gas pipeline engines in terms of size, configuration, emission controls and operation. The objective of the tests was to provide data for developing updated PM2.5

---

[1] *Fine Particulate Emissions from Natural Gas-Fired Combustion Sources: Alternative PM2.5 Emission Factors*, Technical Memorandum, Innovative Environmental Solutions Inc., for Canadian Energy Partnership for Environmental Innovation, October, 2012.

[2] England, G.C. Development of Fine Particulate Emission Factors and Speciation Profiles for Oil and Gas-fired Combustion Systems, Final Report, 2004, prepared for U.S. Department of Energy, Gas Research Institute, American Petroleum Institute, California Energy Commission and New York State Energy Research and Development Authority, http://www.nyserda.org/environment/emepreports.html.

[3] England, G.C., K.R. Loos, K. Ritter. Measurements of PM2.5 Mass and Species Emissions from Natural Gas-Fired Reciprocating Internal Combustion Engines, SPE-94201-PP, Exploration & Production Environmental Conference, Society of Petroleum Engineers, Galveston, TX. March 2005.

emission factors and species profiles representative of engines in Canada without post-combustion controls applicable to upstream and downstream oil and gas operations and natural gas end users. The tests were conducted using a stationary source dilution sampling method combined with ambient air sample collection and analysis methods to determine both the mass and chemical speciation of combined filterable plus condensable PM2.5 emissions. The methodology is similar to that used for the earlier GE EER test program. The chemical composition of the collected aerosols also was determined (elements, selected ions and organic and elemental carbon). Detailed test results obtained in this study are provided in a separate Test Report.

Updated PM2.5 emission factors and species profiles were derived from the CEPEI test results and data from the earlier tests noted above. PM2.5 mass emission factors for gas turbines, gas turbine combined cycle/cogeneration units and for four-stroke reciprocating internal combustion engines, expressed as kilograms of PM2.5 per gigajoule of fuel heat input (kg/GJ), are provided in Table E-1. The maximum and 95% confidence upper bound provide an indication of the upper limits of the data set. The 99% confidence upper prediction limit provides an indication of an upper limit for the average for the next unit tested.

U.S. EPA's *Compilation of Air Pollutant Emission Factors* ("AP-42") is a widely-referenced source of emission factors. The published AP-42 filterable and condensable particulate matter emission factors for natural gas-fired gas turbine and four-stroke reciprocating engines, also shown in Table E-1, are based on tests of three gas turbines[4], two four-stroke lean burn and three four-stroke rich burn reciprocating engines.

The average CEPEI PM2.5 emission factor of 0.000101 kg/GJ for gas-fired gas turbines and cogeneration/combined cycle units based on dilution sampling methods is 1/28 (3.5%) of the combined AP-42 gas turbine emission factor for filterable and condensable particulate matter (0.00285 kg/GJ).

The average emission factor of 0.00150 kg/GJ for four-stroke reciprocating engines is 1/6 (16%) of the combined filterable and condensable particulate matter emission factor for all four-stroke engines derived from the AP-42 data set (0.00673 kg/GJ). Further, there are no condensable particulate matter test data for four-stroke rich burn engines in the AP-42 data set; the condensable particulate matter emission factor reported in AP-42 for four-stroke rich burn engines is based on two four-stroke lean burn engine tests.

Although AP-42 does not report uncertainty associated with the emission factors, the total particulate matter emission factor uncertainty calculated from the underlying data is 85% for the gas turbine and 270% and 438% for four-stroke rich burn and lean burn engines, respectively. The very large uncertainties for the AP-42 four-stroke engine emission factors are due to both the wide range of emissions among the units and the small number of units tested. Although the CEPEI and AP-42 data sets are similar in size, the improved precision of measurements in CEPEI's data set results in lower uncertainties. Although the data sets are small in both cases, we consider the CEPEI emission factors more robust than the AP-42 factors because of much lower uncertainty (in terms of both relative percent and absolute magnitude).

---

[4] Two of the three units were tested with and without power augmentation. EPA treated each test as a separate unit for emission factor calculation. See discussion in Section 6.

Table E-1: Comparison of CEPEI and EPA AP-42 PM emission factors for gas-fired gas turbines, combined cycle/cogeneration units and four-stroke reciprocating engines

Parameter	**Gas-fired gas turbines, gas turbine cogeneration & combined cycle units (kg/GJ)**	**Natural gas-fired spark-ignited reciprocating engines (four-stroke) (kg/GJ)**
CEPEI Emission Factors (PM2.5, dilution sampling methods)		
Number of units tested	6 (5*)	3
Average	0.000101	0.00150
Uncertainty (95% confidence)	80%	116%
maximum	0.000236	0.00216
95% confidence upper bound	0.000148	0.00226
99% confidence upper prediction limit	0.000380	0.00710
U.S. EPA AP-42 Emission Factors (hot filter/cooled impinger sampling methods)		
Number of units tested	5 (3**)	3 (four-stroke rich burn) 2 (four-stroke lean burn)
Total particulate matter (filterable + condensable)	0.00285 (uncertainty 85%)	0.00835 (four-stroke rich burn) (uncertainty 270%) 0.00430 (four-stroke lean burn) (uncertainty 438%) 0.00673 (four-stroke all) (uncertainty 446%)***

*Five units were actually tested. One natural gas combined cycle unit at gas turbine was tested at full load with and without duct burners. Each test was treated as a separate unit, representing emissions for units with and without duct burner (supplementary firing) capability.

**Three units were actually tested. Two units were tested with and without power augmentation. Each test was treated as a separate unit.

***AP-42 does not report an aggregate emission factor for four-stroke engines. This value was calculated for comparison purposes by aggregating the unit average values used to calculate emission factors for rich burn and lean burn engines.

Average PM2.5 chemical species are measured primarily as organic carbon, with minor amounts of sulfate, ammonium, elemental carbon, chloride, nitrate and other elements. Iron and silica were more prevalent in PM2.5 from the reciprocating engines than the gas turbines and combined cycle/cogeneration units. Sulfate and ammonium were not detected in the samples from the CEPEI 2015 test program. This likely reflects low natural gas sulfur content and the absence of post-combustion catalysts (e.g., selective catalytic reduction[5] or CO oxidation catalysts) on this unit, as

---

[5] Catalysts are known to promote oxidation of SO_2 to SO_3, a precursor to particulate sulfate emissions.

compared with the refinery gas and natural gas-fired units tested previously in the U.S which did have post-combustion catalysts.

The CEPEI PM2.5 emission factor for gas turbines and combined cycle/cogeneration units is based on six tests of five units[6] including one unit firing refinery gas and four units firing natural gas. This includes simple and combined cycle/cogeneration units with and without post-combustion catalysts for NO_X and CO emissions reduction. In contrast, the AP-42 PM emission factors include data for five tests of three natural gas-fired gas turbines with water injection (for NO_X emissions control) but without post-combustion catalysts.

The CEPEI PM2.5 emission factor for four-stroke reciprocating engines is based on tests of three units: one four-stroke rich burn engine with non-selective catalytic NO_X reduction and two four-stroke lean burn engines with no post-combustion emission controls. The number of units tested is comparable with the number of units included in the AP-42 data sets. The PM2.5 emission data in the CEPEI data set for the rich burn engine is approximately four times greater than the PM2.5 emission data for the two lean burn engines. The small number of units and range of PM2.5 emissions contribute to large relative uncertainty – 186% - in the average CEPEI PM2.5 emission factor. Nevertheless, the uncertainty associated with the CEPEI PM2.5 emission factor is considerably lower than the uncertainties for the AP-42 filterable and condensable particulate matter (and by summation, total PM) emission factors, as noted above. Previous studies showed that the dilution sampling test methodology on which the CEPEI PM2.5 emission factor is based is more accurate and precise than the hot filter/cooled impinger test methods used for the AP-42 filterable and condensable particulate matter emission factors. Therefore, the CEPEI PM2.5 emission factor for natural gas-fired four-stroke engines is considered more robust than the respective AP-42 emission factors.

As a general precaution, an average or median emission factor should not be used to establish emissions limits or standards because emissions from half of the units will be higher than the average and half will be lower (assuming a normal distribution). However, an average or median emission factor is appropriate to estimate average emissions from a population of similar units. Additional testing of natural gas-fired gas turbines and/or combined cycle/cogeneration units over time could further reduce uncertainty and improve emission factor quality.

---

[6] One combined cycle unit was tested with and without duct burners firing. Each test was treated as a separate unit for emission factor analysis purposes.

2. INTRODUCTION

Atmospheric particles with aerodynamic diameter less than or equal to 2.5 micrometers (PM2.5) contribute to adverse human health, regional haze (visibility) and ecosystem effects. Most airborne PM2.5 derives from gaseous emissions that react slowly in the atmosphere to form fine particles ("secondary" PM2.5). The contribution of directly emitted ("primary") PM2.5 varies among different source types, but is relatively small for engines, boilers and other combustion equipment burning gaseous fuels. Nevertheless, PM2.5 emissions from natural gas-burning engines often receive exceptional scrutiny in populated urban areas.

Widely published PM2.5 emission factors, such as those given in the *Compilation of Air Pollutant Emission Factors* (AP-42)[7] published by the U.S. Environmental Protection Agency (U.S. EPA), are based on traditional emissions test methods for filterable and condensable PM2.5 use using hot filter/cooled impinger techniques. Previous studies showed that these methods lack sufficient sensitivity to accurately and precisely measure the very low PM2.5 concentrations typical of gas-fired combustion sources. Also, PM2.5 results from such methods often are biased high due to substances formed from gases in the samples after collection (a chemical measurement artifact, often in the form of sulfates). Although the degree of high bias due to insufficient sensitivity and chemical artifacts may be small relative to higher PM2.5 concentrations for other source types, typically it is significant relative the low PM2.5 concentrations characteristic of gas-fired combustion sources[8]. Current PM2.5 emission factors for natural gas-fired engines therefore exaggerate estimated human health and environmental impacts and often unnecessarily aggravate concerns during plant siting and licensing.

Dilution sampling methods offer greater sensitivity and precision than traditional hot filter/cooled impinger PM2.5 test methods, leading to more accurate PM2.5 emission factors. The Canadian Energy Partnership for Environmental Innovation (CEPEI) recently published recommended alternative PM2.5 emission factors for natural gas-fired gas turbine engines, gas turbine combined cycle or cogeneration units, boilers and process heaters that are based on tests conducted in the U.S. under a collaborative, multi-stakeholder government-industry research program. That program applied dilution sampling with proven ambient air sample collection and analysis methods. The PM2.5 emission factors resulting from that program are less than 1/10 of the combined filterable plus condensable particulate matter emission factors for natural gas external combustion (boilers and process heaters) and gas turbines published in AP-42. Subsequent tests sponsored by the American Petroleum Institute using the same test methodology produced PM2.5 emission factors for natural gas-fired reciprocating engines that are considerably lower than their respective AP-42 emission factors. More recently, the test methodology was further refined as a modification of a U.S. EPA dilution sampling test method and applied in tests of a natural gas-fired gas turbine combined cycle unit and several gas-fired refinery boilers and process heaters, yielding PM2.5 emission factor results of magnitude similar to those in the earlier tests. Thus, there is a growing body of test results useful for developing improved, more accurate PM2.5 emission factors for gas-fired combustion sources and an emerging test protocol for a standardized PM2.5 dilution sampling test methodology that is capable of reliable measurements at these low levels.

