2024 TECHNICAL UPDATE

Combustion Turbine Stack Trace Metals Testing Analysis

An Analysis of Trace Metals Testing in Combustion Turbine Stacks

Combustion Turbine Stack Trace Metals Testing Analysis

An Analysis of Trace Metals Testing in Combustion Turbine Stacks

3002029941

August 5, 2024

Minor updates from a prior version were made to the numerical analysis due to the addition of a unit previously missing from the former report. The initial analyses did not include the Hilcorp data as a stack report was not available. However, the authors were subsequently advised of the availability of the ERT files; we added this information and redid all the calculations and data analyses. The effects on the numerical results were minor, and overall conclusions were not affected by this addition and reanalysis.

Technical Update, July 2024

EPRI Project Manager
E. Knipping

EPRI
3420 Hillview Avenue, Palo Alto, California 94304-1338 USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

THIS DOCUMENT WAS PREPARED BY THE ORGANIZATION(S) NAMED BELOW AS AN ACCOUNT OF WORK SPONSORED OR COSPONSORED BY THE ELECTRIC POWER RESEARCH INSTITUTE, INC. (EPRI). NEITHER EPRI, ANY MEMBER OF EPRI, ANY COSPONSOR, THE ORGANIZATION(S) BELOW, NOR ANY PERSON ACTING ON BEHALF OF ANY OF THEM:

(A) MAKES ANY WARRANTY OR REPRESENTATION WHATSOEVER, EXPRESS OR IMPLIED, (I) WITH RESPECT TO THE USE OF ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT, INCLUDING MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE, OR (II) THAT SUCH USE DOES NOT INFRINGE ON OR INTERFERE WITH PRIVATELY OWNED RIGHTS, INCLUDING ANY PARTY'S INTELLECTUAL PROPERTY, OR (III) THAT THIS DOCUMENT IS SUITABLE TO ANY PARTICULAR USER'S CIRCUMSTANCE; OR

(B) ASSUMES RESPONSIBILITY FOR ANY DAMAGES OR OTHER LIABILITY WHATSOEVER (INCLUDING ANY CONSEQUENTIAL DAMAGES, EVEN IF EPRI OR ANY EPRI REPRESENTATIVE HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES) RESULTING FROM YOUR SELECTION OR USE OF THIS DOCUMENT OR ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT.

REFERENCE HEREIN TO ANY SPECIFIC COMMERCIAL PRODUCT, PROCESS, OR SERVICE BY ITS TRADE NAME, TRADEMARK, MANUFACTURER, OR OTHERWISE, DOES NOT NECESSARILY CONSTITUTE OR IMPLY ITS ENDORSEMENT, RECOMMENDATION, OR FAVORING BY EPRI.

THE FOLLOWING ORGANIZATIONS PREPARED THIS REPORT:

AECOM

EPRI

This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

Together…Shaping the Future of Energy®

© 2024 Electric Power Research Institute (EPRI), Inc. All rights reserved. Electric Power Research Institute, EPRI, and TOGETHER…SHAPING THE FUTURE OF ENERGY are registered marks of the Electric Power Research Institute, Inc. in the U.S. and worldwide.

ACKNOWLEDGMENTS

The following organizations, under contract to EPRI, prepared this report:

AECOM
250 Apollo Drive
Chelmsford, MA 01824

Principal Investigators
S. Carcieri
S. Jelinek

EPRI

Principal Investigators
P. Chu
L. Angello
E. Knipping

This report describes research sponsored by EPRI.

This publication is a corporate document that should be cited in the literature in the following manner: *Combustion Turbine Stack Trace Metals Testing Analysis: An Analysis of Trace Metals Testing in Combustion Turbine Stacks.* EPRI, Palo Alto, CA: 2024. 3002029941.

ABSTRACT

This report supplements the risk assessments conducted by EPRI[1] in support of the Risk and Technology Review of the National Emission Standards for Hazardous Air Pollutants (NESHAP) for Stationary Combustion Turbines.[2] The report describes the results of the analyses carried out to review the emissions testing data for trace metals and provides an assessment of the emissions testing methodology utilized in the test programs. An analysis of potential sources of combustion turbine metals emissions was also conducted. The report concludes that fuel constituents, ambient air, and oil leaks are unlikely to be the source of trace metals emissions and that potential erosion or corrosion of the combustion turbine components may contribute to these emissions.

Keywords

Hazardous air pollutants (HAPs)
National Emissions Standards for Hazardous Air Pollutants (NESHAP)
Stationary combustion turbines

---

[1] *Inhalation Human Health Risk Assessment for U.S. Stationary Combustion Turbines: 2014 Base Year Evaluation*. EPRI, Palo Alto, CA: 2019. 3002016528.

Multi-Pathway Human Health Risk Assessment for U.S. Stationary Combustion Turbines: 2014 Base Year Evaluation and Refined TRIM. EPRI, Palo Alto, CA: 2019. 3002016745.

Environmental Risk Screening Assessment for U.S. Combustion Turbines: 2014 Base Year Evaluation. EPRI, Palo Alto, CA: 2019. 3002017441.

Supplemental Human Health and Environmental Risk Assessment for U.S. Combustion Turbines: 2014 Base Year Evaluation. EPRI, Palo Alto, CA: 2020. 3002020134.

Supplemental Human Health and Environmental Risk Assessment for U.S. Combustion Turbines (2023 Supplement): 2014 Base Year Evaluation. EPRI, Palo Alto, CA: 2023. 3002026130.

[2] https://www.regulations.gov/docket?D=EPA-HQ-OAR-2017-0688.

ACRONYMS AND ABBREVIATIONS

ADL	Above detection level
BDL	Below detection level
Btu	British thermal unit
CFR	Code of Federal Regulations
CT	Combustion turbine
DLL	Detection level limited
EPA	U.S. Environmental Protection Agency
HAP	Hazardous air pollutant
Hr	Hour
Lb	Pound
m^3	Cubic meter
MACT	Maximum achievable control technology
MDL	Minimum detection level
MMBtu	Million British thermal units
NEI	National Emissions Inventory
NESHAP	National Emission Standards for Hazardous Air Pollutants
RL	Reporting level
RTR	Risk and Technology Review
SCR	Selective catalytic reduction
µg	Microgram

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

The United States Environmental Protection Agency (EPA) is currently working on proposed rulemaking related to the National Emission Standards for Hazardous Air Pollutants (NESHAP) for the combustion turbine (CT) source category (40 CFR 63, Subpart YYYY). EPA has collected emissions testing data from owners/operators of CTs as part of a Section 114 information request to support the Risk and Technology Review (RTR) effort and has published these data online (EPA 2023). EPRI has developed this report to evaluate whether stationary CTs emit additional pollutants not previously assessed by EPA (EPA 2019) or by EPRI (EPRI 2019a; 2019b; 2019c; 2020a; 2023a; 2023b) when estimating human health and ecological risks associated with CTs. This document summarizes the emissions testing data for trace metals, assesses the testing methodology, and suggests potential operational factors that may contribute to or inform the results.

Overview of Combustion Turbines

CTs, often referred to as gas turbines, are a type of engine that can convert natural gas or other liquid or gaseous fuels into mechanical energy. This process is continuous, providing a constant source of power as long as fuel is supplied. CTs work on the principle of the Brayton cycle, which involves four main processes: air intake, compression, combustion, and exhaust.

- Air Intake: The process begins when ambient air is drawn into the engine through an intake structure. Water may also be injected into the intake structure to boost power or fuel efficiency, or to control emissions of nitrogen oxides.
- Compression: This air is then compressed to high pressures by a compressor. This compression raises the temperature of the air to prepare it for combustion.
- Combustion: The combustion system is typically made up of a ring of fuel injectors that inject a steady stream of fuel (usually natural gas or another liquid fuel) into combustion chambers, where it mixes with the pressurized air. The fuel-air mixture is ignited, which produces a high-temperature, high-pressure gas stream.
- Exhaust: This hot combustion gas expands and drives through a turbine, which is an array of blades connected to a generator. As the turbine spins, it drives the generator, which converts the mechanical energy into electrical energy. The exhaust gases are then expelled from the engine.

CTs are used in various applications, including, but not limited to, electrical power generation, natural gas compression along the gathering and transportation pipeline network, and aviation. CTs are also commonly utilized in marine applications for propulsion and power generation on board ships. In power plants, CTs can be used in simple-cycle mode or in a combined-cycle configuration, which operates in tandem with steam turbines to maximize the conversion of fuel energy into electricity. In such setups, the exhaust heat from the CT is used to generate steam that drives the steam turbine, thereby significantly increasing overall efficiency. CTs are chosen for their ability to provide continuous and large-scale power output, as well as their ability to meet peaks in power demand very quickly.

