Capstone Low Emissions MicroTurbine Technology

White Paper

March 6, 2000

Capstone Turbine Corporation
21211 Nordhoff Street, Chatsworth, California 91311
Phone (818) 734-5300 Facsimile (818) 734-5320
www.microturbine.com

Capstone Low Emissions MicroTurbine Technology

Table of Contents

Preface

The purpose of this White Paper is to provide factual information to Capstone Customers and other Stakeholders about the combustion process employed by the Capstone MicroTurbine® and the emissions levels achieved by the technology.

Summary of the Capstone MicroTurbine® System's Emissions Levels[1]

Component	Emissions – Raw (ppmV @ 18.3% O2)	Emissions (Max) (ppmV @ 15% O2)	[gm/kw-hr]	[gm/GJ]	Emissions [gm/hp-hr]	[lb/kw-hr]	[lb/hp-hr]
NOx	3.96	9	0.223	61.94	0.166	4.91E-04	3.66E-04
CO	17.62	40	0.603	167.56	0.450	13.3E-04	9.90E-04
HC	3.96	9	0.078	21.54	0.058	1.71E-04	1.27E-04
NOx+HC			0.301	83.48	0.224	6.61E-04	4.93E-04
CO2			724.0	2.01E+05	540.0	1.59E+00	1.19E+00
O2			7060.0	1.96E+06	5260.0	1.55E+01	1.16E+01

1. Operating on Natural Gas at full power. Capstone Turbine Corp warrants emissions of NOx to be less than 9ppm. Other emissions targets are not warranted.

Capstone Turbine Corporation
21211 Nordhoff Street, Chatsworth, California 91311
Phone (818) 734-5300 Facsimile (818) 734-5320
www.microturbine.com

Capstone Low Emissions MicroTurbine Technology

1. Introduction

The Capstone MicroTurbine® is designed to produce very low emissions of Oxides of Nitrogen (NOx), Carbon Monoxide (CO) and total hydrocarbons (THC). When fueled with natural gas, the MicroTurbine has a warranted NOx emissions level of less than 9 parts per million (ppm). CO emissions are less than 40ppm and THC emissions are below 9ppm . These emissions levels are among the lowest of any fossil fuel combustion technology.

Further, the Capstone MicroTurbine uses 3 injectors and a sophisticated control system, which enable low emissions to be achieved over a wide range of the power output band.

2. Critical Emissions

The US Environmental Protection Agency lists 6 criteria air pollutants for which ambient air limits have been set. These air pollutants comprise nitrogen dioxide (NO_2), carbon monoxide (CO), sulfur dioxide (SO_2), lead (Pb), ozone (O_3) and particulates. Of these criteria pollutants, NO_2 and CO are the most relevant to a gas turbine. Capstone has focussed on minimizing these 2 criteria pollutants as well as Total Hydrocarbons.

The most significant NOx produced in high temperature combustion is Nitric Oxide (NO) which subsequently oxidizes in the atmosphere to produce Nitrogen Dioxide. Nitrogen

Dioxide can have a significant detrimental effect on human wellbeing. NOx are also a precursor to O_3 formation, which causes smog and respiratory problems.

CO is a criteria pollutant because of its potential detrimental impact on human wellbeing. It is a poisonous gas formed when carbon based fuel is not fully burned.

THC are also the product of incomplete combustion. Emission levels of THCs decrease as combustion temperatures increase. Volatile Organic Compounds (VOC) are a subset of THC. Some reactive VOCs contribute to smog.

3. Capstone's Low Emissions Combustion Process

At its full power operating range the Capstone MicroTurbine, fueled with natural gas, produces NOx and THC emissions levels of less than 9ppm. CO emissions are less than 40ppm at full power operating points. There is a variation in emissions between individual units, but Capstone always warrants the NOx emissions to be less than 9ppm.