---

[7] *Compilation of Air Pollutant Emission Factors*, AP-42, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. https://www3.epa.gov/ttnchie1/ap42/.

[8] Wien, S., G.C. England, K.R. Loos, and K. Ritter. Investigation of Artifacts in Condensable Particulate Measurements for Stationary Combustion Sources, 94th Air &Waste Manage Association Annual Conference and Exhibition, Orlando, Florida. June 2001.

The gas turbine and reciprocating engines in the U.S. program employed catalytic emissions controls that are not widely used in Canada. Catalytic emission controls such as selective catalytic NO_X reduction can both reduce and contribute to PM2.5 emissions, depending on site-specific parameters. Therefore, there is a need for improved PM2.5 emission factors representative of units in Canada.

2.1 CEPEI Project Description

The primary goal of the project is to update PM2.5 emission factors and chemical speciation profiles that will be used for federal and provincial/territorial air quality permitting/licensing applicable to engines used in upstream/downstream oil and gas operations in Canada. A key objective is to gain acceptance for using the new emission factors among industry, government, consultants and the community. The project was sponsored by CEPEI and several of its member companies (ATCO Gas, Enbridge Gas Distribution Inc., FortisBC, Manitoba Hydro, SaskEnergy TransGas, TransCanada PipeLines Ltd., and Union Gas Limited) and by the Petroleum Technology Alliance Canada (PTAC), including funding from the BC Oil and Gas Research and Innovation society (OGRIS).

This project generated new test data and updated PM2.5 emission factors for natural gas-fired engines applicable to upstream and downstream oil and gas operations as well as end user engine applications. The tests were conducted using a proven dilution sampling method combined with ambient air sample collection and analysis methods to determine both the mass and chemical speciation of PM2.5 emissions. A modified version of U.S. EPA Conditional Test Method 039 (CTM 39) that has been recently applied to tests of several gas-fired sources was used. The modified method combines key elements of the scientifically proven research dilution sampling method used in the U.S. program within the general framework and equipment of the published U.S. EPA method.

The chemical composition of the collected aerosols also was determined (51 elements by x-ray fluorescence; sulfate, nitrate, chloride & other ions by ion chromatography and organic and elemental carbon by thermal optical reflectance). These results help clarify the true contribution of sulfates to PM2.5 emissions. Chemically speciated PM2.5 profiles will be applicable to source apportionment and health risk analysis.

Tests were conducted on two units: one is a natural gas-fired combustion turbine employing lean premix low-NO_X combustors; the other site is a natural gas-fired lean burn reciprocating engine. The host site units are representative of engine size and configurations for Canadian upstream and downstream oil and gas applications (such as compressor drives). Neither of the units employed post-combustion catalysts for additional emissions control, which distinguishes them from units previously tested in the U.S. They also may be representative of power generation and cogeneration applications. The goal in selecting these units is to assure that the data can be extrapolated to the widest range of gas-burning engines.

3. DATA SOURCES

3.1 CEPEI Test Program Results (2015)

The primary objectives were:

- Measure PM2.5 mass concentrations and selected species (elements, ions, organic and elemental carbon) in the stack gas using a dilution sampler combined with ambient air sample collection and analysis methods;
- Measure O_2 and CO_2 concentrations in the stack gas and fuel composition to enable calculation of PM2.5 emission factors via the use of fuel factors ("F factors") following U.S. EPA Method 19;

The secondary objectives were:

- Collect data needed to evaluate CTM 39 method performance and optimize future test protocols, including collection and analysis of replicate sample and sample train blanks and replicate reagent blanks;
- Compare samples and blanks to determine significance of differences;
- Evaluate replicate blanks to determine overall method sensitivity and reporting limits.

The tests were conducted using a version of CTM 39, a stationary source PM10/2.5 dilution sampling method, modified by adding ambient air sample collection and analysis methods to determine both the mass and chemical speciation of PM2.5 emissions. The method combines key elements of the scientifically proven dilution sampling method used in previous U.S. research programs within the general framework and equipment of a published U.S. EPA test method. The method also reflects several elements of ISO 25597-13, another more recently published stationary source PM10/2.5 dilution sampling method, with respect to splitting the diluted sample and sample collection on 47-mm Teflon® membrane filters and quartz fiber filters.

The chemical composition of the collected aerosols was determined (51 elements by x-ray fluorescence; sulfate, nitrate, chloride, ammonium & other ions by ion chromatography and colorimetry, and organic and elemental carbon by thermal optical absorbance/reflectance). These results help to clarify the contribution of sulfates to air emissions from these types of engines. PM2.5 chemical species profiles developed from the results also will be useful for source apportionment and health risk analysis.

Tests were conducted on two units at different natural gas pipeline compressor stations (Table 3-1): one is a natural gas-fired combustion (gas) turbine engine employing lean premix low-NO_X combustors; the other is a natural gas-fired four-stroke lean burn reciprocating engine. Neither site employs post-combustion emission controls. The engines are considered representative of engine sizes and configurations used in Canadian upstream and downstream oil and gas applications (such as compressor drives). They also may be representative of power generation and cogeneration applications. The tests were designed to assure that the data can be extrapolated to the widest range of gas-burning engines.

A detailed summary of the CEPEI test results is provided in Appendix A.

Table 3-1: Process and air pollution control descriptions.

Unit ID	Process Description	Air Pollution Controls
Site Alfa	Natural gas-fired reciprocating internal combustion engine, four-stroke, lean burn, turbocharged, Waukesha Model 12VAT27GL, 3130 horsepower (2.3 MW), commissioned circa 1997. The engine was nearing the end of its major scheduled maintenance cycle at the time of the tests.	Pre-combustion chambers, air/fuel ratio controller
Site Buick	Natural gas-fired gas turbine engine, Rolls Royce model RB211 24DLE, 27.5 MW mechanical power output capacity, in service as a natural gas compressor drive.	Dry low emissions (lean premix) combustion system, short can version

The engines were operated on natural gas fuel at approximately constant power output, with an engine load of 80% of rated capacity or higher. Process operating conditions for each test run indicate stable operation within the target operating range for each test (Tables 3-2 and 3-3).

Table 3-2: Site Alfa reciprocating engine average operating conditions during PM2.5 tests.

Parameter	Units	Run 1	Run 2	Run 3
Date		20 Oct 2015	20 Oct 2015	21 Oct 2015
Fuel heat input (gross)	GJ/hr	20.8	20.5	20.5
Engine speed	RPM	950	950	949

Table 3-3. Site Buick gas turbine average operating conditions during PM2.5 tests.

Parameter	Units	Run 1	Run 2	Run 3
Date		15 Oct 2015	16 Oct 2015	17 Oct 2015
Power output	kW	21,000*	23,000*	23,072
Turbine speed	RPM	*	*	4,307
Fuel gas flow rate	kg/s	1.29*	1.39*	1.39

*Data not available due to data recorder error. Power and fuel flow rates for Runs 1 and 2 estimated from Run 3 data based on measured stack gas flow rates and O_2 concentrations.

Average PM2.5 mass emission rates in kg/GJ are summarized in Table 3-4. Reconstructed mass (i.e., the sum of individual species adjusted for oxides and organic carbon artifact) and measured mass agree well (within ±6%) for the reciprocating engine tests. The measured PM2.5 mass for gas turbine engine Run 1 is very high relative to Runs 2 and 3. This is accounted for primarily by silicon (as silicon dioxide). This strongly suggests sample contamination for Run 1, which may have been introduced during sample train operation troubleshooting prior to starting the run. The measured mass is much lower than the reconstructed mass for gas turbine Runs 2 and 3. Because the reconstructed masses are more consistent from run to run when excluding silicon in Run 1, the reconstructed masses from each of the three test runs (excluding silicon in Run 1) were used to calculate the average gas turbine PM2.5 mass emission rate shown in Table 3-4. Perhaps fortuitously, the averages of the measured and reconstructed masses for all three runs are nearly the same (2.42E-04 and 2.36 E-04 kg/GJ, respectively).

Table 3-4: Average PM2.5 mass emission factors for natural gas-fired reciprocating engine and gas turbine.

Unit	PM2.5, kg/GJ
Reciprocating Engine (Site Alfa)	0.00150
Gas Turbine Engine (Site Buick)	0.000236

31 elements and ions were not detected in any runs on the reciprocating engine. Twenty species that were detected in at least one reciprocating engine run account for 99.69% of total reconstructed mass (Table 3-5). Ninety-four percent of total mass is accounted for by organic carbon (OC), followed by sulfur (S), elemental carbon (EC) and calcium (Ca) which account for 4.5 percent of total mass. Nitrate ion accounted for 0.33%.

Table 3-5: PM2.5 species profile – Site Alfa reciprocating engine (detected in at least one test run, as fraction of reconstructed mass).

Species	Mass Fraction	Species	Mass Fraction
OC	0.94	Eu	0.00064
S	0.018	Na^+	0.00050
EC	0.017	Ba	0.00031
Ca	0.011	Fe	0.00028
NO_3^-	0.0033	Ti	0.00024
Zn	0.0015	W	0.00021
Cl	0.0014	Ce	0.00022
Si	0.0013	K	0.00021
P	0.0012	Cs	0.00018
Al	0.00060	La	0.00012

36 elements and ions were not detected in any runs on the gas turbine engine. Twenty species account for 98.9 percent of reconstructed mass (Table 3-6). OC accounts for 80 percent of total reconstructed mass, followed by sodium (Na), EC and magnesium (Mg).

The trace element concentrations with mass fractions less than 0.001 generally are near to the analytical minimum reporting limits and or field blank levels (less than 5 times higher than), and Na results should be considered qualitative due to limitations of the analytical technique.

Table 3-6: PM2.5 species profile – Site Buick gas turbine engine (detected in at least one test run, as fraction of reconstructed mass).

Species	Mass Fraction	Species	Mass Fraction
OC	0.80	NO_3^-	0.0018
Na	0.089	W	0.0012
EC	0.042	Br	0.0015
Mg	0.023	Cs	0.00049
P	0.0076	Cl	0.00050
Sm	0.0053	K	0.00054
Eu	0.0046	Cd	0.00045
Si	0.0041	Ba	0.00041
Tb	0.0033	Sb	0.00033
Ce	0.0023	Sn	0.00028

A detailed test report includes a full description of the test methodology and results[9] and a detailed summary of the test results is provided in Appendix A.