Land-based gas turbines, also referred to as stationary gas turbines, are divided into two categories: 1) heavy-frame engines and 2) aeroderivative engines. Heavy-frame engines are characterized by lower pressure ratios (the ratio of the compressor discharge pressure to the inlet air pressure) and tend to be physically large. Aeroderivative engines are derived from jet airplane engines, as the name implies, and operate at very high compression ratios. Aeroderivative engines tend to be very compact and are useful where smaller power outputs are needed.

Despite their widespread use, CTs do come with their own set of challenges and limitations. They are highly sensitive to changes in ambient temperature and pressure, which can impact their performance and efficiency. Moreover, they require careful maintenance and regular inspections to ensure their longevity and reliability.

Combustion Turbine Emission Controls

Available methods to control emissions from stationary CTs include selective catalytic reduction (SCR), lean pre-mix combustion, and water or steam injection to control nitrogen oxide emissions, and oxidation catalyst systems to control carbon monoxide and organic compound emissions, including organic compound hazardous air pollutant (HAP) emissions. The technical feasibility of these control alternatives on a given stationary CT depends on the turbine size (fuel heat input or power output) and operating configuration (simple or combined cycle).

Regulation of Combustion Turbine Emissions

Stationary CTs emit pollutants into the atmosphere as a product of combustion. In the United States, the EPA regulates these air emissions under the Clean Air Act to limit their environmental impact. New Source Performance Standards under 40 CFR Part 60 establish standards for emissions of nitrogen oxides, sulfur dioxide, and particulate matter. Subpart GG covers turbines that commenced construction after October 3, 1977, and before February 18, 2005. Subpart KKKK covers both the CT engine and any associated heat recovery steam generator for units that commenced construction after February 18, 2005.

As discussed above, EPA regulates HAPs from stationary CTs under its NESHAP program. This program establishes source categories and regulates HAPs in two phases. The first phase is “technology based”; EPA develops Maximum Achievable Control Technology (MACT) standards, which are based on emissions levels that are already being achieved by the best-controlled and lower-emitting sources in a source category. In the second phase, which occurs within eight years of setting the MACT standards, EPA assesses the remaining risks from the source category to determine whether the current standards protect public health with an ample margin of safety and protect against adverse environmental effects. This phase is referred to as the residual risk assessment. Under 40 CFR Part 63, Subpart YYYY, EPA in 2004 established formaldehyde emission limits only for “new units” built after the effective date of the rule. EPA finalized the RTR, which includes the residual risk assessment in 2019 (EPA 2019), in 2020.

These findings concluded that risks from the CT source category are acceptable and that no new cost-effective controls are available.

Previous Risk Analyses

As noted above, EPA assessed human health and environmental risks from CTs in the residual risk assessment, which was finalized in 2019 (EPA 2019). In addition, EPRI has published several studies that have assessed human health and environmental risks from stationary CTs. These EPRI studies estimated risks using methodologies consistent with EPA's; however, they included numerous refinements to emissions and stack parameterization for the source category, including diesel fuel oil analyses to determine the presence of trace metals such as arsenic (EPRI 2019a). The initial EPRI studies concluded that the cancer, chronic noncancer, and acute noncancer health risks from CTs for each chemical individually and all emitted chemicals combined were well within EPA's risk thresholds. In addition, all facilities were below the EPA environmental screening thresholds and are therefore likely to have no widespread adverse environmental effects (EPRI 2019a; 2019b; 2019c). Supplemental EPRI studies assessed health and environmental risks for newly identified CTs and similarly concluded that risks for all facilities were below EPA risk thresholds.

Appendix 1 in the CT source category residual risk assessment (EPA 2019) lists the metallic HAPs that CTs are expected to emit for each fuel type. These are summarized in Table 1 below. As EPA noted in a footnote to the table:

"Significant metallic HAP emissions are not expected from natural gas fired stationary combustion turbines, as such metallic HAP emissions were not included in the modeling file for those units. In addition, AP-42 does not have metal HAP emission factors for natural gas turbines."

For landfill gas-, jet fuel-, and process gas-fired turbines, EPA only modeled those HAPs with reported emission values in the 2014 National Emissions Inventory (NEI), which served as the basis for the emission estimates in EPA's CT RTR. EPA noted that CTs firing these fuels are not expected to emit all of the metallic HAPs (EPA 2019). All metal HAPs were modeled for oil-fired CTs.

Table 1. Expected metallic HAP pollutants per fuel category

Metallic HAP	Natural Gas	Distillate Oil	Landfill Gas	Jet Fuel	Process Gas
Manganese Compounds		Yes		Yes	
Nickel Compounds		Yes		Yes	Yes
Lead Compounds		Yes		Yes	Yes
Arsenic Compounds		Yes			Yes
Chromium Compounds		Yes			Yes
Cadmium Compounds		Yes			Yes
Mercury Compounds		Yes		Yes	
Selenium Compounds		Yes			
Cobalt Compounds		Yes			
Beryllium Compounds		Yes		Yes	
Antimony Compounds		Yes			

Source: EPA 2019

Stack Testing

As noted above, when conducting the RTR for the CT source category, EPA did not include any metallic HAPs for natural gas-fired turbines, and it only included those from turbines firing landfill gas, jet fuel, or process gas if these pollutants were reported in the NEI. However, subsequent to conducting the RTR, EPA submitted Section 114 information requests to facilities requesting emission testing results for natural gas-, oil-, and landfill gas-fired CTs, which included testing for the following metallic HAPs:

- Antimony
- Arsenic
- Beryllium
- Cadmium
- Chromium
- Cobalt
- Lead
- Manganese
- Mercury
- Nickel
- Selenium

Emission test reports and electronic reporting tool (ERT) database files were published by EPA for 22 CTs at 13 facilities (EPA 2023). A summary of the CTs tested for metals in response to EPA's Section 114 information request is provided in Table 2 below, along with the fuels fired during the testing of each CT.

Table 2. Turbines tested for trace metals as part of EPA's Section 114 information request[3]

Facility Name	City, State	CT Tested	Size, MW	Size, MMBtu/hr	Year Built	Fuel(s) (During Test)
Texas Eastern Transmission LP—Somerset	Somerset, OH	B011 (12401)—Solar Mars 100	11.2	122.2	2017	Natural gas
Texas Eastern Transmission LP—Danville	Danville, KY	Unit 13—GE Frame 5—179368	13.8	151.9	1969	Natural gas
Hilcorp North Slope, LLC - Central Compressor Plant (CCP)	Prudhoe Bay, AK	Unit 3 (18-1803) - GE MS5371PATP	26.4	395	1990	Natural gas
		Unit 15 (18-1878) - GE MS5382C	26.4	424	1990	Natural gas
BMW Manufacturing Co., LLC	Greer, SC	GT05 Cogen—Solar 60	5.2	75	2009	Landfill gas
		GT06 Cogen—Solar 60	5.2.4	75	2009	Landfill gas
Northern Natural Gas Company—Waterloo Compressor Station	Waterloo, IA	Unit 7—Solar	1.2	11.2	1993	Natural gas
		Unit 8—Solar	1.2	11.2	1993	Natural gas
Northern Natural Gas Company—Beatrice Compressor Station	Beatrice, NE	Unit 29—Solar	11.9	117.6.6	2021	Natural gas
Northern Natural Gas Company—Clifton Compressor Station	Clifton, KS	Unit 30—General Electric	6.8	113.8	1970	Natural gas
Middletown Power LLC—Middletown Generating Station	Middle-town, CT	Unit 13—General Electric LM6000PC	50	510.9	2011	Natural gas
		Unit 15—General Electric LM6000PC	50	482.4	2011	Oil
Sunshine Gas Producers, LLC	Sylmar, CA	CT-4—Solar Mercury 50	4.9	61	2012	Landfill gas

---

[3] The Hilcorp North Slope, LLC - Central Gas facility in Alaska was also part of the Section 114 information request; however, these turbines were not tested for trace metals and are therefore not listed in Table 2.

Facility Name	City, State	CT Tested	Size, MW	Size, MMBtu/hr	Year Built	Fuel(s) (During Test)
		CT-5—Solar Mercury 50	4.9	61	2012	Landfill gas
Georgia Power—Plant McIntosh	Rincon, GA	Simple-Cycle Unit 1	80	1419	1993	Natural gas; oil
		Simple-Cycle Unit 2	80	1419	1993	Natural gas; oil
Georgia Power—Plant McDonough	Smyrna, GA	Combined-Cycle Unit 4A	252	2617	2008	Natural gas
		Combined-Cycle Unit 4B	252	2617	2008	Natural gas
Enbridge Energy Partners—Holbrook Compressor Station	Wind Ridge, PA	Unit 1 (118)—Solar Mars 100-150002s III	11.2	96	1990	Natural gas

A review of the stack testing methodologies employed for each facility was conducted for the trace metals. This verified that appropriate EPA test methods were used to collect the emissions data and that the test programs followed correct EPA methodology. No notable deficiencies were identified during the review of the emission testing methodologies and procedures. During each test program, the testing contractors in general collected field blanks (ambient air testing conducted during leak checks) and/or reagent blanks (to test for any pollutants present in the reagents, solvents or solutions used to collect and store test samples). If pollutants were detected at or above the reporting level (RL) from the blank sampling, facilities “blank corrected” the testing samples to help minimize overreporting of pollutant emissions from the CTs.