Fast and precise control of the combustion process is necessary to achieve Capstone's low overall emissions. NOx formation is minimized at lower combustion temperature, but lower combustion temperature result in higher emissions of CO and THC. To resolve this conflict and achieve low NOx emissions simultaneously with low CO and THC emissions, combustion of the fuel must occur at the lowest possible temperature whilst the air and fuel mix must remain in the combustion chamber long enough to combust most of the fuel

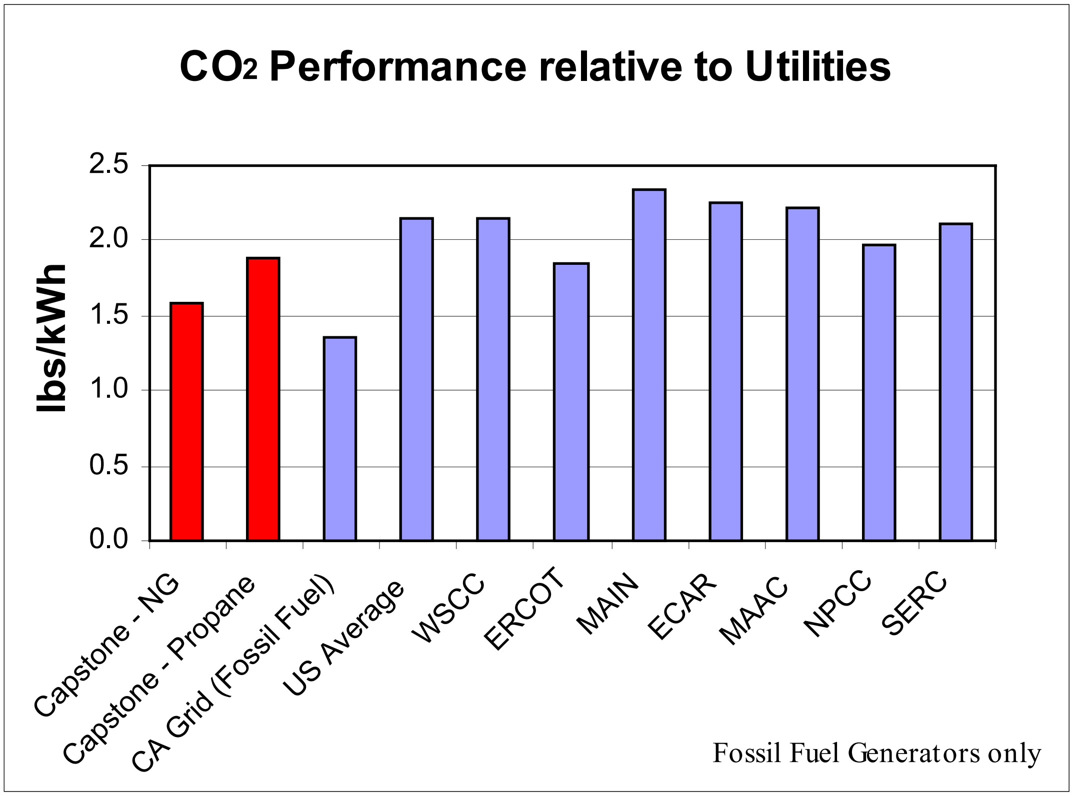
The Capstone MicroTurbine uses a lean-premix combustion system to achieve low emissions levels at the full power range. Lean-premix operation requires operating at a high air to fuel ratio (AFR) within the primary combustion zone. The large amount of air is thoroughly mixed with the fuel before combustion. This premixing of the air and fuel enables clean combustion to occur at a relatively low temperature. Injectors control the air to fuel ratio and the air-fuel mixture in the primary zone to ensure that the optimal flame temperature is achieved for NOx minimization.

The higher air to fuel ratio results in a lower flame temperature, which leads to lower NOx levels. In order to achieve low levels of CO and THC simultaneously with low NOx levels, the air and fuel mixture is retained in the combustion chamber for a relatively long time period. This process allows for more complete combustion of the CO and THC's. The Capstone MicroTurbine has a large primary zone volume within its combustor chamber, which allows the air and fuel to remain in the combustion zone for a relatively long time period. As a result, more complete combustion is achieved at low temperatures, thereby ensuring that very low CO and THC emissions are achieved simultaneously with very low NOx emissions.