3.2 U.S. Collaborative Test Program (1998-2003)

A collaboration between industry (American Petroleum Institute, Gas Research Institute) and U.S. government agencies (California Energy Commission, U.S. Department of Energy, New York Energy Research and Development Authority) from 1998 to 2004 conducted PM2.5 tests using a dilution sampling methodology on nine natural gas- and refinery gas-fired boilers, process heaters, gas turbine combined cycle/cogeneration units, one oil-fired boiler and one diesel engine. The American Petroleum Institute sponsored tests on a boiler and a process heater at U.S. refineries in 1998[10] and 1999[11] using a research dilution sampling methodology and a traditional hot filter/cooled impinger method to characterize PM2.5 mass and chemical species. A laboratory test[10] also was conducted with simulated combustion gases to evaluate "pseudoparticulate" formation in the cooled impingers, used for determining condensable particulate matter (cPM), due to conversion of sulfur dioxide (SO_2) gas to solid residues within the measurement process that contribute to reported cPM ("SO_2 artifact"). These tests first identified that traditional hot filter/cooled impinger method results for gas-fired combustion sources may be significantly biased high due to sulfate artifacts. Gas Research Institute (GRI) subsequently co-sponsored a test with API on a U.S. natural gas-fired steam generator[12] with similar findings. Subsequent tests co-sponsored by API, GRI and the U.S. government agencies listed above collected PM2.5 mass and chemical species data from six additional gas-fired sources: three gas

---

[9] England, G.C., CEPEI PM2.5 Emission Factor Development Test Report, Natural Gas-Fired Reciprocating and Gas Turbine Engines, Ramboll Environ, Irvine California, prepared for Canadian Energy Partnership for Environmental Innovation, Guelph, Ontario.

[10] England, G.C. and S. Wien. Gas Fired Boiler – Test Report Refinery Site A, Characterization of fine Particulate emission factors and Speciation Profiles from Stationary Petroleum Industry Combustion Sources. Publication 4702, GE Energy and Environmental Research Corporation, Irvine, California, prepared for American Petroleum Institute, Washington, D.C. 2001.

[11] England, G.C. and S. Wien. Gas Fired Heater – Test Report Site B – Characterization of Fine Particulate Emission Factors and Speciation Profiles from Stationary Petroleum Industry Combustion Sources. Publication 4704, GE Energy and Environmental Research Corporation, Irvine, California, prepared for American Petroleum Institute, Washington, D.C. 2001.

[12] England, G.C. and S. Wien. Gas-Fired Steam Generator – Test Report Site C: Characterization of Fine Particulate emission factors and Speciation Profiles from Stationary Combustion Sources. Publication 4712, GE Energy and Environmental Research Corporation, Irvine, California, prepared for American Petroleum Institute, Washington, D.C. 2001.

turbine combined cycle/cogeneration units[13],[14],[15] one boiler[16], and two process heaters[17],[18]. In these tests, measurements were made using both a research dilution sampler used in the earlier tests and a compact dilution sampler developed during the program. All tests used the same ambient air sample collection and analysis methods, except that the laboratory analytical protocol for semivolatile organic compounds (SVOC) was changed to focus on determination of polycyclic aromatic hydrocarbons (PAH) rather than total SVOC mass speciation after Site Bravo tests in 2001. CEPEI's 2012 technical memorandum (Appendix E to this report) summarized these tests and developed recommended PM2.5 emission factors and species profiles from the results.

3.3 API Reciprocating Engine Tests (2003)

In 2003, API sponsored tests of three natural gas-fired spark-ignited reciprocating internal combustion engines (RICE) used as compressor drives at a natural gas production facility[19,20]. A two-stroke engine, a four-stroke rich burn engine and a four-stroke lean burn engine were tested (Table 3-7). The four-stroke rich burn engine was equipped with non-selective catalytic reduction for nitrogen oxides (NO_X)

---

[13] Wien, S., England, G.C. and Chang, M.C., Development of Fine Particulate Emission Factors and Speciation Profiles for Oil and Gas-fired Combustion Systems, Topical Report: Test Results for a Combined Cycle Power Plant with Supplementary Firing, Oxidation Catalyst and SCR at Site Bravo, GE Energy and Environmental Research Corporation, Irvine, California, prepared for U.S. Department of Energy, Gas Research Institute, American Petroleum Institute, California Energy Commission and New York State Energy Research and Development Authority, 2004. http://www.energy.ca.gov/pier/project_reports/CEC-500-2005-032_to_44.html.

[14] England, G.C., Wien, S., McGrath, T.P., and Hernandez, D., Development of Fine Particulate Emission Factors and Speciation Profiles for Oil and Gas-fired Combustion Systems, Topical Report: Test Results for a Combined Cycle Power Plant with Oxidation Catalyst and SCR at Site Echo. GE Energy and Environmental Research Corporation, Irvine, California, prepared for U.S. Department of Energy, Gas Research Institute, American Petroleum Institute, California Energy Commission and New York State Energy Research and Development Authority, 2004. http://www.energy.ca.gov/pier/project_reports/CEC-500-2005-032_to_44.html.

[15] England, G.C. and T. McGrath, "Development of Fine Particulate Emission Factors and Speciation Profiles for Oil and Gas-fired Combustion Systems, Topical Report: Test Results for A Cogeneration Plant with Supplementary Firing, Oxidation Catalyst and SCR at Site Golf. GE Energy and Environmental Research Corporation, Irvine, California, prepared for U.S. Department of Energy, Gas Research Institute, American Petroleum Institute, California Energy Commission and New York State Energy Research and Development Authority, 2004. http://www.energy.ca.gov/pier/project_reports/CEC-500-2005-032_to_44.html.

[16] Wien, S., McGrath, T.P., England, G.C. and Chang, O.M.C., Development of Fine Particulate Emission Factors and Speciation Profiles for Oil and Gas-fired Combustion Systems, Topical Report: Test Results for a Dual Fuel-Fired Commercial Boiler (Site Delta). GE Energy and Environmental Research Corporation, Irvine, California, prepared for U.S. Department of Energy, Gas Research Institute, American Petroleum Institute, California Energy Commission and New York State Energy Research and Development Authority, 2004. http://www.energy.ca.gov/pier/project_reports/CEC-500-2005-032_to_44.html.

[17] Wien, S., England, G.C. and Chang, O.M.C., Development of Fine Particulate Emission Factors and Speciation Profiles for Oil and Gas-fired Combustion Systems, Topical Report: Test Results for a Gas-Fired Process Heater (Site Alpha), GE Energy and Environmental Research Corporation, Irvine, California, prepared for U.S. Department of Energy, Gas Research Institute, American Petroleum Institute, California Energy Commission and New York State Energy Research and Development Authority, 2003. http://www.energy.ca.gov/pier/project_reports/CEC-500-2005-032_to_44.html.

[18] Wien, S., England, G.C. and Chang, O.M.C., "Development of Fine Particulate Emission Factors and Speciation Profiles for Oil and Gas-fired Combustion Systems, Topical Report: Test Results for a Gas-Fired Process Heater with Selective Catalytic Reduction (Site Charlie). GE Energy and Environmental Research Corporation, Irvine, California, prepared for U.S. Department of Energy, Gas Research Institute, American Petroleum Institute, California Energy Commission and New York State Energy Research and Development Authority, 2003. http://www.energy.ca.gov/pier/project_reports/CEC-500-2005-032_to_44.html.

[19] England, G.C., K.R. Loos, K. Ritter. Measurements of PM2.5 Mass and Species Emissions from Natural Gas-Fired Reciprocating Internal Combustion Engines, SPE-94201-PP, Exploration & Production Environmental Conference, Society of Petroleum Engineers, Galveston, TX. March 2005.

[20] England, G.C., McGrath, T.P., Hernandez, D. PM2.5, PM2.5 Precursor and Hazardous Air Pollutant Emissions from Natural Gas-Fired Reciprocating Engines: Final Report (Draft). GE Energy and Environmental Research Corporation, Irvine, California, prepared for American Petroleum Institute, Washington, D.C. 2004.

emissions control. The two-stroke engine had precombustion chambers and no post-combustion emission controls and the four-stroke lean burn engine had no post-combustion emission controls.

Table 3-7: Reciprocating engines tested in 2003 API test program.

Type	Make/Model	Size	Emission Controls
four-stroke lean burn	Caterpillar G3606TA	1665 hp	None
four-stroke rich burn	Ingersoll Rand 48 KVSA (turbocharged)	1626 hp	NSCR
two-stroke lean burn	Cooper Bessemer GMVH-12C (turbocharged)	2700 hp	Precombustion chambers

PM2.5 and chemical species were measured using the GE compact dilution sampler and the same ambient air sample collection and analysis methods as used in the earlier tests discussed above. Operating conditions, PM2.5 mass, OC/EC, particulate carbon, elements and ions results for each test run and for each engine are summarized in Appendix D. Volumetric parameters are given at 20 °C reference temperature unless otherwise noted. The average PM2.5 emission factor for each engine type ranged from 0.000774 for the four-stroke rich burn engine to 0.00859 kg/GW for the two-stroke lean burn engine (Table 3-8). The species profiles for all engines are dominated by organic carbon, which accounts for 80 to 98 percent of the PM2.5 mass (Table 3-9).

Table 3-8: PM2.5 emission factors for reciprocating engines tested in 2003 API test program

Type	PM2.5 (kg/GW)
four-stroke lean burn	2.16E-03
four-stroke rich burn	7.74E-04
two-stroke lean burn	8.59E-03

Table 3-9: PM2.5 species profile for reciprocating engines tested in 2003 API test program (percent)

Species	4SRB	4SLB	2SLB
Organic Carbon (OC)	80	90	98
Si	6.0	1.4	0.18
Fe	3.9	5.8	
$SO_4^=$	3.2	0.66	0.24
Elemental Carbon (EC)	2.5		0.75
Ca	1.2	0.53	0.28
NH_4^+	0.89		0.07
Zn	0.57	0.55	0.08
NO_3^-	0.47	0.25	0.19
Cl-	0.38	0.15	0.05
Mo	0.14	0.07	0.03
P	0.14		0.03
Soluble Na^+	0.06	0.05	0.06
Cu	0.05	0.06	0.01
Co	0.03	0.02	
K	0.03	0.04	0.01
Cr	0.02	0.01	
Sn	0.02		
Ba		0.02	0.01
Ni		0.01	

3.4 GE Energy Gas Turbine Combined Cycle Unit Tests (2008)

In 2008, GE Energy developed a modified version of CTM 39 for measuring low concentrations in stack gases from natural gas-fired gas turbines and combined cycle/cogeneration units. U.S. EPA, California Air Resources Board, the South Coast Air Quality Management District, the Sacramento Metropolitan Air Quality Management District, and the San Juaquin Valley Air Pollution Control District participated in test planning and results review. The modifications to CTM 39 included addition of ambient air sample collection and analysis methods similar to those used in the U.S. collaborative program. To evaluate method performance, nine test runs with paired modified CTM 39 sampling trains were conducted on one 170 MW gas turbine unit of a 500 MW a natural gas-fired combined cycle power plant equipped with lean premix combustors and SCR[21]. The unit did not have duct burners.