A summary of the individual and average test results is provided in Appendix A. In addition to information on the facility name and address, fuel fired during testing, and the test date for each pollutant run, Appendix A summarizes the emission controls used for each CT using information reported in the ERT files and augmented using publicly available air quality permit files when available. Air emission control systems employed on the tested CTs include SCR, oxidation catalyst, lean pre-mix, and water/steam injection. As shown in Appendix A, the emission control system employed varied among the turbines. Each test run and run average was marked to indicate whether the emission test results were above or below the minimum detection level (MDL), using the following labels:

- ADL (above detection level): All analyte fractions used to report value were above the MDL.
- DLL (detection level limited): At least one, but not all, analyte fractions were above the MDL.
- BDL (below detection level): All analyte fractions were below the MDL.

In some cases, values that were not reported were calculated using data presented within the stack test reports. This included calculating averages from individual test runs, converting fuel flow in cubic feet per day to cubic feet per hour, or calculating values when the report did not include enough significant digits (and therefore the value was reported as zero). Additionally, fuel heat input rates in million British thermal units per hour (MMBtu/hr) were filled in when not reported using other data within the stack test report or, if otherwise unavailable, from publicly available information such as permits. All instances where data were calculated or filled in are marked as such within Appendix A, and notes are provided to support these additions. Comments were added to note potentially anomalous results or instances where the reported average did not correspond to the calculated average of the individual test runs; however, the results are included in Appendix A as reported without modification.

2 ANALYSIS OF TRACE METALS

Table 3 below summarizes the number of individual stack test runs for each metal, categorized by fuel fired and by detection level (ADL, DLL, or BDL). Table 4 summarizes the average pound per MMBtu (lb/MMBtu) emission rates measured for each pollutant, categorized by fuel fired and by detection level. The lb/MMBtu emission rates were either provided within the stack test report or calculated based on data provided within the report. The use of lb/MMBtu emission rates provides for a “normalized” emission rate among the different-sized CTs.

Note that MDLs for each pollutant are not standardized and vary among the emission test reports. As DLL or BDL test runs were estimated or reported at the MDL, it is likely that only the lb/MMBtu emission rates for ADL test runs are beneficial to help indicate the actual emission rate of each pollutant. However, the table includes emission rates at all detection levels for informational purposes. In addition, it should be noted that the stack test sample size, particularly for the oil-fired and landfill gas-fired CTs, is relatively small. As shown in Appendix A, all four landfill gas-fired CTs that were tested had heat input rates less than 75 MMBtu/hr, which is substantially smaller than the mean heat input rate for all CTs tested, 484 MMBtu/hr. These two factors may skew the analysis results or limit the statistically significant conclusions that can be drawn from this data set. Lastly, while the average emission rates were used for comparison purposes within this document, note that the 95th percentile upper prediction limit emission factor accounts for test result variability and is typically what is used when EPA sets numerical MACT floor limits (EPA 2022).

Several of the HAP metals tested, including antimony, arsenic, beryllium, cadmium, and selenium, were predominantly non-detect in some or all analyte fractions (DLL or BDL), as shown in Table 3. Overall, the metals emission test results for landfill gas-fired CTs skewed slightly higher for the number of samples ADL for these pollutants. Cobalt, lead, and mercury were primarily DLL or BDL for natural gas- and oil-fired CTs; however, these pollutants were mostly ADL/DLL for landfill gas-fired CTs. Chromium, manganese, and nickel test results were mostly ADL across all fuel types. The emission rates of these three metal HAPs were also fairly consistent across the three fuel types, as shown in Table 4. This suggests that these pollutants are emitted at rates independent of fuel type and therefore likely not emitted as a result of being constituents in the fuels. No fuel analyses to measure the levels of the metal HAP constituents in fuel were reported as part of this Section 114 information request.

No distinguishable trends were observed in the emission rates of metal HAPs between CTs with and without various emission controls (SCR, oxidation catalyst, lean pre-mix, or steam/water injection). However, this comparison is provided for chromium, manganese, and nickel (the three trace metals that were predominantly ADL) in Table 5, Table 6, Table 7, and Table 8 below. A comparison for all trace metals is included in Appendix A.

Table 3. Number and percentage of individual test runs by fuel and detection level

	Number of Individual Test Runs									Percentage of Total for Individual Test Runs								
	Natural Gas Turbines			Oil-Fired Turbines			Landfill Gas-Fired Turbines			Natural Gas Turbines			Oil-Fired Turbines			Landfill Gas-Fired Turbines		
Pollutant	**ADL**	**DLL**	**BDL**	**ADL**	**DLL**	**BDL**	**ADL**	**DLL**	**BDL**	**ADL**	**DLL**	**BDL**	**ADL**	**DLL**	**BDL**	**ADL**	**DLL**	**BDL**
Antimony	0	47	56	0	11	8	6	3	11	0%	46%	54%	0%	58%	42%	30%	15%	55%
Arsenic	8	13	82	0	0	19	1	4	15	8%	13%	80%	0%	0%	100%	5%	20%	75%
Beryllium	0	9	94	0	0	19	2	4	14	0%	9%	91%	0%	0%	100%	10%	20%	70%
Cadmium	4	29	70	0	5	14	8	7	5	4%	28%	68%	0%	26%	74%	40%	35%	25%
Chromium	74	11	18	15	0	4	20	0	0	72%	11%	17%	79%	0%	21%	100%	0%	0%
Cobalt	9	18	76	0	0	19	10	7	3	9%	17%	74%	0%	0%	100%	50%	35%	15%
Lead	20	31	52	2	0	17	20	0	0	19%	30%	50%	11%	0%	89%	100%	0%	0%
Manganese	81	14	8	19	0	0	20	0	0	79%	14%	8%	100%	0%	0%	100%	0%	0%
Nickel	84	8	11	16	3	0	20	0	0	82%	8%	11%	84%	16%	0%	100%	0%	0%
Selenium	2	29	72	0	6	13	0	18	2	2%	28%	70%	0%	32%	68%	0%	90%	10%
Mercury	0	18	85	0	0	19	6	14	0	0%	17%	83%	0%	0%	100%	30%	70%	0%

Table 4. Average emission rates by fuel and detection level

	Average Emission Rates (lb/MMBtu)								
	Natural Gas Turbines			**Oil-Fired Turbines**			**Landfill Gas-Fired Turbines**		
Pollutant	**ADL**	**DLL**	**BDL**	**ADL**	**DLL**	**BDL**	**ADL**	**DLL**	**BDL**
Antimony		7.94E-07	1.58E-06		7.28E-07	1.44E-06	3.98E-07	2.79E-06	1.71E-07
Arsenic	3.06E-05	6.98E-07	8.66E-07			7.03E-07	7.11E-08	5.40E-07	2.87E-07
Beryllium		8.97E-08	7.12E-08			6.06E-08	9.08E-08	2.49E-08	2.93E-08
Cadmium	1.71E-06	2.64E-07	2.32E-07		1.35E-07	1.04E-06	1.41E-07	6.11E-08	4.10E-08
Chromium	8.62E-06	2.01E-06	6.22E-06	1.80E-06		3.25E-06	2.53E-06		
Cobalt	3.87E-07	1.09E-06	8.54E-07			6.63E-07	1.28E-07	4.65E-08	4.20E-08
Lead	3.32E-06	2.31E-06	7.94E-07	6.89E-07		5.70E-07	1.07E-06		
Manganese	7.78E-06	3.60E-05	1.22E-06	9.72E-06			1.89E-06		
Nickel	5.36E-06	5.64E-05	6.25E-06	3.38E-06	1.51E-06		1.28E-06		
Selenium	9.25E-07	9.33E-07	1.72E-06		8.50E-07	3.67E-06		1.95E-06	4.14E-08
Mercury		6.02E-07	2.33E-07			1.90E-07	3.85E-07	2.90E-07	

Note: Where no value is listed, there were no test values at the specified detection level category for that fuel.