The NOx, CO and THC levels are at their lowest when the Capstone MicroTurbine is operating over an output range between 90 per cent and 100 per cent.

4. Green House Gases

CO_2 levels per kWh of electricity produced are directly related to the efficiency of the system. Higher engine efficiencies will result in lower CO_2 levels. The following graph shows that, fueled with Natural Gas, the Capstone MicroTurbine has lower CO_2 emissions than the US national average and has emissions of CO_2 less than all the major US grids.



5. Oxygen Rich Exhaust

The oxygen concentration in the engine exhaust is high (~18.3%), allowing the exhaust to be potentially used in direct heating or as an air pre-heater for downstream burners. This oxygen rich exhaust together with low emissions and air bearings (which allow the turbine to operate without oil lubrication) make the direct exhaust suitable even for certain applications in food processing and green houses.

6 How the Capstone MicroTurbine's Emissions Compares to Others

6.1 Compared to other turbines

Gas turbine emissions data are commonly corrected to 15% oxygen in the exhaust gases, since they operate in an "excess air" mode. Other combustion sources such as IC engines, boilers, furnaces, etc., may be corrected to 3% or 7% oxygen, or reported uncorrected. For an accurate comparison of emissions between different types of equipment, the emissions should be corrected to the same level of oxygen in the exhaust gases. In addition, the load state during the test (part load or full load operation) should be noted.

Table 1 compares data from several turbine and IC engines to the Capstone Model 330 operated at full power[1].

Table 1. Comparison of emissions (ppm @ 15% O_2) from Capstone MicroTurbine Model 330 to other stationary combustion sources. Fuel: natural gas.

Manufacturer/Model	Rating	NOx	CO	THC
MicroTurbines				
Capstone (1)	30 kW	9	40	9
Other MicroTurbines (2)	45 - 75 kW	9 - 25	25-240	25
Industrial Turbines(3)	0.8 - 11 MW	6 –140	1 - 462	6 - 559

(1) Derived from internal Capstone testing, fuelled with Natural Gas
(2) As reported by manufacturers
(3) EPA test results as reported by EPA

[1] While the load state is shown in the table, the source data did not specify to which level of exhaust oxygen the data were corrected. Therefore these data should be used for rough comparisons only.

6.2 Compared to Internal Combustion Engines

In the absences of a post combustion device such as a catalytic converter, internal combustion engines can have very high emissions levels. The following table summarizes the emissions levels of a broad range of these engines. It indicates that the very best internal combustion engines have emissions of NOx that are significantly higher than the Capstone MicroTurbine. Both CO and THC are much higher for an internal combustion engine than for the Capstone MicroTurbine.

