State of the Art (SOTA)

Manual for

Stationary Combustion Turbines

Original Date:	July 1997
1st Revision:	November 1999
2nd Revision:	December 21, 2004

State of New Jersey
Department of Environmental Protection
Division of Air Quality
Air Quality Permitting Element

State of the Art (SOTA)
Manual for Stationary Combustion Turbines
Section 3.14

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3.14.i ABBREVIATIONS

BACT	Best Available Control Technology
CFR	Code of Federal Regulations
CO	Carbon Monoxide
DLN	Dry low NOx combustor technology
DB	Duct Burner
USEPA	United States Environmental Protection Agency
HHV	Higher Heating Value
HRSG	Heat Recovery Steam Generator
LAER	Lowest Achievable Emission Rate
MM BTU	Million British Thermal Units
N.J.A.C.	New Jersey Administrative Code
NOx	Nitrogen Oxides
NSPS	New Source Performance Standards
PM-10	Particulate Matter equal or smaller than 10 microns in diameter
PPMVD	Parts Per Million by Volume on a Dry Basis
SCR	Selective Catalytic Reduction Technology
SI	Steam Injection system
SOTA	State-of-the-Art
SO_2	Sulfur Dioxide
TSP	Total Suspended Particulates
VOC	Volatile Organic Compounds
WI	Water Injection System
lbs/MW-hr	Pounds per Megawatts Hour
ISO	International Standards Organization

3.14 SOTA MANUAL FOR STATIONARY COMBUSTION TURBINES

3.14.1 Scope

State-of-the-Art (SOTA) performance levels outlined below apply to stationary combustion turbines with heat input capacity greater than 10 million BTUs per hour (HHV basis).

3.14.1.1. Description of Stationary Combustion Turbine Design and Different Operating Cycles

A combustion turbine is an internal combustion engine that operates with rotary motion. In stationary applications, the hot gases are directed through one or more fan-like turbine wheels to generate shaft horsepower. In larger facilities the heat from the exhaust gases may be recovered through add-on heat exchangers or other devices. Three primary sections of a turbine include the compressor, combustor, and turbine. The compressor draws in ambient air and compresses it to approximately 30 times ambient pressure. The compressed air is then directed to the combustor section, where fuel is introduced, ignited and burned. There are three types of combustors: annular, can-annular and silo. An annular combustor type is a single continuous chamber roughly the shape of the doughnut that rings the turbine in a plane perpendicular to the air flow. The can-annular type uses a similar configuration but is a series of can-shaped chambers rather than a single continuous chamber. The silo combustor type is one or more chambers mounted external to the gas turbine body. Following the combustors, hot gases are diluted with additional cool air from the compressor section and directed to the turbine section at temperatures up to 1285 ^{o}C. Energy is recovered in the turbine section in the form of shaft horsepower of which greater than 50% is required to drive the internal compressor section.

The two types of turbine design are industrial and aero-derivative. Industrial turbines were designed to supply mechanical energy to industrial equipment, i.e., generators and compressors. The aero-derivative turbines are jet engines based on the designs used in the aerospace industry, which have been converted to drive a shaft.

The four basic operating cycles for gas turbines are simple cycle, regenerative cycle, cogeneration cycle, and combined cycle.

Simple Cycle

A simple cycle turbine functions with only the three primary sections; compressor, combustor, and turbine, which typically drives an electric generator. Simple cycle efficiency is typically in the 35-39 percent range. This cycle offers the lowest installed capital cost but also provides the least efficient use of fuel, therefore the highest operating cost. Simple cycle turbines are quick in generating electricity.

Regenerative Cycle

This is essentially a simple cycle turbine with an added heat exchanger, called a recuperator, which preheats the combustion air. In this cycle, thermal energy from the exhaust gases is transferred to the compressor discharge air prior to being introduced into the combustor. Regenerative cycle thermal efficiency ranges from 44 to 47%.

Cogeneration Cycle

This is essentially a simple cycle turbine with an added exhaust heat exchanger, called a heat recovery steam generator. The steam is generated by the exhaust that can be delivered at a variety of pressure and temperature conditions to meet site specific thermal process requirements. Adding a heat recovery steam generator increases the capital cost, but also increases the overall thermal efficiency typically in the 70 – 74 percent range. Heat recovery steam generators can be with or without duct burners. Duct burners are used to combust fuel to generate more steam from heat recovery steam generators.