Table 5. Comparison of select trace metals with and without SCR

	Percentage of Total for Individual Test Runs						lb/MMBtu Average Emission Rate			
	With SCR			Without SCR			With SCR		Without SCR	
Pollutant	**ADL**	**DLL**	**BDL**	**ADL**	**DLL**	**BDL**	**ADL**	**Overall**	**ADL**	**Overall**
Chromium	69%	14%	17%	79%	6%	15%	1.54E-06	1.99E-06	7.99E-06	7.41E-06
Manganese	83%	17%	0%	85%	7%	7%	1.44E-05	2.58E-05	4.77E-06	4.34E-06
Nickel	94%	6%	0%	81%	8%	10%	4.24E-06	4.00E-06	4.49E-06	8.55E-06

Table 6. Comparison of select trace metals with and without lean pre-mix

	Percentage of Total for Individual Test Runs						lb/MMBtu Average Emission Rate			
	With Lean Pre-Mix			Without Lean Pre-Mix			With Lean Pre-Mix		Without Lean Pre-Mix	
Pollutant	**ADL**	**DLL**	**BDL**	**ADL**	**DLL**	**BDL**	**ADL**	**Overall**	**ADL**	**Overall**
Chromium	94%	1%	5%	59%	9%	32%	7.87E-06	7.72E-06	3.95E-06	4.36E-06
Manganese	87%	3%	10%	89%	11%	0%	4.35E-06	3.97E-06	1.10E-05	1.84E-05
Nickel	76%	10%	14%	95%	5%	0%	2.19E-06	8.20E-06	7.14E-06	6.89E-06

Table 7. Comparison of select trace metals with and without oxidation catalyst

	Percentage of Total for Individual Test Runs						lb/MMBtu Average Emission Rate			
	With Oxidation Catalyst			Without Oxidation Catalyst			With Oxidation Catalyst		Without Oxidation Catalyst	
Pollutant	**ADL**	**DLL**	**BDL**	**ADL**	**DLL**	**BDL**	**ADL**	**Overall**	**ADL**	**Overall**
Chromium	76%	12%	12%	77%	5%	17%	1.27E-05	1.03E-05	3.43E-06	3.86E-06
Manganese	67%	16%	16%	94%	6%	0%	1.58E-05	2.08E-05	3.81E-06	3.75E-06
Nickel	67%	10%	22%	94%	6%	0%	4.24E-06	1.33E-05	4.49E-06	4.32E-06

Table 8. Comparison of select trace metals with and without water/steam injection

	Percentage of Total for Individual Test Runs						lb/MMBtu Average Emission Rate			
	With Water/Steam Injection			Without Water/Steam Inj.			With Water/Steam Inj.		Without Water/Steam Inj.	
Pollutant	**ADL**	**DLL**	**BDL**	**ADL**	**DLL**	**BDL**	**ADL**	**Overall**	**ADL**	**Overall**
Chromium	87%	0%	13%	72%	11%	16%	2.33E-06	2.44E-06	8.93E-06	7.76E-06
Manganese	100%	0%	0%	77%	14%	8%	1.09E-05	1.09E-05	4.84E-06	9.04E-06
Nickel	93%	7%	0%	80%	8%	11%	2.86E-06	2.77E-06	5.26E-06	9.59E-06

Comparison of Emission Rates by Turbine Age

The installation dates of the CTs were determined to assess their ages. The lb/MMBtu emission rates for the three metals that were mostly ADL across all fuel types (chromium, manganese, and nickel) were plotted against the turbine age. As shown in Figure 1 for chromium, no distinguishable trend was observed between the age of the CT and the emission rate. Thus, turbine age does not appear to be a determinant factor in metal emission rates. The plots for manganese and nickel are very similar and are included in Appendix A for reference.

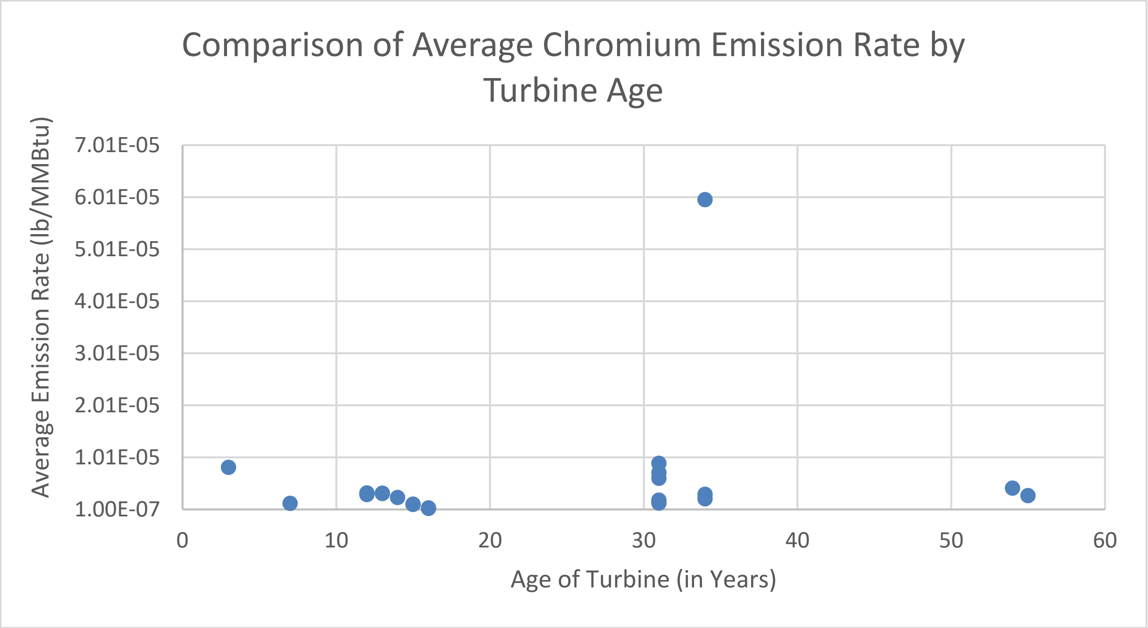


Figure 1. Comparison of average chromium emission rate by turbine age

Comparison of Emission Rates by Turbine Size

The heat input capacities (in MMBtu/hr) of the CTs were determined and similarly plotted against the lb/MMBtu emission rates for chromium, manganese, and nickel. As shown in Figure 2 for chromium, no distinguishable trend was observed between the size of the CT and the emission rate, which suggests that turbine size (heat input capacity) is not a determinant factor in metals emission rates. The plots for manganese and nickel are very similar and are included in Appendix A for reference.

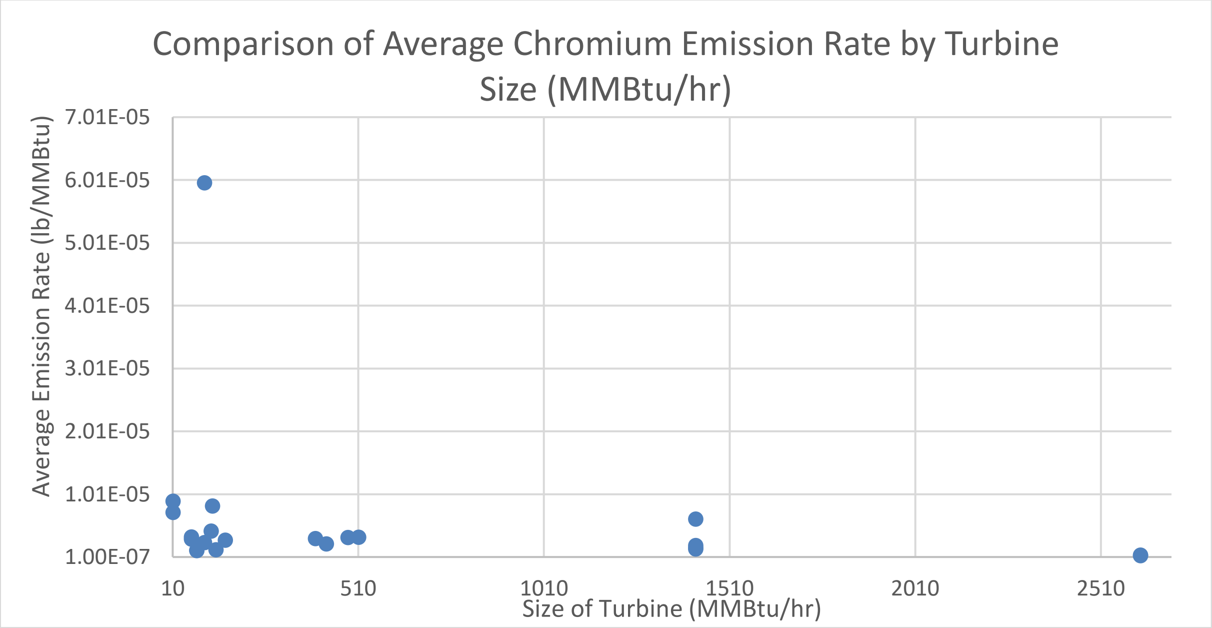


Figure 2. Average chromium emission rate by turbine size (MMBtu/hr)

Identification of Potential Outliers

An overview assessment of the stack test results for each metal HAP was conducted to identify apparent instances of erroneous individual results. Under the assumption that the test results for each metal follow a normal distribution, box charts were created for each set of results. Such charts, where the test data are plotted in quartiles, generally allow for identification of data outliers by inspection. Individual test results that fall above or below 1.5 times the top or bottom of the interquartile range (i.e., the range of values representing the middle 50% of the stack test results) are typically considered to be outliers and not representative of the rest of the data. For a normally distributed data set, a value 1.5 times greater than the value at the top of the interquartile range is approximately three standard deviations from the mean.