CTM 39 specifies recovery of particles deposited on the sampler surfaces by quantitatively rinsing the surfaces with acetone and water after each test. The results showed that PM2.5 masses reported in the acetone and water recovery rinses for samples and for six replicate sample train field blanks are indistinguishable. This indicates that the levels measured in the samples are below the minimum reporting limit of the recovery rinse procedure; i.e., the true mass of PM2.5 in the samples is below the "noise" level of the recovery rinse procedure. Further, the reporting limit of the recovery rinse procedure is much greater than measured PM2.5 masses on the 47-mm TMFs[22]. Particles emitted from natural gas combustion are smaller than 1 micrometer and primarily smaller than 0.1 micrometers[23,24]. An earlier study of particle deposition in a dilution sampler showed that deposition of particles smaller than 1 micrometer on surfaces of the sampler prior to the filter is expected to be less than 7% and probably less than 1% for particles smaller than 0.1 micrometer[25]. Thus, there is very little, if any, PM2.5 from natural gas combustion expected to be present on the sampler surfaces.

Measured PM2.5 masses on the TMFs are greater than the minimum reporting limit for the TMFs and are thus reliable measurements. Therefore, PM2.5 emission factors derived from the 2008 GE Energy test results are based on TMF results only. PM2.5 mass (TMFs) and chemical species results (Tables 3-10 and 3-11) agree reasonably well in magnitude with results for similar units tested during the U.S. collaborative program. A detailed summary of test results is provided in Appendix C.

Table 3-10: Average PM2.5 emission factor from 2008 GE Energy natural gas-fired gas turbine combined cycle unit tests – TMF results.

	PM2.5 (kg/GJ)
Sample Train A	2.55E-05
Sample Train B	1.76E-05
Average Sample Trains A & B	2.15E-05

---

[21] Matis, C., England, G.C., Crosby, K., Rubenstein, G., Tong, C. Evaluation Report, Evaluation of CTM-039 Dilution Method for Measuring PM10/PM2.5 Emissions from Gas-Fired Combustion Turbines, GE Energy, Schenectady, New York, 2009.

[22] Matis, C., G.C. England, K. Crosby and G. Rubenstein. Field Demonstration of a Dilution-Based Particulate Measurement System, Symposium on Air Quality Measurement Methods and Technology, Air & Waste Management Association, Chapel Hill, NC. November 2008.

[23] Chapter 4, Section 1.4 – Natural Gas Combustion, in *Compilation of Air Pollutant Emission Factors* AP-42, U.S. Environmental Protection Agency, 2000.

[24] Spang, B., S. Yoshimura, R. Hack, V. McDonell, S. Samuelsen (2013). Evaluation of the Level of Gaseous Fuel-Bound Sulfur on Fine Particulate Emission From a Low Emission Gas Turbine Engine, *J. Eng. Gas Turbines & Power*, 135:03501.1-03501.8.

[25] Hildemann, L. M., G. R. Cass & G. R. Markowski (1989). A Dilution Stack Sampler for Collection of Organic Aerosol Emissions: Design, Characterization and Field Tests, *Aerosol Science and Technology*, 10:1, 193-204, DOI: 10.1080/02786828908959234

Table 3-11: Average PM2.5 species profile from 2008 GE Energy natural gas-fired gas turbine combined cycle unit tests – TMF results.

Species	%	Species	%
OC	85	Sr	0.018
EC	7.34	Ti	0.016
$SO_4^=$	1.89	Y	0.01
Cl^-	1.67	Ni	0.0066
Si	1.56	Mo	0.0056
NH_4^+	0.94	Cr	0.0052
NO_3^-	0.64	Pb	0.0049
Al	0.23	Se	0.0047
Fe	0.21	Cu	0.0041
Ca	0.18	Br	0.003
Cl	0.13	Sm	0.0023
Zn	0.041	Rb	0.0016
S	0.03	V	0.001
K	0.025		

Note, the run-to-run variability of the 47-mm TMF results is greater in the GE Energy 2008 tests than was generally observed in the U.S. collaborative program – this was attributed to defects in the filter holders which resulted in adhesive contamination and filter tearing for some of the samples. As a result, some of the TMF net weights are less than zero and there are two very high outliers in the data set. The data were examined excluding the negative values and two high outliers; however, this changed the mean emission factor by only -11%. Since the high outliers could not be attributed to a definitive measurement defect, and since the negative values and outliers provide information regarding measurement uncertainty in these tests, the mean emission factor of the full data set is considered the most representative statistic for these tests.

3.5 Refinery Boiler and Process Heater Tests (2014)

Although the primary focus of this emission factor update is on reciprocating engines and gas turbines, PM10 (expressed as total PM) tests were conducted on six refinery gas-fired boilers and process heaters in 2014[26] using a modified version of U.S. EPA CTM 39 similar to that used in the 2015 CEPEI tests. The refinery gas contained 7 to 9 ppm hydrogen sulfide. The three boilers were equipped with SCR, and one boiler also had low-NO_X burners. The three process heaters were equipped with low-NO_X burners but no post-combustion emissions controls. The results (Table 3-12) are generally consistent in magnitude with earlier results obtained during the U.S. collaborative program. Boiler A was tested

---

[26] Astin, M.S., Benson, E., England, G.C., Croghan, S. PM10/2.5 Emissions from Gas-Fired Refinery Boilers and Heaters: Test Methods, Results and Better Emission Factors for Air Quality Impact Assessment, 2015 Environmental Conference, American Fuels & Petrochemicals Manufacturers, Salt Lake City, Utah, 2015.

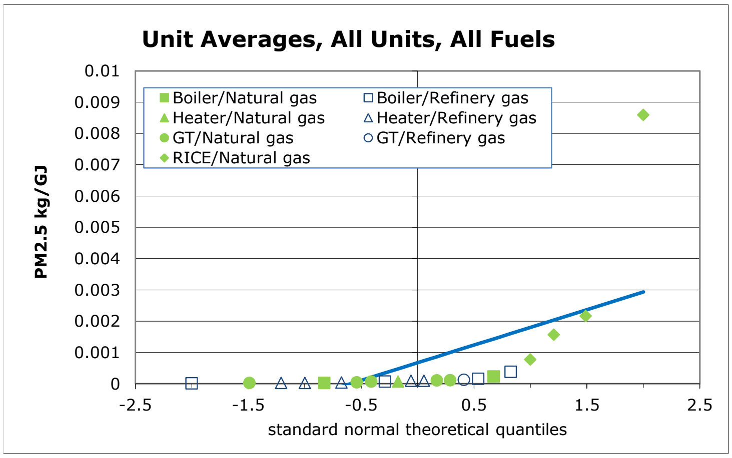
both before (Runs 1-3) and after (Runs 4-6) tuning the SCR ammonia flow rate, and the difference in results likely illustrates the contribution of ammonium sulfate/bisulfate to PM emissions.

Table 3-12: PM2.5 test results for refinery boilers and process heaters (2014).

	Run ID	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Average
Boiler A	mg/dscm	1.76E+00	1.40E+00	1.69E+00	6.53E-01	7.05E-01	5.62E-01	1.13E+00
Boiler A	kg/GJ	5.93E-04	4.73E-04	4.64E-04	2.52E-04	2.74E-04	2.15E-04	3.79E-04
Boiler B	mg/dscm	1.76E-01	1.90E-01	1.80E-01	--	--	--	1.82E-01
Boiler B	kg/GJ	6.71E-05	7.27E-05	6.88E-05	--	--	--	6.95E-05
Boiler C	mg/dscm	2.93E-02	3.62E-02	3.56E-02	--	--	--	3.37E-02
Boiler C	kg/GJ	1.20E-05	1.48E-05	1.46E-05	--	--	--	1.38E-05
Heater A	mg/dscm	2.93E-01	4.12E-01	1.60E-01	--	--	--	2.88E-01
Heater A	kg/GJ	9.24E-05	1.28E-04	4.99E-05	--	--	--	9.01E-05
Heater B	mg/dscm	2.67E-01	3.89E-01	2.44E-01	--	--	--	3.00E-01
Heater B	kg/GJ	7.35E-05	1.26E-04	7.01E-05	--	--	--	9.00E-05
Heater C	mg/dscm	1.51E-01	1.50E-01	1.48E-01	--	--	--	1.50E-01
Heater C	kg/GJ	3.97E-05	3.94E-05	3.90E-05	--	--	--	3.94E-05

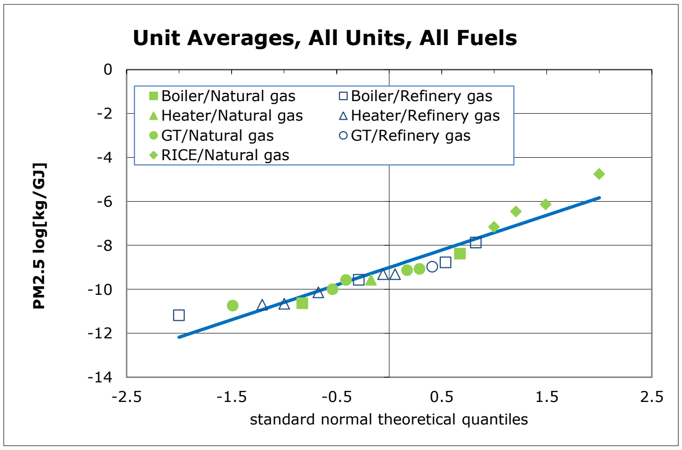
4. PM2.5 EMISSION FACTORS

The average emission factors for each unit including the U.S. collaborative program, 2015 CEPEI, 2014 refinery and 2008 GE Energy test results were compared to determine if data should be aggregated or separated by fuel, unit type or configuration. The ranked data (low to high) were examined on theoretical normal quantile-quantile (Q-Q) plots to both compare the magnitude, data trends, fit to a normal distribution and central tendency of the data (Figure 4-1). Data fitting a normal distribution will fall on a straight line on a Q-Q plot. Inflection points in the ranked data indicate subsets of data with different distributions – this may suggest natural divisions within the data where it makes sense to subdivide emission factors. Comparing the entire data set to a fitted normal distribution correlation (blue line in Figure 4-1a) shows the data do not fit a normal distribution – the RICE data which constitute the high end of the data range, particularly the two-stroke engine result, heavily skew the distribution. Environmental data often are skewed high and fit a lognormal distribution (i.e., the log-transformed data fit a normal distribution). A similar evaluation also shows the data do fit an approximate lognormal distribution with a geometric mean PM2.5 emission factor of 0.000122 kg/GJ (Figure 4-1b).