Combined Cycle

A combined cycle gas turbine is used to generate electric power in two ways. The gas turbine drives an electric generator, and the steam produced in the heat recovery steam generator is delivered to a steam turbine, which also drives an electric generator. Heat recovery steam generators can be with or without duct burners. Duct burners are used to combust fuel to generate more steam from heat recovery steam generators. Combined cycle mode has thermal efficiency in the range of 50 to 54%.

3.14.2 SOTA Performance Levels

Table 1 presents the SOTA performance levels for criteria pollutants (CO, VOC, and NOx) and control technologies for stationary combustion turbines with heat input capacity greater than 10 MMBTU/Hr (HHV basis). Also, in addition to criteria pollutants, performance levels for ammonia (NH_3), NOx emission levels in lbs/MW-hr for combustion turbines used for electrical energy generation and opacity have been addressed. No emission levels for SO_2, TSP, and PM-10 are specified. Permits for these sources will include limits for SO_2, TSP, and PM-10 developed based on the fuel type. Percentage sulfur by weight in liquid fuel must at a minimum comply with N.J.A.C. 7:27-9.2 (Sulfur Content Standards) and NSPS Subpart GG, whichever is more stringent. Lower sulfur requirements may result from the permitting process.

3.14.3 Technical Basis

The SOTA performance levels and control technologies listed in Table 1 below are based on permit applications filed with the New Jersey Department of Environmental Protection, and data from the United States Environmental Protection Agency's RACT/BACT/LAER Clearinghouse and permit applications filed with other states.

TABLE - 1
SOTA Performance Levels and Control Technology

Pollutant	**Heat Input Capacity MMBTU Per Hour (HHV Basis)**	**Air Pollution Control Technology**				**Emission Rate [$] - ppmvd @ 15% Oxygen**			
		Natural Gas *		Fuel Oil **		**Combined Cycle and Cogeneration Cycle**		**Simple Cycle #**	
		Simple Cycle #	**Combined Cycle ##**	**Simple Cycle #**	**Combined Cycle ##**	**Natural Gas***	**Fuel Oil****	**Natural Gas***	**Fuel Oil ****
NOx	10 - 150	DLN	DLN	DLN	DLN	12 – Combined Cycle 15- Cogeneration Cycle [%%]	25[a]	25 (10-500 MMBtu/hr)	65
	>= 150	DLN	DLN and SCR	DLN	DLN and SCR	2.5	3.5[a]	9 [##]	42
CO	10 - 150	Good combustion	Good combustion	Good combustion	Good combustion	50 [b]	50 [b]	50 [b]	50 [b]
	>= 150	Good combustion or CO oxidation catalyst	Good combustion and CO oxidation catalyst	Good combustion or CO oxidation catalyst	Good combustion and CO oxidation catalyst	3 [b, c]	3 [b, c]	15[b]	15 [b]
VOC	10-150	Good combustion	Good combustion	Good combustion	Good combustion	25 [d]	25 [d]	25 [d]	25 [d]
	> =150	Good combustion or CO Oxide. catalyst	Good combustion	Good combustion	Good combustion	4 [d]	4 [d]	10 [d]	10 [d]
Ammonia Slip	all turbines with SCR	---	---	---	---	5	5		
NOx-Lb/MW-hr	> 150		DLN and SCR and > 54% thermal efficiency		DLN and SCR and > 54% thermal efficiency	0.1 [f]			
Opacity	all turbines	Good combustion	Good combustion	Good combustion	Good combustion	Please refer to note "e" for opacity levels		Please refer to note "e" for opacity standards	

[$] All emission rates are at ISO conditions

* - Natural gas or any other gaseous fuel (Butane, refinery gas, digester gas, etc.)

** - No.2 fuel, or Aviation Kerosene, or low sulfur distillate oil

\# - Emission limits and air pollution control technologies shall be the same for simple cycle or regenerative cycle turbines.

\## - 9 PPM NOx performance level applies to Simple cycle turbines greater than 500 MMBTU/hr heat input rate.