Figure 3, Figure 4, and Figure 5 present examples of the box charts for chromium, manganese, and mercury. Box charts for the data set for each metal are provided in Appendix A.

In each of these instances, potential outliers in the emissions data are all data points that are higher than the mean emission rates. This is also the case for the potential outliers in the other metals data sets. More rigorous statistical analysis would need to be conducted on each data set to establish definitively whether any of the potential outlying data points should be excluded from further consideration by EPA, but the implication of this observation is that the true mean of each metal's emission rate may be lower than the mean derived from all the observed results.

The magnitude of the variability between test run results for certain metals, particularly manganese, is striking. The maximum emission test result for manganese (4.03×10^{-4} lb/MMBtu) is more than two orders of magnitude higher than the median test result for this metal (2.60 x 10^{-6} lb/MMBtu). An example of the run-to-run variability for a single facility's stack test is shown in Figure 6. The cause of high variability between these data points is not easily identifiable. It is challenging to isolate and attribute causality accurately due to the complex interplay of numerous factors contributing to the stack test results.

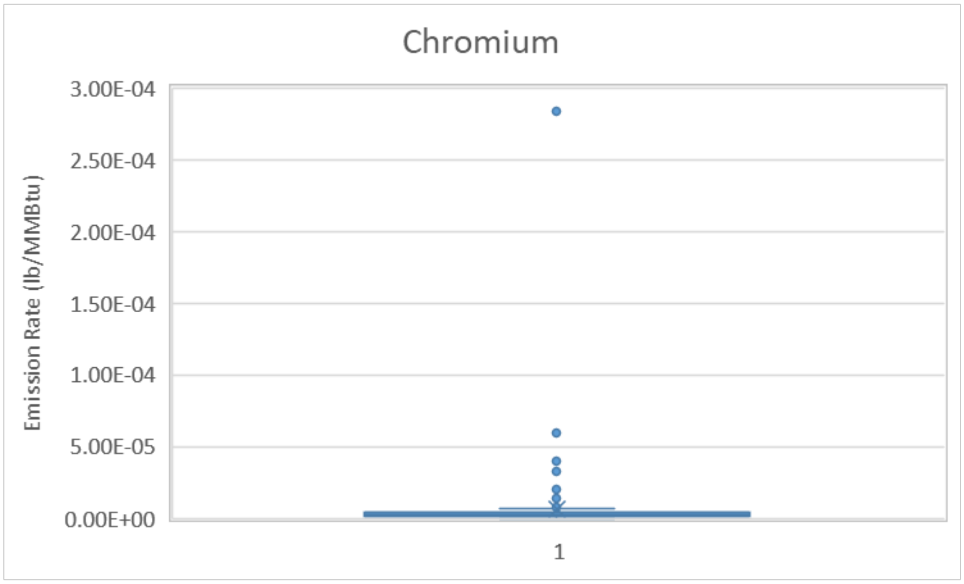


Figure 3. Box chart for chromium emissions data

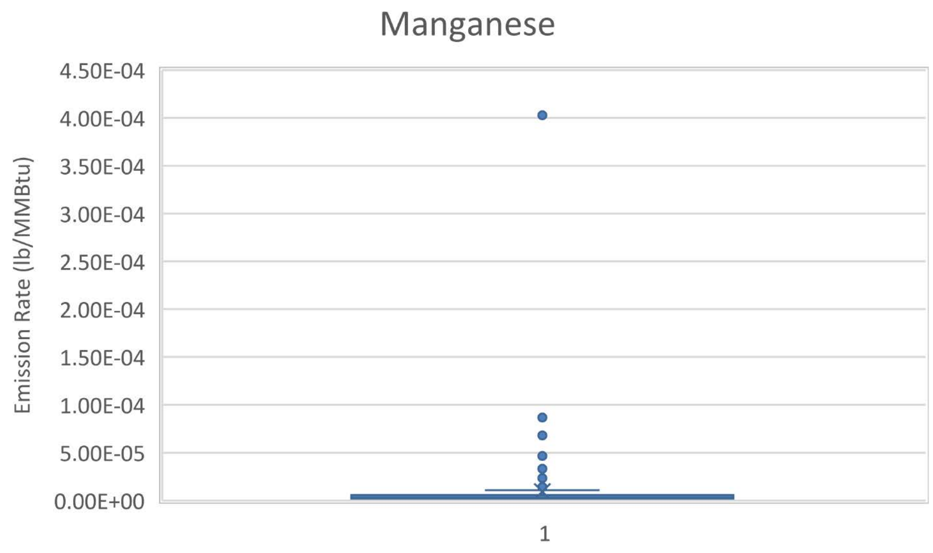


Figure 4. Box chart for manganese emissions data

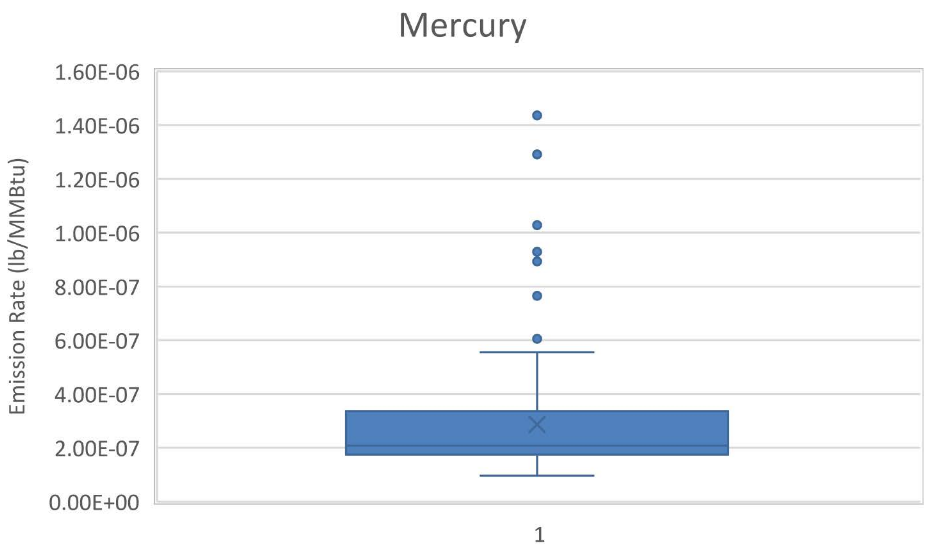


Figure 5. Box chart for mercury emissions data

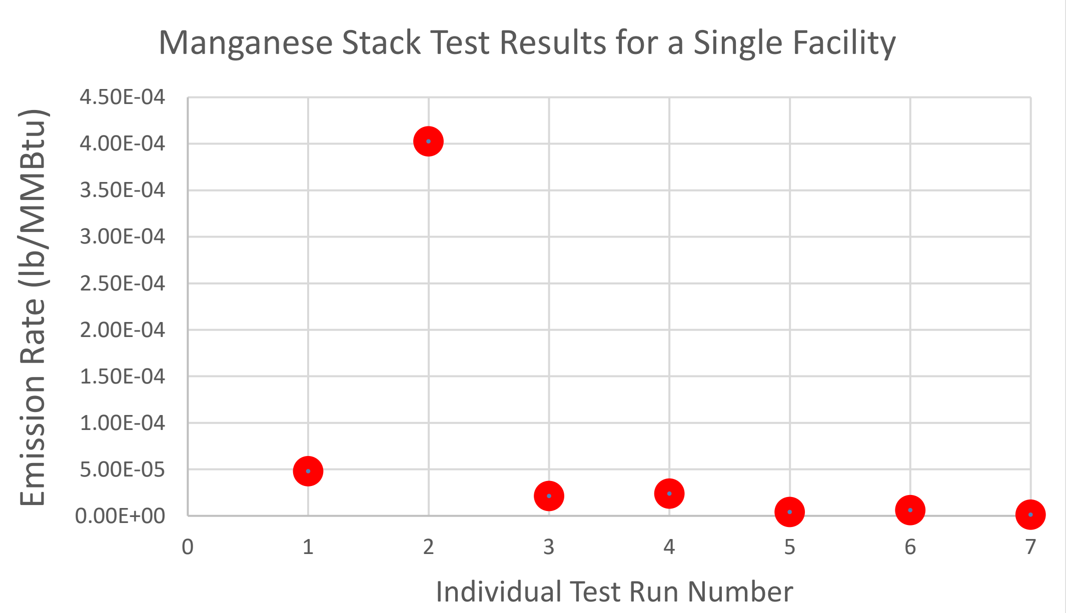


Figure 6. Example of manganese run-to-run variability

3 POTENTIAL SOURCES OF TRACE METALS

As discussed above, EPA did not include emissions of metallic HAPs for CTs firing natural gas when conducting risk analyses for the CT source category, as these constituents were not expected to be emitted from natural gas-fired turbines. In addition, EPA only included emissions of metallic HAPs from turbines firing landfill gas, jet fuel, and process gas if these pollutants were reported in the NEI. However, the stack test results for the natural gas-, oil-, and landfill gas-fired CTs tested in response to EPA's Section 114 information request showed emissions of metals from turbines firing all three types of fuels. An analysis was conducted to identify potential sources of metals that would result in these constituents being emitted out of the CT stacks. This analysis is detailed below.

Fuel

The most common sources of emissions from combustion stacks are the fuel and products of incomplete combustion. However, as metals, unlike organic HAPs, are not products of incomplete combustion, this source was ruled out. Fuel analysis testing, which was conducted for natural gas as part of a study used during the development of EPA's emission factor database, AP-42 (EPRI 1996), demonstrated that all metals were non-detect within the natural gas. However, it should be noted that in some instances the MDLs for the fuel analyses were lower than the detected level in the stack. As noted above, chromium, manganese, and nickel are generally ADL and have average emission rates that are consistent across the three fuel types. These considerations support a conclusion that emissions of these pollutants likely originate from a source outside of the fuel constituents.

Oil Leaks

A possible, but unlikely, source of emissions is combustion of used oil from oil leaks. Used engine oil may contain metal particles from bearing and shaft wear.

Heavy-duty gas turbine units operate with bearings located at some distance from the heat sources and bearing temperatures in the range of 160°F to 250°F (71°C to 121°C). Heavy-duty gas turbine lube oil sump capacities can range in size from 1000 to 20,000 gallons, and turbine oil makeup rates are approximately 5% per year (Hannon 2001). For a conservative analysis of 8000 operating hours per year, that would be 50 to 1000 gallons per year, or 0.006 to 0.125 gallons per hour.

Aeroderivative gas turbines operate with bearings located relatively close to sources of heat. The lube oil in aeroderivative turbines is in direct contact with metal surfaces ranging from 400°F to 600°F (204°C to 316°C). Aeroderivative turbines operate with much smaller lube oil sumps, typically 50 gallons or less. Average lube oil makeup rates are 0.15 gallons per hour (Hannon 2001).

No "used oil" sample testing for metals and no measured oil consumption rates were published as part of EPA's information request. A mass balance analysis was conducted, assuming the average lube oil makeup rate of 0.15 gallons per hour for the oil leak rates. Assuming that all metals emitted out of the stack of the CT come from combustion of the leaking oil, lube oil concentrations of metals in parts per million by weight (ppmw) were established using the average emission rates of chromium, manganese, and nickel during testing for each of the metals. As demonstrated in Table 9 below, the concentrations of these metals would need to be greater than 1000 ppmw in the lube oil in order for that to be the primary source of the trace metal emissions. Based on our best professional judgment, potential oil leaks do not appear to be a likely source for the trace metal emissions from the existing data set of gas turbine engines.