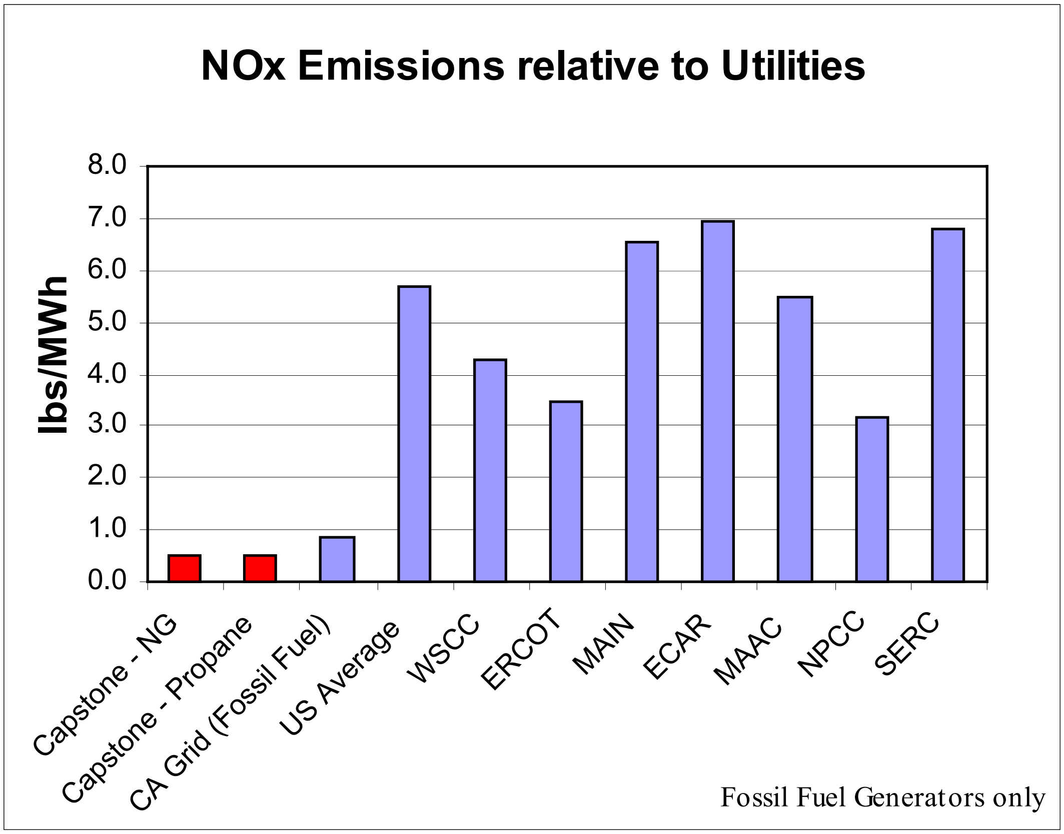
Table 2. Comparison of emissions (ppm @ 15% O_2) from Capstone Model 330 to other stationary Internal combustion sources. Fuel: natural gas.

IC Engine Size	**NOx**	**CO**	**THC (1)**
170kW – 1500kW (3)	30 - 3214	325 - 833	2747
35kW (3)	31-454	244-378	NR
Capstone MicroTurbine (2)	9	40	9

(1) THC data is available only for the 1500kW IC engine.
(2) Fueled with Natural gas
(3) Source: EPA, ICCR

6.3 Compared to the Grid

Capstone's NOx emissions are very favorable in comparison to grid supplied power. The following graph illustrates this benefit in respect of NOx for which there is reasonable information.