%% - To qualify for cogeneration, the design useful thermal energy output of the facility must be no less than 5% of the total energy output averaged over 12 months.

[a] - If the gas turbine is combusting liquid fuel only during gas curtailments a higher emission limit for fuel oil only may be granted based on a case by case analysis. For combined cycle and cogeneration combustion turbines in the size range 10-150 MMBTU/hr the NOx level is 65 ppmdv at 15% Oxygen during gas curtailments.

[b] - During low load operating scenario (<30% of base load capacity), CO emissions shall not exceed 250 ppmvd at 15% oxygen.

[c] - For combined cycle turbine without duct burner, state of the art performance level for CO is 15 ppmvd at 15% oxygen.

[d] - During low load operating scenario (<30% of base load capacity), VOC emissions shall not exceed 50 ppmvd at 15% oxygen

[e] - Opacity levels:

10% - During gaseous fuel burning, except during start-up, shutdown, and fuel transfer periods (exclusive of visible condensed water vapor)..

20% - During start-up, shutdown, fuel transfer periods and liquid fuel burning (exclusive of visible condensed water vapor).

[f] lbs/MW-hr limit does not apply to less than 150 mmbtu/hr combined or cogeneration cycle turbines.

NOTE:

1. Compliance averaging times for NOx, CO, and VOC performance levels for combined cycle units greater than 150 MMBTU/Hr are as follows:

   When compliance by CEM is required - 3 hour rolling average based on 1-hour block basis

   When compliance by stack testing is required - Average of 3, one-hour test runs

2. Compliance averaging times for all other scenarios and contaminants shall be based on each of the three, one hour tests.

Combined Cycle and Cogeneration Cycle Turbines (10 – 150 MMBTU/Hr):

Based on the information presented, the Department sets for combined cycle units a performance level of 12 PPM corrected to 15% oxygen for natural gas and 25 PPM corrected to 15% oxygen for fuel oil.

Based on the information provided by cogeneration facilities and vendors, the additional capital cost of SCR on top of the higher capital cost of cogeneration may discourage the construction of cogeneration facilities. The alternative would be the use of boilers and grid power that would result in more air contaminant emissions than a cogeneration facility. Hence, the Department sets a performance level of 15 PPM NOx level for natural gas firing in a cogeneration cycle to both encourage high efficiency cogeneration systems and to minimize air contaminant emissions overall. This higher allowable emission number for cogeneration cycles using natural gas is based on the fact that cogeneration units have a higher thermal efficiency (typically 70 to 74%) compared to the thermal efficiency of combined cycle units (typically 50 to 54%). Therefore, both emission rates (12 PPM for combined cycle and 15 PPM for cogeneration cycle) are similar in terms of useful heat output. To be eligible for the emission limits for cogeneration facilities, the design useful thermal energy output of the cogeneration facility must be no less than 5 percent of the total energy output averaged over 12 months.

The Department has also revised the range of small size combined cycle and cogeneration cycle turbines from 10-100 MMBTU/hr to 10-150 MMBTU/hr.

Simple Cycle Turbines:

Simple cycle turbines are quick in generating electricity but are far less efficient compared to combined cycle systems. Accordingly, it emits more carbon dioxide (a greenhouse gas), NOx and other air contaminants per unit production of electricity. The SOTA levels listed in Table – 1 above are for simple cycle turbines having an annual capacity factor of no more than 10%. Simple cycle turbines having annual capacity factors greater than 10% shall establish SOTA levels on a case-by-case basis, with the presumption that the combined cycle SOTA rates would apply. The Department generally expects combined cycle turbines to be used for annual capacity factors greater than 10%.

3.14.4 Control Technologies For Stationary Combustion Turbines (Pollution Prevention and Post -Combustion Control)

NOx Formation

NOx is formed in the combustion turbine through fuel NOx formation and thermal NOx formation. Fuel NOx is formed when nitrogen compounds in the fuel combine with oxygen present in the combustion zone to form NOx. Fuel NOx can be reduced by reducing the amount of nitrogen in the fuel (burning lower fuel-bound nitrogen fuel such as natural gas) and/or by reducing the amount of excess oxygen in the combustion zone. Thermal NOx is formed when nitrogen from the combustion air combines with oxygen in the combustion zone at temperatures in excess of 2100 degrees Fahrenheit to form NOx. Thermal NOx can be reduced by reducing the amount of oxygen in the combustion zone and/or lowering the temperature in the combustion zone (lowering flame temperature).