Table 9. Calculated concentration in lube oil to account for trace metals measured in stack flue gas (ppmw)

Constituent	Chromium	Manganese	Nickel
Concentration (ppmw)	1164	3024	1194

Ambient Air

As previously discussed, turbines operate by pulling in large amounts of intake air, compressing it, then combining it with fuel to drive combustion. This intake air is pulled from the ambient environment and is expected to contain trace amounts of pollutants, including metallic HAPs. It is anticipated that a majority of these metals would be filtered out prior to entering the CT, as most turbines are equipped with inlet air conditioning systems that include mechanical filters. However, a mass balance analysis was conducted to determine if the metals emitted out of the stack could feasibly be originating from the intake air.

Intake air flow rate information was provided by the operator for four of the CTs tested as part of EPA's Section 114 information request (Plant McIntosh Units 1 and 2 and Plant McDonough Units 4A and 4B). Assuming that all metals emitted out of the stack of the CT come from the intake air, intake air concentrations in micrograms per cubic meter ($\mu g/m^3$) were established using the average emission rate during testing for each of the metals.

These calculated intake air concentrations were then compared to ambient air concentrations measured at locations in proximity to power plants in the southeastern United States (EPRI 2020b). These concentrations are expected to be reasonably representative of ambient air for the four CTs included in this mass balance analysis, which are at power plants in the southeastern United States. Ratios of the calculated intake air concentrations of metals to the average measured ambient air concentrations are shown in Table 10. As shown in the table, the ratios range from 57 to over 13,000, indicating that intake air cannot be the primary source of the emissions of metals out of the CT stacks.

Table 10. Ratio of calculated inlet air concentrations (to account for trace metals measured in stack flue gas) to measured ambient air concentrations

Facility Name	Unit ID	Fuel	Antimony	Arsenic	Beryllium	Cadmium	Cobalt	Lead	Manganese	Nickel	Selenium
Plant McIntosh	CT Unit 1	Natural gas	1540	1186	835	2414	1792	582	2200	151	2244
Plant McIntosh	CT Unit 1	No. 2 fuel oil	1231	1328	933	2040	1995	478	508	102	1413
Plant McIntosh	CT Unit 2	Natural gas	1549	1297	913	2256	1950	467	803	426	1368
Plant McIntosh	CT Unit 2	No. 2 fuel oil	1628	1340	943	1897	2375	482	337	190	1304
Plant McDonough	CT Unit 4A	Natural gas	696	1633	1007	13472	2447	752	387	57	1536
Plant McDonough	CT Unit 4B	Natural gas	864	1411	989	9919	2113	504	330	80	1384

Turbine Component Corrosion and Erosion

Given that other potential sources have been eliminated as unlikely, the remaining and most likely sources of chromium, manganese, and nickel are materials of construction of the components that are in contact with CT exhaust, such as the turbine blades, combustors, rotors, casings, ductwork, and exhaust manifold. These components are frequently made of metal alloys containing chromium, manganese, nickel, and other metals. The exact composition likely changes across different manufacturers and plant designs. All indications are that the emission rates represented by these data were obtained under normal operation.

Compressor Section

The primary metal used for compressor blades in aeroderivative gas turbines is titanium, in the form of a range of titanium alloys. The metal is preferred for its low weight and relatively high temperature resistance. The best titanium alloys are resistant to up to around 540°C. However, this is too low for the last stages of the compressors of modern, advanced-design aeroderivative engines, and these must be made from higher-temperature nickel alloys, which weigh almost twice as much as the equivalent titanium alloys.

For stationary applications, weight is not usually a consideration, and the compressor blades and nozzles for heavy-duty and certain aeroderivative gas turbines can be made from steels. These steels usually contain chromium and carbon, and some more recent ones contain nickel, manganese, and molybdenum as well, as detailed in Table 11 below.[4,5,6,7] These steels have high tensile strength and high cycle fatigue strength. They are resistant to acidic salts too, but compressor blades are often provided with a special coating[8] to improve their corrosion and erosion resistance (EPRI 2000; Wing and McGill 1981). However, over time these coatings can become stripped away, thereby allowing corrosion and erosion of the blades, which could lead to emissions of the metal alloys from the CT.

---

[4] Specifications for XM-25/GTD-450: https://www.goldenwinsteel.com/product-XM-25-%5bRound-Bar-5%E2%89%A6%C3%B8%E2%89%A6600%5d-p600-XM-25.html.

[5] Specifications for 403 Cb: https://tool-die-steels.com/Grades/Stainless-Steels/31/7820/ASTM_403Cb(ESR).pdf.

[6] Specifications for 403 SS: https://www.rextonsteel.com/ss-403-round-bar-supplier-stockist.html.

[7] Specifications for carbon steel: NiDI 2020.

[8] A zirconium nitride coating is most appropriate for protecting gas turbine compressor blades made of titanium alloys. A chromium carbide coating is best for protecting compressor steel blades (Alqallaf et al., 2020).