Raw Statistics	
Number of Valid Observations	22
Number of Distinct Observations	21
Minimum	0.000013814
Maximum	0.00859
Mean of Raw Data	0.0006717
Standard Deviation of Raw Data	0.00185
Khat	0.388
Theta hat	0.00173
Kstar	0.366
Theta star	0.00184
Mean of Log Transformed Data	-9.009
Standard Deviation of Log Transformed Data	1.654
Normal GOF Test Results	
Correlation Coefficient R	0.601
Shapiro Wilk Test Statistic	0.388
Shapiro Wilk Critical (0.05) Value	0.911
Approximate Shapiro Wilk P Value	6.42E-10
Lilliefors Test Statistic	0.381
Lilliefors Critical (0.05) Value	0.189
Data not Normal at (0.05) Significance Level	

(a)

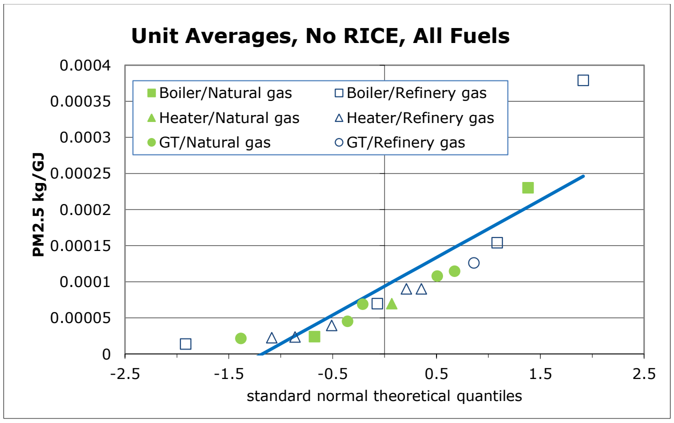


Raw Statistics	
Number of Valid Observations	22
Number of Distinct Observations	21
Minimum	0.000013814
Maximum	0.00859
Mean of Raw Data	0.0006717
Standard Deviation of Raw Data	0.00185
Khat	0.388
Theta hat	0.00173
Kstar	0.366
Theta star	0.00184
Mean of Log Transformed Data	-9.009
Geometric Mean of Raw Data	0.000122
Standard Deviation of Log Transformed Data	1.654
Lognormal GOF Test Results	
Correlation Coefficient R	0.954
Shapiro Wilk Test Statistic	0.909
Shapiro Wilk Critical (0.05) Value	0.911
Approximate Shapiro Wilk P Value	0.043
Lilliefors Test Statistic	0.174
Lilliefors Critical (0.05) Value	0.189
Data appear Approximate_Lognormal at (0.05) Significance Level	

(b)

Figure 4-1: Q-Q plot for PM2.5 emission factors from gas-fired boilers, process heaters, gas turbines and reciprocating engines, measured with dilution sampling methods.

If the RICE data are excluded, the remaining data approximately fit a normal distribution (Figure 4-2). Goodness of fit to a normal distribution was confirmed using ProUCL[27], a statistical analysis application developed by U.S. EPA for environmental data analysis. Thus, it is reasonable to consider the data set excluding RICE for an aggregate PM2.5 emission factor.



Raw Statistics	
Number of Valid Observations	18
Number of Distinct Observations	17
Minimum	0.000013814
Maximum	0.00037876
Mean of Raw Data	0.000093801
Standard Deviation of Raw Data	0.00009035
Khat	1.478
Theta hat	0.000063459
Kstar	1.269
Theta star	0.000073928
Mean of Log Transformed Data	-9.649
Standard Deviation of Log Transformed Data	0.904
Normal GOF Test Results	
Correlation Coefficient R	0.872
Shapiro Wilk Test Statistic	0.775
Shapiro Wilk Critical (0.05) Value	0.897
Approximate Shapiro Wilk P Value	0.00038199
Lilliefors Test Statistic	0.194
Lilliefors Critical (0.05) Value	0.209
Data appear Approximate Normal at (0.05) Significance Level	

Figure 4-2: Normal Q-Q plot of PM2.5 emission factors for gas-fired boilers, process heaters and gas turbines, measured with dilution sampling methods.

The average emission factor for all gas-fired units excluding the RICE data may be expressed as the mean (average) of the unit average emission factors for 16 units using refinery gas or natural gas as fuels. Tests for one gas turbine combined cycle unit, Site Echo from the U.S. collaborative tests, tested at high load with duct burners on and reduced load with duct burners off are included as separate data points to represent emissions from similar units with and without duct burners). The data are skewed high due to a single data point at the high end of the range, resulting in a mean emission factor of 0.00010 kg/GJ ±48% (mean ± uncertainty) which is 45% greater than the median (Table 4-1). However, the high data point is not a statistical outlier (Dixon's test) so there is no reason to exclude it.

The high data point is Boiler A from the 2014 refinery tests, which exhibited higher emissions attributed to ammonium sulfate/bisulfate produced by ammonia slip from the SCR. Although the data are considered valid, results for two other boilers with SCRs at the same facility are lower indicating this unit may not be representative of most such units. Removing the Boiler A data point reduces the mean and uncertainty to 0.000084 kg/GJ ±43%. Considering only the natural gas-fired units results in a mean emission factor that is the same as for the full data set but with greater uncertainty, 0.00010 kg/GJ ±72%. Because the full data set remains small in statistical terms (fewer than 25 data points), we recommend using the full data set including the Boiler A data point as a general emission factor for all gas-fired units. However, we recommend using the median emission factor rather than the mean when applying emission factors in situations where the central data characteristic is indicated. For example, the median value may be appropriate when estimating emissions from a population of many similar units such as in regional air quality analysis.

The maximum and 95% confidence upper bound (95% CUB) provide measures of the upper limits of the data set. The 99% confidence upper prediction limit (99% UPL) provides a measure of an upper limit of the mean value for the <u>next</u> unit that is tested. In this data set, the maximum is the highest value, followed by the 99% UPL and the 95% CUB in descending order. An upper limit or maximum may be appropriate in situations where a conservative estimate of emissions is necessary. For

---

[27] http://www.epa.gov/land-research/proucl-software.

example, an upper limit may be appropriate when evaluating emissions from one unit within a larger population of units or when establishing emissions limits or standards.

Table 4-1: Aggregate PM2.5 emission factor statistics for boilers, process heaters, gas turbines and gas turbine combined cycle/cogeneration units.

Parameter	Units	Value	Value	Value
Data set		NG+RG	NG+RG (exclude outlier)	NG
Number of units		17	16	6
Number of data points		18	17	8
Mean	kg/GJ	1.01E-04	8.42E-05	1.00E-04
Median	**kg/GJ**	**6.95E-05**	6.95E-05	6.91E-05
Geometric mean	kg/GJ	6.71E-05	6.06E-05	7.11E-05
Minimum	kg/GJ	1.38E-05	1.38E-05	2.15E-05
Maximum	**kg/GJ**	**3.79E-04**	2.36E-04	2.36E-04
Standard deviation	kg/GJ	9.64E-05	6.89E-05	8.66E-05
COV	%	96	82	86
Confidence level	%	95%	95%	95%
Measurement bias	%	6.5	6.5	6.5
t factor (2 tail)		2.11	2.12	2.36
t factor (1 tail)		1.33	1.34	1.41
Total uncertainty	%	48	43	72
Total uncertainty	kg/GJ	4.84E-05	3.58E-05	7.27E-05
95% confidence upper bound	**kg/GJ**	**1.32E-04**	1.07E-04	1.44E-04
Data distribution		normal	normal	normal
99% confidence upper prediction limit	**kg/GJ**	**3.55E-04**	2.67E-04	3.76E-04

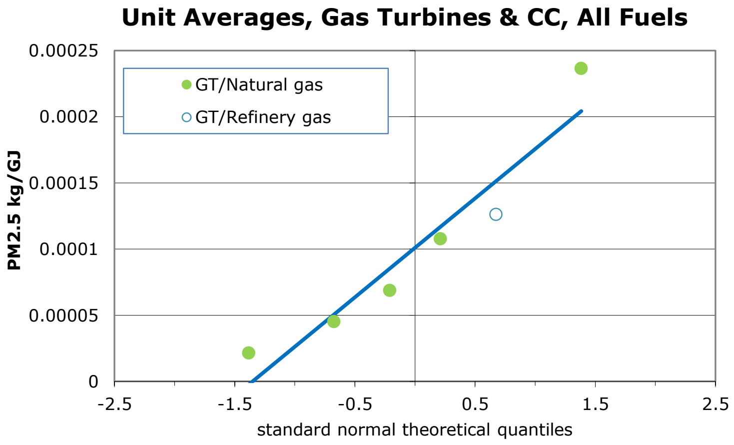
4.1 Gas Turbines and Gas Turbine Combined Cycle/Cogeneration Units

The current data set includes test results for five units utilizing gas turbines. Three units (Bravo, Echo, GE 2008) are natural gas-fired gas turbine combined cycle units (GTCC) employing large heavy-duty frame gas turbines with lean premix combustors (LPC) with SCR for NO_X emissions control. Two of these (Bravo and Echo) employ duct burners for supplementary steam generation and CO oxidation catalysts for additional emissions control. One (Golf) is a refinery cogeneration unit employing an aeroderivative gas turbine with diffusion flame combustors employing water injection (WI) and SCR for NO_X emissions control and CO oxidation catalyst. The CEPEI Buick unit is an aeroderivative gas turbine with lean premix combustors but no post-combustion controls applied as a natural gas pipeline compressor drive. One unit (Echo) was tested at base gas turbine load with duct burners on and at near base gas turbine load with duct burners off. The two conditions are treated as separate units in this analysis since the tests with duct burners off may also represent emissions from similar units without duct burner (supplementary firing) capability.

PM2.5 mass emission factors determined by dilution sampling methods are within the same order of magnitude, spanning a 11:1 range (Table 4-2) and the data are normally distributed (Figure 4-3). The 2015 CEPEI gas turbine test produced the highest PM2.5 emission factor in the data set. A natural gas-fired combined cycle unit (Site Echo, duct burners on) has the lowest PM2.5 mass emission factor. The refinery gas-fired unit has the second highest PM2.5 emission factor. The refinery gas contained an average of 27 ppm total sulfur, which is higher than the sulfur content of the natural gas-fired units and 2 to 20 times higher than typical natural gas sulfur content. The PM2.5 sulfate concentration for Site Golf is 3 to more than 10 times higher than that for the natural gas-fired units, which accounts for much of the difference in PM2.5 emission factor. Data for the natural gas-fired units only also are normally distributed (Figure 4-4).