3.14.4.1 Control Technologies

Reductions in NOx, CO and VOC emissions can be achieved using combustion control technologies or flue gas treatment (post-combustion control technologies).

a) Combustion Control Technologies for NOx

Combustion control technologies listed below are pollution prevention techniques. By controlling the most important factors effecting combustion chemistry (temperature, excess oxygen and residence time) these techniques are effective in minimizing the formation of pollutants. Pollution prevention techniques also include improved thermal efficiency (i.e., cogeneration and combined cycle systems).

i. Wet Controls [water injection (WI) or steam injection (SI)]

Water injection or steam injection is a technology to reduce or limit thermal NOx formation by reducing the combustion turbine flame temperature. Water/steam is injected into the turbine combustors, which mixes in the flame with the combustion by-products, and reduces flame temperatures by dilution and evaporative cooling of combustion by-products. The result is a lower flame temperature and consequently reduced formation of thermal NOx. Injection rates for both water and steam are usually described by a water/steam-to-fuel ratio and are usually given on a weight basis. The water/steam-to-fuel injection ratio is the most significant factor affecting the performance of water injection. Higher ratios result in greater NOx reductions, but also may increase emissions of CO and hydrocarbons, may reduce turbine efficiency, and may increase turbine maintenance requirements.

ii. Dry Low NOx Combustors (DLN)

Combustion modifications that lower NOx emissions without water injection include lean combustion, reduced combustor residence time, lean premixed combustion, and two-stage rich-lean combustion.

- Lean Combustion

An equivalence ratio of 1.0 indicates a stoichiometric ratio of fuel (F) to air (A). Equivalence ratios below 1.0 indicate fuel-lean conditions. With lean combustion, the additional excess air cools the flame, which reduces the peak flame temperature and reduces the rate of thermal NOx formation.

- Reduced Combustor Residence Time

In all gas turbine combustor designs, the high temperature combustion gases are cooled with dilution air to an acceptable temperature prior to entering the turbine. With reduced residence time combustors, dilution air is added sooner than with standard combustors. Because the combustion gases are at a high temperature for a shorter time, the amount of thermal NOx formation decreases.

- Lean Premixed Combustors

In a lean premixed combustor design, the fuel (F) and air (A) is premixed at very lean F/A ratios prior to introduction into the combustion zone. The excess air in the lean mixture lowers combustion temperature, which greatly reduces NOx formation rates.

- Rich/Quench/Lean Combustion (RQL)

RQL combustors burn fuel-rich in the primary zone and fuel-lean in the secondary zone of combustion. Incomplete combustion under fuel-rich conditions in the primary zone produces an atmosphere with a high concentration of CO and hydrogen gas (H_2). The CO and H_2 replaces some of the oxygen for NOx formation and also acts as a reducing agent for any NOx formed in the primary zone. Thus fuel nitrogen is released with minimal conversion to NOx. The lower peak flame temperatures due to partial combustion also reduces the formation of thermal NOx. Both thermal and fuel NOx are controlled with this design.

iii. Flameless Catalytic Combustion System

This system is a way to carry out combustion to minimize the formation of NOx while achieving low CO and unburned hydrocarbon levels. The system is totally contained within the combustor of the gas turbine. The combustor consists of four sections:

-The pre-burner (for start-up and acceleration of the engine).
-The fuel injection and fuel/air mixing system
-The catalyst module, where a portion of the fuel is combusted without a flame to maintain low temperature gas.
-The homogeneous combustion region, where the remainder of the fuel is combusted.