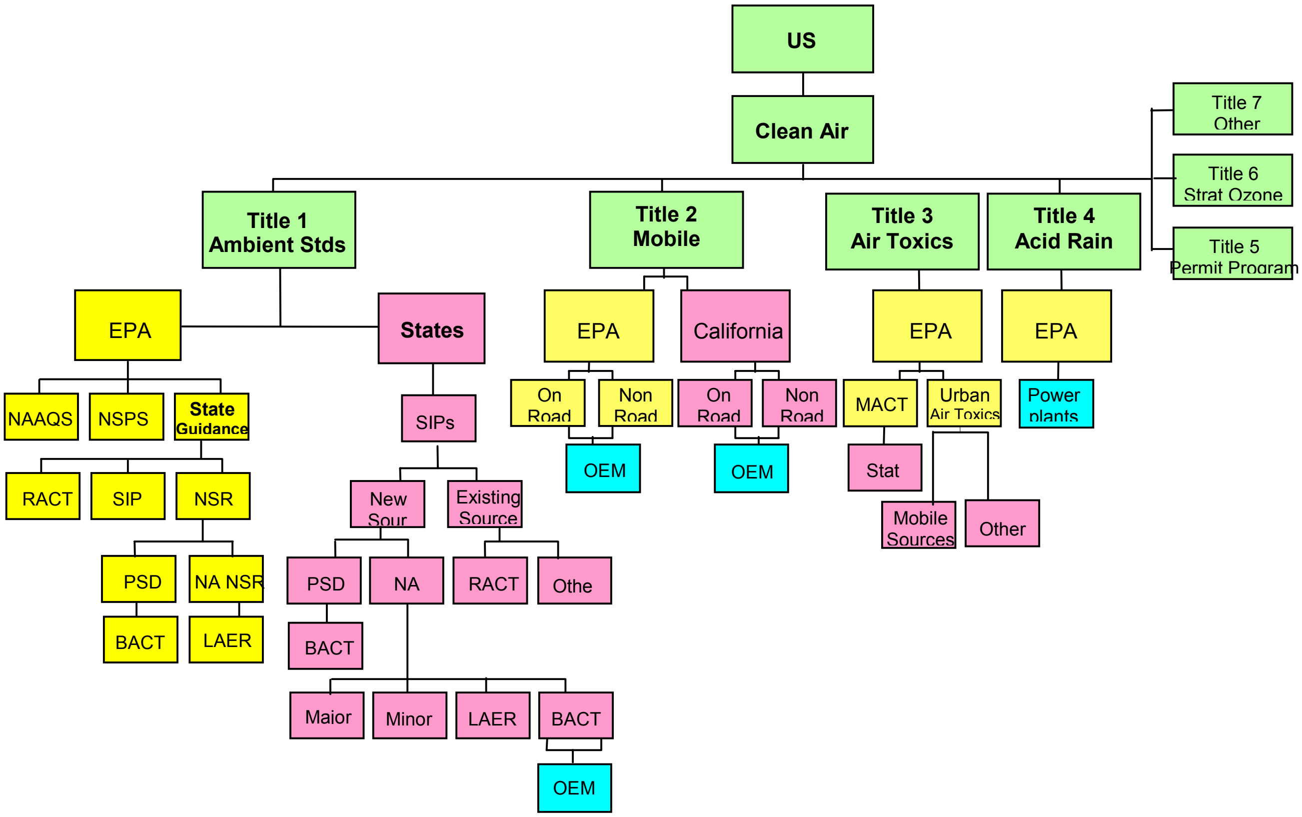


Note: The emissions levels for the grids are not adjusted for distribution and transmission losses, which average 5% - 7%.

7. Current Emissions Regulations

7.1 The U.S. Regulatory Frame.

The Clean Air Act is the Federal government's principal mechanism for controlling emissions. This legislation requires that the states regulate the level of emissions produced by various types of machinery and various applications. Additionally, the Clean Air Act requires that the states provide the Environmental Protection Agency (EPA) with a plan of their State Implementation Plan. The Clean Air Act also requires that the EPA regulate emissions from mobile sources. The roles and responsibilities of the state and federal agencies in emissions control are detailed in the following chart.