Table 11. Compressor blade material compositions by steel type

Steel Type	Manganese	Chromium	Nickel
GTD-450	0.35	17	4.5
403 Cb	0.45	12	0.5
403 SS	1.0	12	0.5
Carbon Steel	0.6	None	None

Turbine Section

The hot gas path or turbine section of gas turbines are composed of blades and vanes made of superalloys, which are heat-resistant alloys of nickel, iron-nickel, and cobalt that can be used at high temperatures, often in excess of 0.7 of the absolute melting temperature. They frequently operate at temperatures exceeding 1050°C, occasionally working at temperatures up to 1200°C. The properties of these superalloys can be tailored to a certain extent through the addition of various other elements, common or exotic, including not only metals, but also metalloids and nonmetals. Chromium, nickel, iron, cobalt, molybdenum, tungsten, tantalum, aluminum, titanium, zirconium, niobium, rhenium, yttrium, vanadium, carbon, boron, and hafnium are some examples of the alloying additions used. Each addition serves a particular purpose in optimizing properties. See Table 12 below. As with compressor blades, corrosion of these components could lead to emissions of metals.

Table 12. Superalloy compositions

Element	Composition Range
Ni, Fe, Co	50–70%
Cr	5–20%
Al	0.5–6%
Ti	1–4%
C	0.05–0.2%
B, Zr	0–0.1%
Nb	0–5%
Re, W, Hf, Mo, Ta	1–10%

Source: https://en.wikipedia.org/wiki/Superalloy

Exhaust Section

The exhaust system is responsible for expelling the exhaust gas from the gas turbine to the environment. The exhaust system may include a diffuser, which is used to slow down the gas stream and increase its pressure, and a stack, which is used to discharge the gas stream to the atmosphere. ASTM A240 347 steels typically contain 0–2% manganese, 17–19% chromium, and 9–13% nickel. As with the other CT components, corrosion of the exhaust manifold could lead to emissions of metals.

4 CORRELATION AMONG TESTED METALS

Correlation coefficients were calculated for the trace metals to gauge possible emissions rate relationships among these pollutants. A correlation coefficient of +1 indicates a "perfect positive correlation," which means that as the magnitude of one variable (pollutant in this context) increases, the magnitude of the other variable increases at the same rate. A correlation value of -1 is a "perfect negative correlation," which means that as one variable increases, the second variable *decreases* at the same rate. A correlation analysis may return results anywhere between -1 and +1, indicating that variables do not change at identical rates. A correlation coefficient of 0 means that variables have no impact on one another; increases or decreases in one show no consistent correlation to increases or decreases in the other.

This analysis focuses on the correlation coefficients for all of the individual test runs as a whole; however, Appendix A provides additional details on the correlation coefficients broken out by fuel type. Table 13 summarizes the correlation coefficients for the metal HAPs. In general, the metals noted above as being primarily DLL or BDL also showed fair to strong correlation to one another, presumably because they were reported at the detection level, which would be consistent across all metals for each test run. Chromium and nickel showed poor correlation to all other metals, except one another. Manganese showed generally poor correlation to all metals. This may be due to its high run-to-run variability (discussed in Section 2), which has the potential to mask manganese's correlation to other constituents commonly found in metal alloys, such as chromium and nickel.

Table 13. Correlation coefficients for metals

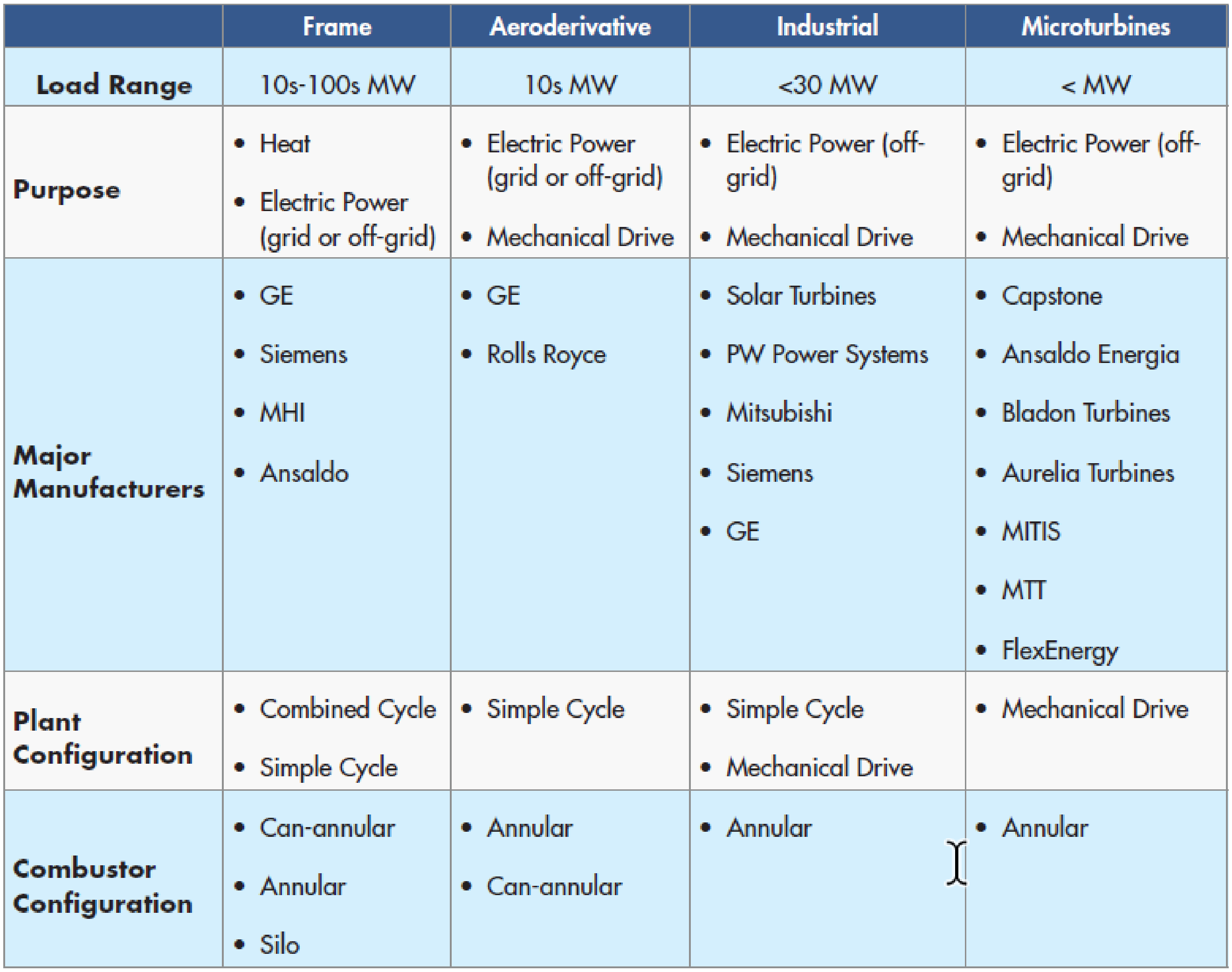
Correlation of → To ↓	**Antimony**	**Arsenic**	**Beryllium**	**Cadmium**	**Chromium**	**Cobalt**	**Lead**	**Manganese**	**Nickel**	**Selenium**	**Mercury**
Antimony		0.29	0.76	0.33	0.30	0.70	0.44	0.30	0.21	0.50	0.78
Arsenic	0.29		0.02	0.05	0.02	0.12	0.93	-0.03	-0.01	0.02	0.34
Beryllium	0.76	0.02		0.49	0.12	0.63	0.19	0.40	0.16	0.59	0.63
Cadmium	0.33	0.05	0.49		0.00	0.43	0.16	0.10	0.02	0.40	0.44
Chromium	0.30	0.02	0.12	0.00		0.22	0.07	0.15	0.86	0.08	0.13
Cobalt	0.70	0.12	0.63	0.43	0.22		0.35	0.05	0.13	0.38	0.89
Lead	0.44	0.93	0.19	0.16	0.07	0.35		0.01	0.03	0.13	0.52
Manganese	0.30	-0.03	0.40	0.10	0.15	0.05	0.01		0.19	0.24	0.07
Nickel	0.21	-0.01	0.16	0.02	0.86	0.13	0.03	0.19		0.07	0.02
Selenium	0.50	0.02	0.59	0.40	0.08	0.38	0.13	0.24	0.07		0.39
Mercury	0.78	0.34	0.63	0.44	0.13	0.89	0.52	0.07	0.02	0.39	

Note: Correlation coefficients are shaded using a color scale from red to green to indicate values at or near 0 (red), which have limited to no correlation, to values at or near 1 (green), which have a strong correlation.