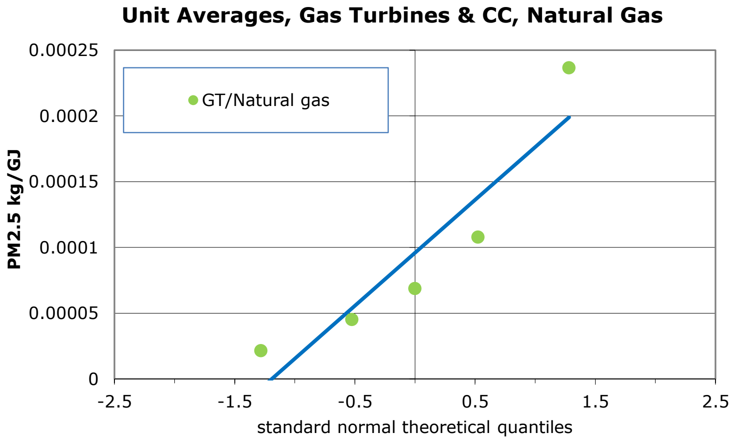
Table 4-2: PM2.5 emission factor data set for gas-fired gas turbines (dilution test methods)

Facility ID	Unit ID	Fuel	Controls	Test Date	kg/GJ
Bravo	GTCC/C (2xDB on + 1x DB off), 159 MW	Natural gas	LPC+CO Cat+SCR	2001	1.08E-04
Echo	GTCC/C (High load, DB on), 170	Natural gas	LPC+CO Cat+SCR	2003	4.51E-05
Echo	GTCC/C (Reduced load DB off), 170	Natural gas	LPC+CO Cat+SCR	2003	6.88E-05
Golf	GT-Cogen (DB on), 48 MW	Refinery gas	WI+CO Cat+SCR	2003	1.26E-04
GE 2008	GTCC (no DB), 170 MW	Natural gas	LPC+SCR	2008	2.15E-05
CEPEI Buick	Gas turbine, 27.5 MW	Natural gas	LPC	2015	2.36E-04



Raw Statistics	
Number of Valid Observations	6
Number of Distinct Observations	6
Minimum	2.15E-05
Maximum	2.36E-04
Mean of Raw Data	1.01E-04
Standard Deviation of Raw Data	7.68E-05
Khat	2.03
Theta hat	4.97E-05
Kstar	1.126
Theta star	8.97E-05
Mean of Log Transformed Data	-9.467
Standard Deviation of Log Transformed Data	0.841
Normal GOF Test Results	
Correlation Coefficient R	0.954
Shapiro Wilk Test Statistic	0.916
Shapiro Wilk Critical (0.05) Value	0.788
Approximate Shapiro Wilk P Value	N/A
Lilliefors Test Statistic	0.205
Lilliefors Critical (0.05) Value	0.362
Data appear Normal at (0.05) Significance Level	

Figure 4-3: Q-Q plot and goodness of fit statistics for gas turbine PM2.5 emission factor data set – natural gas and refinery gas fuels



Raw Statistics	
Number of Valid Observations	5
Number of Distinct Observations	5
Minimum	2.15E-05
Maximum	2.36E-04
Mean of Raw Data	9.59E-05
Standard Deviation of Raw Data	8.48E-05
Khat	1.747
Theta hat	5.49E-05
Kstar	0.832
Theta star	1.15E-04
Mean of Log Transformed Data	-9.564
Standard Deviation of Log Transformed Data	0.902
Normal GOF Test Results	
Correlation Coefficient R	0.928
Shapiro Wilk Test Statistic	0.868
Shapiro Wilk Critical (0.05) Value	0.762
Approximate Shapiro Wilk P Value	N/A
Lilliefors Test Statistic	0.245
Lilliefors Critical (0.05) Value	0.396
Data appear Normal at (0.05) Significance Level	

Figure 4-4: Q-Q plot and goodness of fit statistics for gas turbine PM2.5 emission factor data set – natural gas fuel only

The mean and median for both data sets are similar, reflecting a good data fit to a normal distribution (Table 4-3). The mean PM2.5 emission factor and uncertainty are 0.000096 kg/GJ ±110% for natural gas-fired units alone and 0.00010 kg/GJ ±80% for all units firing natural gas or refinery gas. Because the uncertainty is lower for the emission factor including the refinery gas-fired unit, we recommend the latter emission factors for estimating emissions from gas-fired gas turbines and combined cycle units.

4.2 RICE Data Set

The PM2.5 emission factor data set (Table 4-4) includes results for four natural gas-fired engines encompassing three different engine types and different emission controls ranging from pre-combustion chambers (PCC) and air/fuel ratio controllers (A/F) to non-selective catalytic reduction (NSCR). The data set includes one four-stroke rich burn (4SRB) engine and two four-stroke lean burn (4SLB) engines. PM2.5 emission factor for the two-stroke lean burn (2SLB) engine is 4 to 11 times higher than the other units. Since two-stroke engines are different in many respects from four-stroke engines and generally exhibit higher emissions of organic combustion byproducts from fuel gas and lubrication oil blow-by, PM2.5 emission factors are evaluated for the four-stroke engines alone in this analysis. The four-stroke engine data set fit a normal distribution (Figure 4-5).

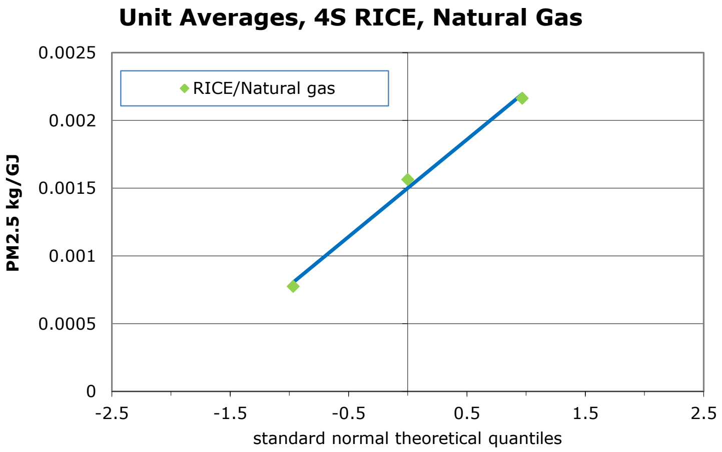
Because the data set is very small – 3 units - an aggregate PM2.5 emission factor for both lean burn and rich burn four-stroke engines combined, so that it can be expressed with an associated uncertainty. The mean PM2.5 emission factor and uncertainty is 0.00150 kg/GJ ±116% (Table 4-5). The mean and the median are nearly the same. Therefore, the mean is an appropriate statistic for emission factor use.

Table 4-3: PM2.5 emission factor statistics for gas-fired gas turbine and gas turbine combined cycle/cogeneration units.

Parameter	Units	Value	Value
Fuel		Natural gas	Natural gas & refinery gas
Number of units tested		4	5
Number of unit averages		5	6
Mean	**kg/GJ**	9.59E-05	1.01E-04
Median	kg/GJ	6.88E-05	8.83E-05
Geometric mean	kg/GJ	7.02E-05	7.74E-05
Minimum	kg/GJ	2.15E-05	2.15E-05
Maximum	**kg/GJ**	2.36E-04	**2.36E-04**
Standard deviation	kg/GJ	8.48E-05	7.68E-05
Coefficient of variation	%	88	76
Confidence level	%	95%	95%
Measurement bias	%	6.5	6.5
t factor (2 tail)		2.78	2.57
t factor (1 tail)		1.53	1.48
Total uncertainty	%	110	80
Total uncertainty	kg/GJ	1.05E-04	8.09E-05
95% confidence upper bound	**kg/GJ**	1.54E-04	**1.48E-04**
Data distribution		normal	normal
99% confidence upper prediction limit	**kg/GJ**	4.44E-04	**3.80E-04**

Table 4-4: PM2.5 emission factor data set for natural gas-fired reciprocating engines.

Source	Unit ID	Fuel	Controls	Test Date	PM2.5 kg/GJ
API RICE	RICE 2SLB	Natural gas	PCC	2004	0.00859
API RICE	RICE 4SRB	Natural gas	NSCR	2004	0.000774
API RICE	RICE 4SLB	Natural gas	None	2004	0.00216
CEPEI RICE	Alfa 4SLB	Natural gas	PCC, A/F	2015	0.00156



Raw Statistics	
Number of Valid Observations	3
Number of Distinct Observations	3
Minimum	7.74E-04
Maximum	0.00216
Mean of Raw Data	0.0015
Standard Deviation of Raw Data	6.97E-04
Khat	6.059
Theta hat	2.48E-04
Kstar	N/A
Theta star	N/A
Mean of Log Transformed Data	-6.587
Standard Deviation of Log Transformed Data	0.525
Normal GOF Test Results	
Correlation Coefficient R	0.997
Shapiro Wilk Test Statistic	0.994
Shapiro Wilk Critical (0.05) Value	0.767
Approximate Shapiro Wilk P Value	N/A
Lilliefors Test Statistic	0.203
Lilliefors Critical (0.05) Value	0.512
Data appear Normal at (0.05) Significance Level	

Figure 4-5: Q-Q plot and goodness of fit statistics for four-stroke reciprocating engine PM2.5 emission factor data set – natural gas fuel

Table 4-5: PM2.5 emission factor statistics for four-stroke reciprocating engines.

Parameter	Units	Value
Number of units tested		3
Mean	kg/GJ	1.50E-03
Median	kg/GJ	1.56E-03
Geometric mean	kg/GJ	1.38E-03
Minimum	kg/GJ	7.74E-04
Maximum	kg/GJ	2.16E-03
Standard deviation	kg/GJ	6.97E-04
Coefficient of variation	%	46
Confidence level	%	95%
Measurement bias	%	6.5
t factor (2 tail)		4.30
t factor (1 tail)		1.89
Total uncertainty	%	116
Total uncertainty	kg/GJ	1.73E-03
95% confidence upper bound	kg/GJ	2.26E-03
Data distribution		normal
99% confidence upper prediction limit	kg/GJ	7.10E-03

5. PM2.5 SPECIES PROFILES

Species profiles were calculated as a percentage of reconstructed mass concentration. Reconstructed mass concentration is the sum of species concentrations assuming that ions and anions are balanced and excess ions and elements are present as higher stable oxides.

It is important to note that these species profiles should be applied only to PM2.5 mass measured by dilution methods similar to those used in the underlying data. They should not be applied to PM2.5 mass measured by hot filter/cooled impinger or other test methods because of measurement artifacts that may alter mass and species in those results.

5.1 Gas Turbine PM2.5 Species

Organic carbon (OC) is the predominant component of PM2.5 for the gas-fired gas turbine and combined cycle/cogeneration units (Table 5-1) regardless of fuel. Sulfate and ammonium ions comprise a minor fraction of PM2.5, except for the gas turbine (“Site Buick”) tested in the CEPEI 2015 test program where none was detected. This may be a reflection of low natural gas sulfur content and absence of post-combustion catalysts at Site Buick, as post-combustion catalysts used at the other sites are known to partially oxidize sulfur dioxide gas (SO_2) to sulfur trioxide (SO_3), a particulate sulfate precursor. Ammonium likely results from ammonia used in the SCR systems present on all of the units tested except for Buick. Elemental carbon (EC), chloride and nitrate comprise the majority of the remaining mass.

5.2 Reciprocating Engine PM2.5 Species

Organic carbon is the predominant component of PM2.5 mass from reciprocating engines, accounting for 88% of PM2.5 mass for four-stroke engines on average and 98% of PM2.5 mass for the two-stroke engine (Table 5-2).