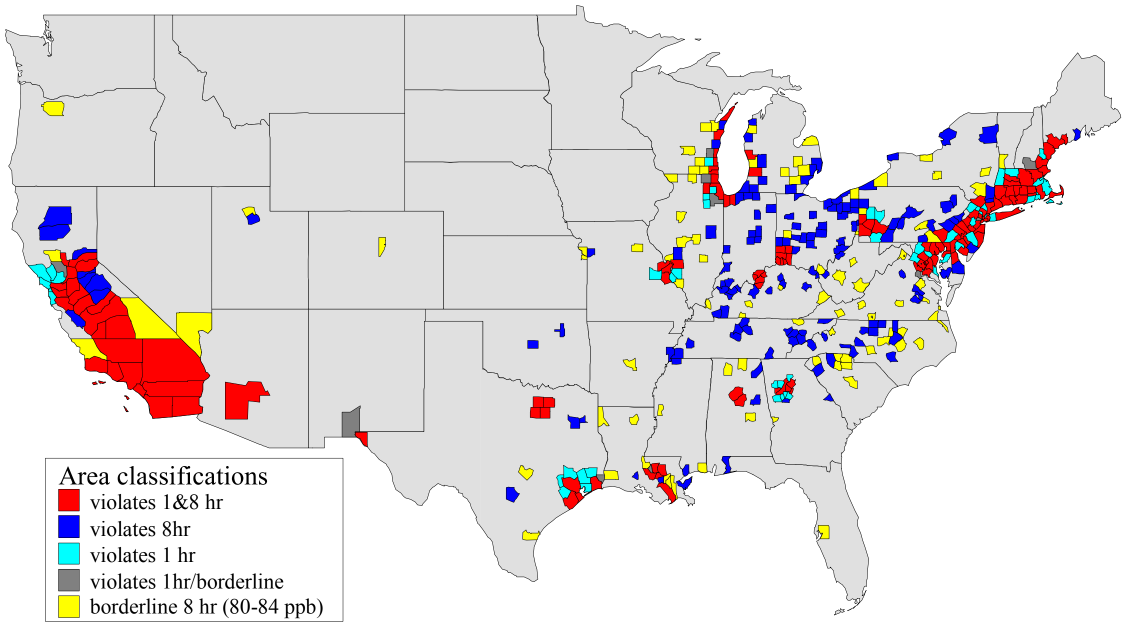


7.2 *Stationary Applications*

There are many (perhaps hundreds) of air quality regulations which impact stationary combustion sources in the US. Despite the number and complexity of these regulations, a conceptual summary is fairly straightforward.

The federal US Clean Air Act (1970) and Clean Air Act Amendments (1990) set concentration limits in ambient air for six air pollutants known to cause damage to human health and/or the environment. These tropospheric air pollutants, known as "criteria" pollutants, are: particulate matter less than 10 microns (PM_{10}), SO_2, CO, NO_2, O_3 and Pb.

Urban areas in the US are categorized according to their level of "attainment" with the National Ambient Air Quality Standards (NAAQS) for these six pollutants. Los Angeles, for example, still has the nation's worst air quality, and is currently in "extreme" non-attainment for O_3, and is also out of attainment with respect to CO and NO_2. Current and potential non-attainment areas in the United States are illustrated in the following map.



Source: U.S. EPA data through 1996

Pursuant to the Clean Air Act, each local Air District must submit to EPA their plan (State Implementation Plan or SIP) which demonstrates a strategy for controlling emissions, as well as the results of complex 3-dimensional modeling showing that control strategies will reduce ambient pollutants. One important part of these control strategies are often the requirement that newly permitted combustion sources demonstrate "BACT", the Best Available Control Technology, for a given regulated pollutant.

BACT typically applies to new sources, while fixed emissions limits ("command and control" approach) or emissions trading programs (such as "RECLAIM" in Southern California) affect existing sources. Unit size also determines which sources must comply with which regulations. Determining which regulations apply to a given source is complex, and is usually done in the permitting process on a case-by-case basis.

Table 3. Comparison of regulations affecting stationary combustion sources in Southern California Air Quality Management District (SCAQMD).

Source Type	**Size**	**Emissions**				
		NOx	**CO**	**THC**	**NMHC**	**Units**
Capstone MicroTurbine (Natural Gas fueled)	30 kW	9	40	9	NR	ppmv @ 15% O2
		0.166	0.450	0.058	NR	g/hp-hr
		61.94	167.56	21.54	NR	g/GJ
SCAQMD Best Available Control Techology (typically applies to new sources)						
Boiler	<16.7 MMBtu/hr	20	50	---	---	ppmv @ 3% O2
Compressor, centrifugal	NR	500	---	---	---	ppmv @ 3% O2
Gas turbine	>3 MW	2.5*	10	---	---	ppmv @ 15% O2
IC engine, spark ignition	portable	80	176	---	240	ppmv @ 15% O2
IC engine, emergency	<750 HP	6.9	8.5	---	1	g/hp-hr
IC engine, compression ignition	portable	7	8.5	---	1	g/hp-hr
IC engine, non-emergency	<2064 HP	0.15	0.6	---	0.15	g/hp-hr
SCAQMD Regulation XI, Source Specific Standards **(typically applies to existing sources)**						
Furnaces, gas fired fan type	<175,000 Btu/hr	40	---	---	---	g/GJ
Water heaters, gas fired	residential	40	---	---	---	g/GJ
Stationary IC engines	>50 HP	90	2000	---	---	ppmv @ 15% O2
Gas turbine engines	0.3-2.9 MW	25**	---	---	---	ppmv @ 15% O2
Gas turbine engines	2.9-10 MW	9**	---	---	---	ppmv @ 15% O2