5 COMPARISON OF U.S. COMBUSTION TURBINE FLEET WITH COMBUSTION TURBINES TESTED IN EPA'S INFORMATION REQUEST

This section characterizes the CTs used in U.S. power generation applications and compares them to the CTs tested in EPA's information request. The major categories and distinguishing features of land-based CTs are shown in Table 14.

Table 14. Summary of land-based CT types and distinguishing features



	Frame	Aeroderivative	Industrial	Microturbines
Load Range	10s-100s MW	10s MW	<30 MW	< MW
Purpose	• Heat • Electric Power (grid or off-grid)	• Electric Power (grid or off-grid) • Mechanical Drive	• Electric Power (off-grid) • Mechanical Drive	• Electric Power (off-grid) • Mechanical Drive
Major Manufacturers	• GE • Siemens • MHI • Ansaldo	• GE • Rolls Royce	• Solar Turbines • PW Power Systems • Mitsubishi • Siemens • GE	• Capstone • Ansaldo Energia • Bladon Turbines • Aurelia Turbines • MITIS • MTT • FlexEnergy
Plant Configuration	• Combined Cycle • Simple Cycle	• Simple Cycle	• Simple Cycle • Mechanical Drive	• Mechanical Drive
Combustor Configuration	• Can-annular • Annular • Silo	• Annular • Can-annular	• Annular	• Annular

Source: Low-Carbon Fuel Pathways for Gas Turbine Applications. EPRI. Palo Alto, California: 2022. 3002020539. [McCoy Power Reports, Gas Turbines 12M'19 Report, February 2020. http://mccoypower.net Includes ordered, installed, operating between 1980 and 2019.]

Table 15 presents the total number of CTs in four size ranges and the total power capacity in each range. With respect to the number of CTs within each capacity range, the ≥300-MW range represents 7% of the population, the 100- to 300-MW range represents 22%, the 20- to 100-MW range represents 38%, and the <20 MW range represents 32%.

More importantly, with respect to MW capacity, the ≥300-MW size range dominates this population, with 71% of MW capacity; the 100- to 300-MW range is the next largest, with 19%. The 20- to 100-MW range represents less than 9% of MW capacity, and the <20 MW range represents only 1%.

Table 15. Comparison of current CT fleet with CTs tested in EPA's information request

Capacity Range, MW	Total Number of CTs	Percentage of Total CTs	Total Capacity, MW	Number of CTs Tested	Percentage of CTs Tested	CTs Tested/Total Number of CTs
<20	303	32%	2,359	12	60%	4%
20 ≤ MW < 100	353	38%	17,179	6	30%	2%
100 ≤ MW < 300	210	22%	37,613	2	10%	1%
≥300	68	7%	141,442	0	0%	0%
Total	934	100%	198,594	20	100%	2%

More than half (12 of 20) of the CTs tested for trace metals as part of EPA's Section 114 information request are less than 20 MW. These CT applications primarily included municipal waste and compressor station plants burning landfill gas and pipeline natural gas, respectively. However, gas turbines for power generation dominate MW capacity relative to these applications.

Another key observation is the limited number of measurements for CTs greater than 100 MW, with only two units at one facility, and the absence of measurements for CTs greater than 300 MW. The lack of representation of larger power generation CTs in the test population—in addition to the low sample numbers in the other categories—limits the overall analyses and conclusions that can be developed.

6 PRELIMINARY SUMMARY AND CONCLUSIONS

For HAP metals, no distinguishable trends were observed in the test results between CTs with and without various emission controls (SCR, oxidation catalyst, lean pre-mix, or steam/water injection). In addition, no trends were observed between either turbine size or turbine age and the emission rates of metals.

An overview assessment of the stack test results for each metal HAP was conducted to identify outliers in the data. The results of this preliminary analysis suggest that potential outliers are all data points that are higher than the mean emission rates in each metal's data set. More rigorous statistical analysis would need to be conducted on the data to establish definitively whether any of the potential outlying data points should be excluded from further consideration by EPA.

Many of the metals showed fairly consistent findings with respect to percentage of non-detect versus detect runs and the average emission rates for detected samples, regardless of the fuel. However, cobalt, lead, and mercury were detected at higher rates in landfill gas-fired turbines than in natural gas- or oil-fired turbines. Chromium, manganese, and nickel were overall above their detection levels substantially more often than other HAP metals.

An analysis of potential sources leading to emission of metals from the CT stacks leads to the conclusion that fuel constituents, ambient air, and oil leaks are unlikely to be the source. The presence of metals in the CT exhaust stream is posited to be from turbine blade erosion and corrosion of other turbine components, such as the rotors, combustors, casings, and exhaust manifolds, which are exposed to high-temperature, high-humidity environments. The precise mechanisms leading to these emissions are not known, and we cannot identify any actions a turbine manufacturer or operator could take to reduce these emission rates.

7 REFERENCES

Alqallaf, Jasem, Ali, Naser, Teixeira, Joao A., and Addali, Abdulmajid. 2020. *Solid Particle Erosion Behaviour and Protective Coatings for Gas Turbine Compressor Blades—A Review*. https://www.mdpi.com/2227-9717/8/8/984.

EPA 2019. *Residual Risk Assessment for the Stationary Combustion Turbines Source Category in Support of the 2019 Risk and Technology Review Proposed Rule*. EPA's Office of Air Quality Planning and Standards, EPA-HQ-OAR-2017-0688, March 2019.

EPA 2022. *Proposed Maximum Achievable Control Technology (MACT) Floor Analysis for the Lime Manufacturing Plants Industry*. EPA's Office of Air Quality Planning and Standards, EPA-HQ-OAR-2017-0015-0135, October 2022.

EPA 2023. *Section 114 Information Request Documents*. https://www.epa.gov/stationary-sources-air-pollution/stationary-combustion-turbines-national-emission-standards.

EPRI 1996. *Gas-Fired Boiler and Turbine Air Toxics Summary Report*. EPRI, Palo Alto, CA: 1996. TR-105646.

EPRI 2000. *Combustion Turbine Hot Section Life Management: High Temperature Coating Systems*. EPRI, Palo Alto, CA: 2000. 1000432.

EPRI 2019a. *Inhalation Human Health Risk Assessment for U.S. Stationary Combustion Turbines: 2014 Base Year Evaluation*. EPRI, Palo Alto, CA: 2019. 3002016528.

EPRI 2019b. *Multi-Pathway Human Health Risk Assessment for U.S. Stationary Combustion Turbines: 2014 Base Year Evaluation*. EPRI, Palo Alto, CA: 2019. 3002016745.

EPRI 2019c. *Environmental Risk Screening Assessment for U.S. Stationary Combustion Turbines: 2014 Base Year Evaluation*. EPRI, Palo Alto, CA: 2019. 3002017441.

EPRI 2020a. *Supplemental Human Health and Environmental Risk Assessment for U.S. Combustion Turbines: 2014 Base Year Evaluation*. EPRI, Palo Alto, CA: 2020. 3002020134.

EPRI 2020b. *Corrosive Constituents in Ambient Air: An Air Quality Study at a Combined-Cycle Plant in the Southeastern United States*. EPRI, Palo Alto, CA: 2020. 3002018565.

EPRI 2023a. *Supplemental Human Health and Environmental Risk Assessment for U.S. Combustion Turbines (2023 Supplement): 2014 Base Year Evaluation*. EPRI, Palo Alto, CA: 2023. 3002026130.

EPRI 2023b*. Supplemental Human Health and Environmental Risk Assessment for U.S. Combustion Turbines (2023 Supplement Addendum): 2014 Base Year Evaluation*. EPRI, Palo Alto, CA: 2023. 3002026783.

Hannon, James B. 2001. *How to Select and Service Turbine Oils*. *Machine Lubrication*, July 2001. https://www.machinerylubrication.com/Read/210/turbine-oils.

Nickel Development Institute (NiDI). 2020. *Design Guidelines for the Selection and Use of Stainless Steel*. https://www.nickelinstitute.org/media/1667/designguidelinesfortheselectionanduseofstainlesssteels_9014_.pdf.

Wing, R. G., and McGill, I. R. 1981. *The Protection of Gas Turbine Blades: A Platinum Aluminide Diffusion Coating*. https://technology.matthey.com/article/25/3/94-105/.

A TEST DATA SUMMARY

See attachment: Appendix A – Test Data Summary (Metals).xlsx

About EPRI

Founded in 1972, EPRI is the world's preeminent independent, non-profit energy research and development organization, with offices around the world. EPRI's trusted experts collaborate with more than 450 companies in 45 countries, driving innovation to ensure the public has clean, safe, reliable, affordable, and equitable access to electricity across the globe. Together, we are shaping the future of energy.

Program:

Air Quality Assessments and Multimedia Characterization, P235

3002029941

EPRI
3420 Hillview Avenue, Palo Alto, California 94304-1338 USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com