The overall combustion process in the Flameless Catalytic Combustion system is a partial combustion of fuel in the catalyst module followed by completion of the combustion downstream of the catalyst. The partial combustion within the catalyst produces no NOx. Homogenous combustion produces only 1-2 ppm NOx because the combustion occurs at a uniformly low temperature. This is a relatively new technology that is not yet in widespread use.

b) Post Combustion Control Technologies

i. Selective Catalytic Reduction (SCR)

SCR is an add-on NOx control technique that is placed in the exhaust stream following the gas turbine. SCR is a process in which ammonia is directly injected into the flue gas and then passed over a catalyst to react with NOx, converting the NOx and ammonia to nitrogen and water. The catalyst allows this reaction to take place at a lower temperature than would be required without it. The temperature of the catalyst should be between approximately 570 ^{O}F to 750 ^{O}F depending on the catalyst used. The catalyst is usually either a noble metal, base metal (titanium or vanadium), or a zeolite based material. SCR is a common techniques for combined cycle turbines. It has also been used in some simple cycle applications.

ii. Catalytic Absorption System Without Ammonia Injection

This system utilizes a single catalyst for the removal of both carbon monoxide and nitrogen oxide emissions. The catalyst works by simultaneously oxidizing CO to CO_2, NO to NO_2, and then absorbing NO_2 onto its surface through the use of a potassium carbonate absorber coating. These reactions are shown below, and are referred to as the "Oxidation/Absorption Cycle".

$$CO + 1/2\ O_2 \rightarrow CO_2$$
$$NO + 1/2O_2 \rightarrow NO_2$$

$$2NO_2 + K_2CO_3 \rightarrow CO_2 + KNO_2 + KNO_3$$

The CO_2 in reaction (1) and reaction (3) is exhausted up the stack. During this cycle, the potassium carbonate coating reacts to form potassium nitrites and nitrates, which are then present on the surface of the catalyst. When the surface of the catalyst becomes saturated with NO_x the catalyst must enter the regeneration cycle. The regeneration cycle is accomplished by passing a dilute hydrogen reducing gas across the surface of the catalyst in the absence of the oxygen. This is a relatively new technology that is not yet in widespread use.

c) CO and VOC Control Technology (Pollution Prevention and Post Combustion Control)

i. Combustion Controls (Pollution Prevention)

Combustion controls involve optimizing the factors effecting combustion chemistry (i.e., temperature, excess oxygen and residence time) to minimize emissions of CO, VOC and other products of incomplete combustion (PIC's) as well as NO_X in a balanced manner. Sometimes efforts to control NOx cause increases in PICs. Therefore, it is important to set limits on carbon monoxide to ensure CO and other PIC emissions do not increase significantly when controlling NOx. This is done by careful control of the combustion parameters, as well as add on oxidation catalysts.

ii. Oxidation Catalyst (Post Combustion Control)

Oxidation catalyst can be used to reduce emissions of CO, VOC, and other PICs. For effective combustion of PICs, the flue gas must be lean (excess Oxygen) to promote the following reactions:

$$CO + O_2 \text{ -------> } CO_2$$
$$HC_x + O_2 \text{ ------->} H_2O + CO_2$$
$$H_2 + O_2 \text{ -----}\rightarrow H_2O$$

The operating temperature window of oxidation catalyst is between 500^{O} F - 1100^{0} F. There are several catalysts available to reduce emissions of CO and VOC.

3.14.5 Energy Efficiency Considerations

Greater energy efficiency reduces all air contaminant emissions, including the greenhouse gas carbon dioxide. Higher efficiency processes include combined cycle operation and combined heat and power (CHP) generation. For electric generation the energy efficiency of the process expressed in terms of MMBTU per Megawatt-hr must be reported in the permit application. The Department is using an energy efficiency level of 54% to specify a SOTA NOx emission level of 0.1 pound per MW-hr for combined cycle combustion turbines that are used for electrical energy generation. The combustion turbines that are used for cogeneration of steam for use for other than electricity, and electricity simultaneously would have even lower pounds per MW-hr. Cogeneration units have much higher thermal efficiency typically over 70% than combined cycle units. To calculate lbs/MW-hr for cogeneration units, useful steam energy must be converted to equivalent MW-hr and added to the electric output. USEPA has published “A handbook for Air Regulators – Output based Regulations” which provides the conversion factor and different approaches on how to convert steam output into equivalent MW-hr. An applicant is encouraged to do this and increase the use of otherwise wasted heat.