* assuming an efficiency of 34%

** assuming an efficiency of 25%

NR - not reported

Note that there is an NAAQS limit for NO_2, not NO_x. NO_x is a shorthand expression for the sum of nitric oxide (NO) and nitrogen dioxide (NO_2). Many Air Districts control emissions of NO_x via permit limits, trading programs and BACT because NO_x reacts with volatile organic compounds (VOC) in the presence of sunlight to form O_3 (urban "smog"), which is an NAAQS pollutant. VOC is also known as NMHC (non-methane hydrocarbon), ROG (reactive organic gases), TGNMO (total gaseous non-methane organics), and others. Capstone's measurement of THC (total hydrocarbons) includes VOC and methane, and is therefore a more conservative measure of hydrocarbon emissions than is VOC.

Most emissions sources will require some form of after burn treatment of exhaust gases in order to achieve the low emissions required by the regulations. The Capstone MicroTurbine uses very clean combustion technology to achieve low emissions without the aid of such devices.

7.3 Mobile Applications

The EPA is authorized to regulate emissions from mobile sources in all states except California where the California Air Resources Board regulates emissions.

The EPA regulates mobile sources within 2 broad categories; heavy-duty vehicles (which includes the engines for Urban Buses) and passenger vehicles. One of the applications of the Capstone MicroTurbine is as a low emissions on board battery charger in electric buses (this application is generally referred to as a Hybrid Electric Vehicle or HEV). In this application, the EPA under the heavy-duty category could potentially regulate the emissions of the Capstone MicroTurbine. While regulations have been established for heavy-duty diesel engines in mobile applications, the EPA has not established regulations that apply to MicroTurbines at this time. Capstone has, however, undertaken its own assessment of the emissions of the Capstone MicroTurbine in HEV applications. The following table compares the emissions of the Capstone MicroTurbine with the heavy-duty diesel engine regulations.

Table 4. Mobile emissions performance and regulations (g/hp-hr)

Pollutant	**Capstone HEV Natural Gas**[1]	**EPA Urban Bus 1999**	**EPA Urban Bus 2004**	**California Urban Bus 2000/5**[(2)]
NOx	0.42	4.00	*2.00*[3]	2.00
CO	0.75	15.50	15.50	15.50
Non-methane hydrocarbons	0.04	1.30	0.50	1.20
NOx + Non-methane hydrocarbons	0.46	*5.30*[3]	2.50	*3.20*[3]
Particulates	-	0.05	0.05	0.03/0.01

(1) The emissions tests undertaken on the Capstone MicroTurbine model 330 in an HEV application used procedures and power requirements adopted from the EPA engine-dyno test for HD Otto-cycle natural gas engines

(2) California regulations for 2000 – 2005 reflect the September 1999 CARB Proposal for Urban Bus Engine Standards "Incentive Path".

(3) These are derived figures. The EPA 1999 and California regulations address NOx and NMHCs separately, while the EPA 2004 standard combines NOx and NMHCs.

The Capstone MicroTurbine offers significant improvements over the regulatory threshold for heavy duty vehicular applications.

8. Emissions Measurement and Testing

Emissions measurements are taken using Capstone's Horiba Model 1650 MicroBench. During emissions testing, a gaseous sample is continuously extracted from the exhaust duct and transported to the analyzer console through hoses, which are heated above the dewpoint of water. The sample is split between the THC analyzer, which receives the sample hot without water knockout, and the remaining analyzers, which receive gas, which has been dried and cooled in a refrigeration bath. This equipment is state-of-the-art for emissions testing from stationary sources, and is referred to as a continuous emissions monitoring system or CEMS. Capstone's test equipment and sampling procedures comply with applicable US Environmental Protection Agency and local air district regulations.[2]

There are currently no specific regulations regarding the emissions test procedure for small gas turbines. The test procedure that we have chosen is based on the procedure specified for emissions of new and in-use non-road compression ignited engines greater than 37 kW[3].