Table 5-1: PM2.5 species profiles for gas-fired gas turbines and combined cycle/cogeneration units (% of reconstructed mass)

	CEPEI 2015 Buick	Bravo	Echo Hi	Echo Lo	GE 2008	Golf	Average all	Average Nat. Gas
OC	80	73	68	73	83	50	72	76
$SO_4^{=}$		4.4	13	8.7	1.8	27	9.2	5.6
NH_4^+			7.0	5.9	0.92	9.6	3.9	2.8
EC	4.2	2.9	1.8		7.2	5.4	3.6	3.3
Cl^-		3.8	2.1	5.1	1.6	0.74	2.2	2.5
NO_3^-	0.18	5.2	2.1	1.2	0.62	2.4	2.0	1.9
Si	0.41	3.5	1.2	0.72	2.3	2.0	1.7	1.6
Na^+	0.57		2.9	2.7		1.3	1.3	1.2
Fe	0.023	2.7	0.25	0.16	0.29	0.57	0.67	0.69
Ca	0.029	1.0	0.23	0.22	0.35	0.30	0.36	0.37
Al		0.78	0.41		0.53	0.22	0.33	0.35
K	0.054	0.45	0.35	0.23	0.11	0.30	0.25	0.24
Zn	0.019	0.27	0.078	0.018	0.096	0.055	0.090	0.097
Cl	0.050				0.28		0.055	0.067
Cu	0.022	0.18				0.038	0.040	0.041
Br	0.15	0.014		0.059		0.015	0.040	0.045
Ti	0.022	0.14			0.04	0.014	0.036	0.041
Ni	0.0040	0.10			0.023	0.013	0.024	0.026
Ba	0.041					0.059	0.017	0.0083
Mn	0.056	0.073				0.017	0.025	0.026
V	0.0082	0.059			0.0061	0.0086	0.014	0.015
Sr	0.0036				0.063	0.0023	0.012	0.013
Cr	0.016				0.046	0.0031	0.011	0.013
Y	0.007				0.046		0.0089	0.011
Pb	0.017	0.027					0.0074	0.0089
Co		0.018				0.0012	0.0032	0.0036
Na	8.9						1.5	1.8
Mg	2.3						0.39	0.46
P	0.76						0.13	0.15
Sm	0.53						0.089	0.11
Eu	0.46						0.077	0.093
Tb	0.33						0.055	0.067
Ce	0.23						0.039	0.046
W	0.12						0.020	0.024
La						0.086	0.014	
Cd	0.045						0.0076	0.0091
Cs	0.049						0.0082	0.0099
Mo						0.038	0.0064	
Sb	0.033						0.0055	0.0067
Sn	0.028						0.0047	0.0057
Hg	0.016						0.0027	0.0032
U	0.015						0.0025	0.003
Se	0.010						0.0017	0.0020
Zr	0.0097						0.0016	0.0020
Tl	0.0080						0.0013	0.0016
In	0.0052						0.00087	0.0011
Rb	0.0013						0.00022	0.00026

Shaded area indicates species detected only for one unit. Results may not be representative of other units.

Table 5-2: PM2.5 species profiles for natural gas-fired reciprocating engines

	CEPEI 2015 Alfa 4SLB	API 4SRB	API 4SLB	Average 4S*	API 2SLB
OC	94	80	90	88	98
Fe	0.028	3.9	5.8	3.2	0.0041
Si	0.13	6.0	1.4	2.5	0.18
EC	1.7	2.5	0.16	1.5	0.75
SO42-	1.0	3.2	0.66	1.6	0.24
Ca	1.1	1.2	0.53	0.94	0.28
Zn	0.15	0.57	0.55	0.42	0.076
NO3-	0.33	0.47	0.25	0.35	0.19
NH4+		0.89	0.090	0.33	0.068
Cl-		0.38	0.15	0.18	0.049
P	0.12	0.14	0.032	0.097	0.03
Al	0.06	0.03	0.13	0.073	0.0014
Mo		0.14	0.073	0.071	0.028
Na+	0.050	0.057	0.049	0.052	0.063
Cu	0.00094	0.051	0.057	0.036	0.010
K	0.021	0.029	0.036	0.029	0.0078
Ba	0.031	0.022	0.020	0.024	0.0057
Co		0.029	0.021	0.017	
Mn	0.0033	0.018	0.022	0.014	
Cr	0.0060	0.022	0.0099	0.013	0.00080
La	0.012	0.010	0.011	0.011	
Sn	0.0081	0.015	0.0019	0.0083	
Ni	0.00060	0.0042	0.0061	0.0036	
Br	0.0042	0.00092	0.0013	0.0021	0.0010
V		0.0026	0.0032	0.0019	
Cd	0.0045		0.00086	0.0018	
Sr	0.0024	0.00034	0.00064	0.0011	0.00018
Ag	0.0022		0.00060	0.00093	
Y	0.0017		0.00044	0.00071	0.00019
Rb	0.0014	0.00020	0.00048	0.00069	0.00016
Se		0.0011	0.00060	0.00057	
S	1.8			0.60	
Cl	0.14			0.047	
Eu	0.064			0.021	
Ti	0.024			0.0080	
Ce	0.022			0.0073	
W	0.021			0.0070	
Cs	0.018			0.0060	
Sm	0.0084			0.0028	
Sb	0.0047			0.0016	
U	0.0043			0.0014	0.00013
Pb	0.0042			0.0014	
Au	0.0033			0.0011	
Zr			0.00024	0.000080	0.00026

Shaded area indicates species detected for only one unit. Results may not be representative of other units.
*Some species were not detected in all tests. To calculate the average species profile, the species percentage for undetected results is treated as zero. This results in an average species profile that sums to 100%.

6. DISCUSSION

6.1 PM2.5 Emission Factor Comparison – EPA AP-42

AP-42 is a widely referenced resource for emission factors when site- or industry-specific emission factors are not available. AP-42 Chapters 3.1 and 3.2 include emission factors for filterable particulate matter (fPM) - total and/or PM10 - and cPM for natural gas-fired gas turbines and natural gas-fired reciprocating internal combustion engines (RICE), respectively. The data sets on which the emission factors are based are available as Microsoft Access files that can be downloaded from U.S. EPA's website[7]. Summaries of the data sets used for these published AP-42 emission factors are provided in Appendix B.

6.1.1 AP-42: Gas Turbines

The AP-42 gas turbine data set for fPM and cPM consists of five tests on three different 86 MW units of the same make and model between 1994 and 1996. Two of the units were tested with and without water injection for gas turbine power augmentation and NO_X control (Table 6-1). The emission factors are based on U.S. EPA hot filter/cooled impinger PM test methods (U.S. EPA Methods 201, 201A or 5 for fPM and EPA Method 202 or modified Method 5 back half for cPM). EPA rates the data quality as high, but the quality of the emission factor is rated only "C" (on EPA's scale of "A" to "E", "A" being the highest quality and "E" being the lowest – refer to Appendix E for definition of EPA's quality rating system).

The limited nature of the AP-42 gas turbine data set and large degree of variability are striking for both fPM and cPM (Figure 6-1). Variability among the data sets contributes to large uncertainty in the reported emission factor, especially for cPM.

The CEPEI PM2.5 emission factor based on dilution sampling test methods, which includes fPM and cPM together from six tests of five different units, is far lower than either the AP-42 fPM or cPM emission factors alone and the uncertainty in the average emission factor is very small in comparison to that for either the fPM or cPM AP-42 factor. The large difference in the average emission factor is believed to be due to bias in the hot filter/cooled impinger measurement methods used in the AP-42 data set, related to sensitivity limitations of the gravimetric procedures used for both fPM and cPM and SO_2 artifacts in the cPM measurement procedure[8].

6.1.2 AP-42: Reciprocating Engines

The AP-42 four-stroke reciprocating engine PM emission factors (Table 6-2) are based on very limited data sets:

- Three four-stroke rich burn engine tests: fPM was measured in tests conducted in 1993 of three engines equipped with pre-combustion chambers (no post-combustion catalysts) using hot filter methods. cPM was not measured in any of these tests;
- Two four-stroke lean burn engine tests: Both fPM and cPM were measured in tests conducted in 1994 of two engines with no emission controls using hot filter/cooled impinger methods.

Although the actual measurements are of total fPM (without any size classification), AP-42 provides emission factors for filterable PM10 and filterable PM2.5 assuming that all particles are smaller than 2.5 micrometers (a reasonable assumption). The wide range of values among the data sets

Table 6-1: Average PM emission factors for natural gas-fired gas turbines.

Engine Type	Emission Controls	Pollutant	Emission Factor	Emission Factor Quality	Number of Units Tested (Test Dates)
U.S. EPA AP-42 emission factors (hot filter/cooled impinger test methods)					
Gas turbine (natural gas-fired)	None (water-steam injection for power augmentation)[28]	PM (filterable)	1.9 E-03 lb/MMBtu (8.17 E-04 kg/GJ)	C	3 (1994-1996)
		PM (condensable)	4.7 E-03 lb/MMBtu (2.03 E-03 kg/GJ)	C	
		PM (total)	6.6 E-03 lb/MMBtu (2.85 E-03 kg/GJ)	C	
CEPEI Emission Factor (dilution test methods)					
Gas turbine simple cycle and combined cycle/cogeneration units	Lean premixed combustors, with and without post-combustion catalysts	PM2.5 (filterable + condensable)	1.01 E-04 kg/GJ	--	5 (2002-2015)

---

[28] EPA cites water-steam injection as emission controls; however, comments in EPA database suggest this was for turbine power augmentation. This may be co-beneficial in reducing NO_X emissions. Some runs were conducted with power augmentation on and some with power augmentation off.

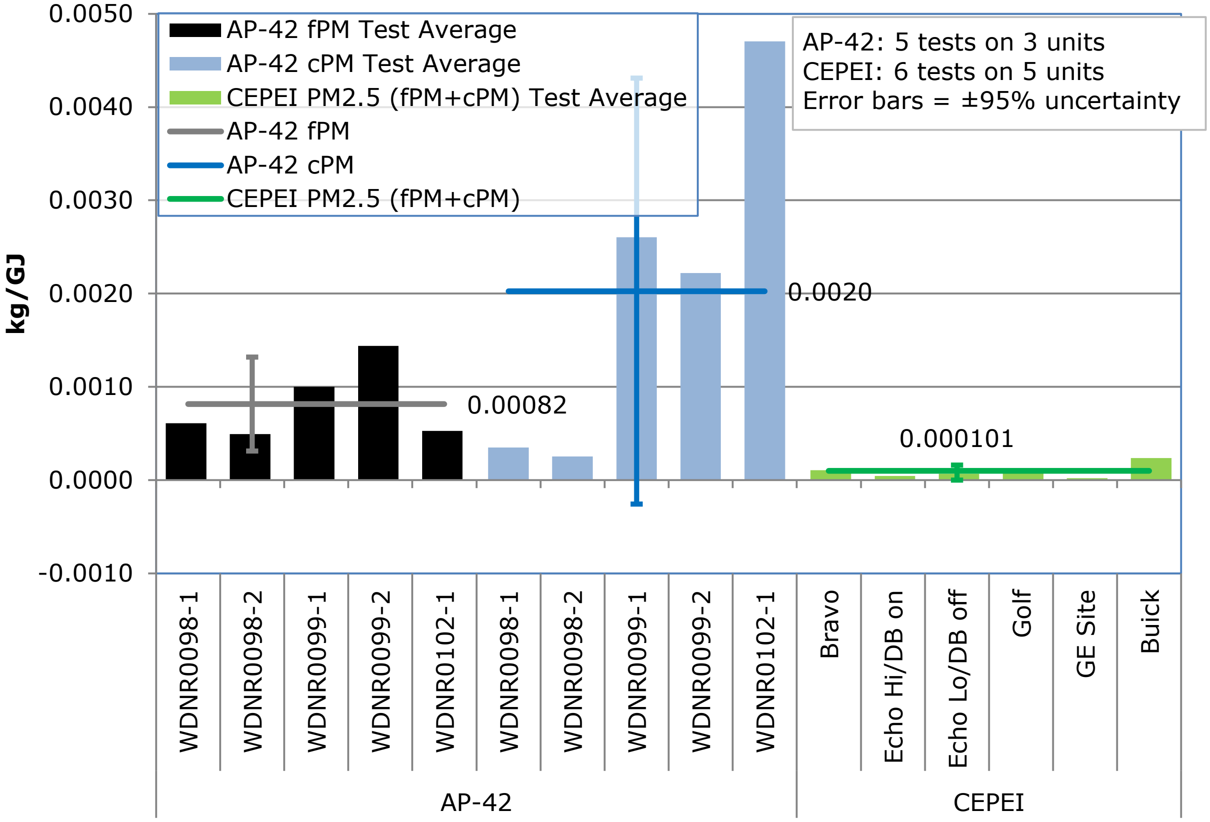


Figure 6-1: Comparison of EPA AP-42 and CEPEI emission factor data sets for filterable and condensable particulate matter – gas-fired gas turbines and combined cycle/cogeneration units.