9. Emissions Corrections

Emissions levels are corrected using the following methods. The reported emissions levels are corrected for ambient concentrations of NOx, CO or THC's sometimes found in the test cell. The levels are also corrected to 15% O_2 (typical measurement for gas turbines) using the following formula.

Carbon Monoxide (CO):

$$CO_{corrected} = \left(CO_{exhaust} - CO_{ambient} - 0.088\ THC_{ambient}\right)\left(\frac{20.9 - 15}{20.9 - O_{2\,exhaust}}\right)$$

Total Hydrocarbons (THC): The reported value will be the maximum of:

$$THC_{corrected} = \left(THC_{exhaust} - THC_{ambient}\right)\left(\frac{20.9 - 15}{20.9 - O_{2\,exhaust}}\right)$$

or 0.0

[2] These are specified in Title 40 CFR 60, Appendix A (EPA Method 3A, EPA Method 7E, EPA Method 25A, Method 205) and SCAQMD Method 100.1.
[3] The number of engines sampled will correspond to the schedules specified in Title 40 CFR 89, Appendix A to Subpart F. This could entail a minimum of three engine tests or a maximum of 60 engine tests depending on the pass/failure rate and the total engine production rate. This regulation does not require a 100% success rate

Oxides of Nitrogen (NOx):

$$NO_{x\,corrected} = \left(NO_{x\ exhaust} - NO_{x\ ambient}\right)\left(\frac{20.9-15}{20.9-O_{2\ exhaust}}\right)\left(ambient\ correction\ factor\right)$$

The ambient correction factor is obtained from CFR 60 Part 40 Subpart GG Paragraph 335. It is also contained in ES-97-01-0091.

GLOSSARY OF TERMS

Abbreviation	Definition
AFR	Air-Fuel Ratio
BACT	Best Available Control Technology
Btu	British Thermal Unit
CA	California
CARB	California Air Resources Board
CEMS	Continuous Emissions Monitoring System
CO	Carbon Monoxide
CO2	Carbon Dioxide
ECAR	East Central Area Reliability Coordination Agreement
EPA	Environmental Protection Agency
ERCOT	Electricity Reliability Council of Texas
g	gram
HP, hp	Horse Power
hp-hr	Horse Power Hour
IC	Internal Combustion
HEV	Hybrid Electric Vehicle
kW	Kilowatt
kWh	Kilowatt hour
LAER	Lowest Achievable Emissions Rate
lb	Pounds
MAAC	Mid Atlantic Area Council
MACT	Maximum Achievable Control Technology
MAIN	Mid America Interconnected Network, Inc
MW	Megawatt
NAAQS	National Ambient Air Quality Standards

NMHC	Non Methane Hydrocarbons
NO	Nitric Oxide
NO_2	Nitrogen Dioxide
NOx	The sum of NO and NO_2
NPCC	Northeast Power Coordinating Council
NSPS	New Source Performance Standard
NSR	New Source Review
O_2	Oxygen
O_3	Ozone
OEM	Original Equipment Manufacturer
PM10	Particulate Matter less than 10 microns
ppm	Parts per million
PSD	Prevention of Significant Deterioration
RACT	Reasonably Available Control Technology
RECLAIM	Regional Clean Air Incentives Market
ROG	Reactive Organic Gases
SCAQMD	South Coast Air Quality Management District
SERC	Southeastern Electric Reliability Council
SIP	State Implementation Plan
SO_2	Sulfur Dioxide
TGNMO	Total Gaseous Non-methane Hydrocarbon
THC	Total Hydrocarbons
VOC	Volatile Organic Compounds
WSCC	Western System Coordinating Council