contributing to large uncertainty in the average values for rich burn engine fPM and lean burn engine cPM is apparent, (Figure 6-2). AP-42 reports the same cPM emission factor for both 4SLB and 4SRB engines, although cPM measurements were made only for the 4SLB engines. The AP-42 lean burn engine fPM emission factor is much lower than the fPM emission factor for rich burn engines. The CEPEI PM2.5 emission factor for all four-stroke reciprocating engines is lower than the average fPM emission factor for rich burn engines and higher than the fPM emission factor for lean burn engines, and much lower than the cPM emission factor for all engines; thus, the CEPEI PM2.5 emission factor is much lower than the combined fPM + cPM AP-42 emission factors for either type of engine.

6.2 PM2.5 Emission Factor Uses and Implications

The emission factors used in this study will be useful for a variety of applications. Regional air quality models are often used to assess emissions management strategies to achieve an air quality goal. Estimated PM10/2.5 emissions from natural gas-fired combustion equipment typically comprise a very minor part of emission inventories in areas with a mix of stationary and mobile sources burning a variety of fuels and other sources of PM2.5 and PM2.5 precursor emissions. For example, PM2.5 from commercial fuel combustion (some of which is natural gas), natural gas use in power generation, natural gas transmission and natural gas distribution is reported to be less than 0.2% of total PM2.5 emissions in Canada[29]. PM2.5 emissions from natural gas combustion in power generation,

---

[29] Air Pollutant Emission Inventory Report 1990-2014, Environment and Climate Change Canada, Gatineau, Quebec, 2016.

Table 6-2: Average PM emission factors for natural gas-fired four-stroke reciprocating engines.

Engine Type	Emission Controls	Pollutant	Emission Factor	Emission Factor Quality	Number of Units Tested (Test Dates)
U.S. EPA AP-42 emission factors (as published, hot filter/cooled impinger test methods)					
Four-Stroke Rich Burn RICE	Pre-combustion chambers --	PM10 & PM2.5 (filterable)	9.50 E-03 lb/MMBtu (4.08 E-03 kg/GJ)	E	3 (1993)
		PM (condensable)	9.91 E-03 lb/MMBtu (4.26 E-03 kg/GJ)	E	none (cPM factor for 4SLB engines)
		PM 10 & PM2.5 (total)	19.41 E-03 lb/MMBtu (8.35 E-03 kg/GJ)	--	Sum
Four-Stroke Lean Burn RICE	No controls	PM10 & PM2.5 (filterable)	7.71 E-05 lb/MMBtu (3.31 E-05 kg/GJ)	D	2 (1994)
		PM (condensable)	9.91 E-03 lb/MMBtu (4.26 E-03 kg/GJ)	D	
		PM10 & PM2.5 (total)	9.99 E-03 lb/MMBtu (4.30 E-03 kg/GJ)	--	Sum
Four-Stroke RICE*	All	PM10 & PM2.5 (filterable)	2.46 E-03 kg/GJ uncertainty=124%	--	5
		PM (condensable)	4.26 E-03 kg/GJ uncertainty=428%	--	2
		PM10 & PM2.5 (total)	6.73 E-03 kg/GJ uncertainty=446%	--	Sum
CEPEI emission factors (dilution test methods)					
four-stroke rich burn and lean burn engines	Lean burn: no controls Rich burn: non-selective catalytic reduction	PM2.5 (filterable + condensable)	1.50 E-03 kg/GJ	--	3 (2003-2015)

*AP-42 does not report aggregate emission factors for four-stroke engines. Mean values derived from unit average test results used for AP-42 rich burn and lean burn reciprocating engine emission factors.

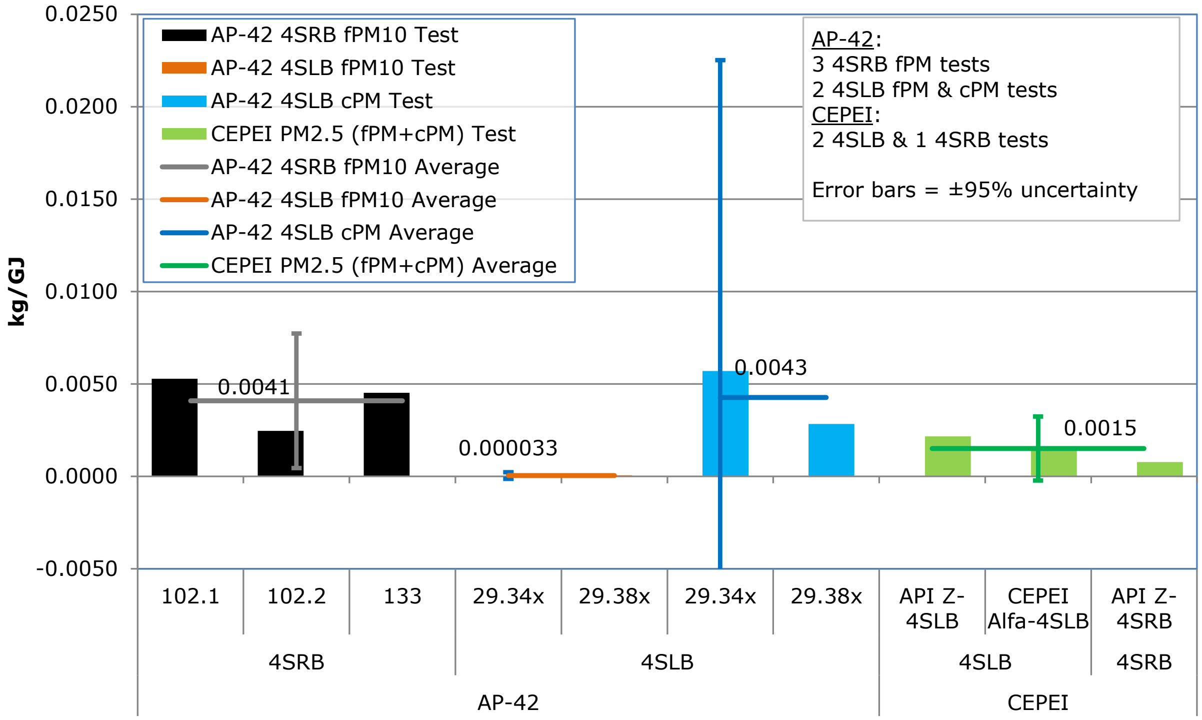


Figure 6-2: Comparison of EPA AP-42 and CEPEI PM2.5 emission factor data sets for filterable and condensable particulate matter– four-stroke reciprocating engines.

commercial, institutional and industrial boilers, internal combustion engines and residential sources comprise approximately 1% of PM2.5 emissions from all sources across the U.S. according to U.S. EPA's 2011 National Emissions Inventory[30]. Nonetheless, estimated PM2.5 emissions impacts from specific sources can generate apparent air quality impacts and human health risk concerns when using AP-42 and similar emission factors. Estimated PM2.5 emissions using the CEPEI emission factors will likely reduce the projected air quality impact of natural gas-fired engines, boilers and process heaters even further and perhaps to "de minimus" levels compared with other sources that have higher air quality impact. With application of appropriate caution considering the uncertainty and variability of the data and the small size of the data sets, the results may be used to evaluate the impact of potential PM2.5 emission limits on air quality. An average emission factor should not be used as an emission limit for a specific unit since emissions from some units are above the average and some are below. Other statistics such as the maximum, 95% confidence upper bound or 99% confidence upper prediction limit may be more appropriate metrics to consider as potential emissions limits.

As an example, using the AP-42 total particulate matter emission factor of 0.0032 kg/GJ, estimated annual PM10/2.5 emissions total 80 metric tons per year for a typical 500-MW natural gas-fired combined cycle plant with two large heavy duty gas turbines and one steam turbine operating at full load for 8760 hours. This would decrease to just 2 metric tons per year using the average CEPEI PM2.5 emission factor.

A lower estimate of PM2.5 emissions and updated PM2.5 chemical species profiles also have implications for evaluating human health risk impacts surrounding new or existing natural gas-fired

---

[30] 2011 National Emission Inventory Data, U.S. Environmental Protection Agency, 2016. https://www.epa.gov/air-emissions-inventories/2011-national-emissions-inventory-nei-data.

combustion equipment. For example, estimated PM2.5 emissions from a 20 MW gas turbine pipeline compressor drive operating 8760 hours per year at full load are 0.5 metric tons/year using the AP-42 emission factor and 0.02 metric tons per year using the CEPEI 99% UPL PM2.5 emission factor, a 28-fold decrease. Health risk associated with particulate matter is often based on diesel engine studies. CEPEI PM2.5 species profiles show that PM2.5 emissions from natural gas-fired engines at these very low levels is primarily organic carbon with very low levels of elemental carbon and only very minor amounts of sulfate, nitrate and other ions and elements. The chemical species profiles along with lower PM2.5 emission factors provide useful information for estimating the health risk associated from natural gas PM2.5 emissions.

It should be noted that PM2.5 measurements made during short operating periods represent a snapshot of emissions and may not represent emissions at all times. The emission factors derived in this study may not represent emissions from all similar units due to differences in unit design, fuels, operating conditions, emission controls, seasonal influences, and many other factors that influence emissions. Emission factors do not necessarily represent emissions from any particular unit. An average emission factor should not be used to establish emissions limits or standards because the emissions from half of the units will be higher than the average and half will be lower (assuming a normal distribution). The particular statistic (mean, median, maximum, etc.) associated with each emission factor data set should be carefully chosen as appropriate for a specific end use.