New Jersey Department of Environmental Protection
Division of Air Quality, Bureau of Stationary Sources

State of the Art (SOTA) Manual for Stationary Compression Ignition Reciprocating Internal Combustion Engines

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Section 3.13a - State of the Art (SOTA)
Manual for Stationary Compression Ignition Reciprocating Internal Combustion Engines

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3.13a SOTA MANUAL FOR STATIONARY COMPRESSION IGNITION RECIPROCATING INTERNAL COMBUSTION ENGINES

3.13a.0 Definitions

"Air-to-Fuel Ratio (A/F)" means the ratio of air to fuel for combustion.

1. An A/F ratio of 1.0 indicates an equal stoichiometric ratio of air (A) to fuel (F).
2. An A/F ratio greater than 1.0 indicates fuel-lean (excess air) or lean burn combustion, with some of the fuel unable to be fully oxidized (combusted).
3. An A/F ratio less than 1.0 indicates fuel-rich (excess fuel) or rich burn combustion, with the fuel able to be fully oxidized (combusted).

"Biodiesel" is a renewable, biodegradable fuel manufactured domestically from vegetable oils, animal fats, or recycled restaurant grease.

"Brake-Specific Fuel Consumption (BSFC)" is a measure of fuel efficiency in an engine. It is the rate of fuel consumption (pounds per hour) divided by the amount of power produced (horsepower).

"Diesel" means any fuel sold and suitable for use in diesel engines (including biodiesel). Diesel fuel can contain other additives to meet the requirements of Title 40 of the Code of Federal Regulations, Part 80 and is one of the following:

1. A distillate fuel commonly or commercially known or sold as No. 1 diesel fuel or No. 2 diesel fuel;
2. A non-distillate fuel other than residual fuel with comparable physical and chemical properties (e.g., biodiesel fuel); or
3. A mixture of either of these types of fuels.

"International Organization for Standardization (ISO) standard dry conditions" means 288 degrees Kelvin (58.7 ºF), 60% relative humidity, and 101.3 kilopascals (14.70 pounds per square inch) pressure.

"Lower Heating Value (LHV)" means the heat content of a fuel in units of energy per mass or volume.

"Natural Gas" means a fluid mixture of hydrocarbons composed of at least 70 percent methane by volume that is merchantable and marketable that meets an interstate or intrastate transmission company's minimum specifications with respect to:

(i) delivery pressure;
(ii) delivery temperature;
(iii) heat content between 950 and 1,100 British Thermal Units (BTU) per dry standard cubic foot;
(iv) mercaptan sulfur;
(v) total sulfur less than 20.0 grains per 100 standard cubic feet;
(vi) moisture and/or water content;
(vii) CO_2;
(viii) oxygen (O_2);
(ix) total inerts (the total combined CO_2, helium, nitrogen, O_2, and any other inert compound percentage by volume);
(x) hydrocarbon dew point limits;
(xi) merchantability;
(xii) content of any liquids at or immediately downstream of the delivery point into a pipeline; and

(xiii) interchangeability with the typical composition of the gas in the pipeline with respect to the following indices: Wobbe Number, Lifting Index, Flashback Index, and Yellow Tip Index per AGA Bulletin No. 36.

Natural gas can include renewable natural gas that meets the requirements for natural gas but does not include the following gaseous fuels: Landfill gas, digester gas, refinery gas, sour gas, blast furnace gas, coal-derived gas, producer gas, coke oven gas, or any gaseous fuel produced in a process which might result in highly variable sulfur content or heating value.

"Renewable Natural Gas (RNG)" means landfill gas or digester gas that has been processed to remove impurities and increase methane concentration to meet interstate or intrastate transmission company's minimum specifications.

"Saybolt Universal Seconds" is a measure of viscosity determined using a standardized test, specified in ASTM D2161. Viscosity is measured as the time (seconds) taken for 60 milliliters of a liquid to flow through a calibrated tube at 100 ºF.

"Stroke" is one complete direction of piston motion within the cylinder, resulting in 180º of circular motion on the crankshaft. The piston head moves either between the top center to the bottom of the cylinder or bottom to the top center of the cylinder.

1. In a 2-stroke engine, the combustion cycle is completed in one crankshaft revolution.
2. In a 4-stroke engine, the combustion cycle is completed in two crankshaft revolutions.

"Steady state" means all operations except for startup, shutdown, and fuel type switching.

3.13a.1 Scope

This State-of-the-Art (SOTA) manual establishes emissions performance levels and control technologies for the best performing sources within the U.S. Conformance to the requirements established in this manual by a permit applicant alleviates the need for the applicant to review and establish a case-by-case SOTA for any air contaminant source included in this manual.

These SOTA performance levels apply to stationary compression ignition (CI) reciprocating internal combustion engines (RICE) with a rating of 198 brake horsepower (bhp) or more that are not classified as an "Emergency Stationary RICE" or "Black Start Engine" in Title 40 of the Code of Federal Regulations (40 CFR), Part 60, Subpart ZZZZ.[1]

The SOTA thresholds for source operations, which must obtain a Preconstruction Permit pursuant to N.J.A.C. 7:27-8, can be found in:

1. N.J.A.C. 7:27-8, Appendix 1, Table A for criteria pollutants; and
2. N.J.A.C. 7:27-17.9, Tables 3A and 3B for hazardous air pollutants (HAP) and toxic substances (TXS) regulated by the New Jersey Department of Environmental Protection (the Department).

The SOTA thresholds for source operations which must obtain an Operating Permit, pursuant to N.J.A.C. 7:27-22 can be found in:

[1] 40 CFR §63.6675

1. N.J.A.C. 7:27-22, Appendix, Table A; and
2. N.J.A.C. 7:27-17.9, Tables 3A and 3B for HAP and TXS.

If a source operation was omitted in this manual or an engine combusts a fuel not included in this manual, the applicant must represent SOTA technology using a case-by-case approach, if applicable, pursuant to N.J.A.C. 7:27-8.12 and N.J.A.C. 7:27-22.35. For air contaminants that may be emitted from the sources described in this manual, but for which a performance level is not specified, SOTA will be done on a case-by-case basis pursuant to N.J.A.C. 7:27-8 and N.J.A.C. 7:27-22.

This SOTA Manual includes SOTA standards from the combustion of diesel or a combination of natural gas and diesel fuel from CI RICE. Additional SOTA standards for the combustion of landfill gas can be found in the SOTA Manual for Equipment Used to Vent Municipal Solid Waste Landfills - Section 3.18. SOTA standards for the combustion of gaseous or liquid fuels from SI RICE can be found in the SOTA Manual for Stationary Spark Ignition Reciprocating Internal Combustion Engines - Section 3.13b.

3.13a.1.1 Operation of CI RICE

An internal combustion engine operates by combusting a mixture of air and fuel in the combustion chamber, the space between the piston head and surrounding engine cylinder. In a CI RICE, air enters the combustion chamber via a valve; fuel enters via a fuel injector. Upon ignition, the air/fuel mixture forms higher-pressure gases, pushing the piston downwards, generating linear motion. The combustion gases are exhausted from the cylinder via a separate valve, the piston head returns to its original position, and the process repeats. Linear motion from the piston is transferred via the connecting rod to the crankshaft. At the crankshaft, the linear motion from multiple cylinders is converted into rotary motion.

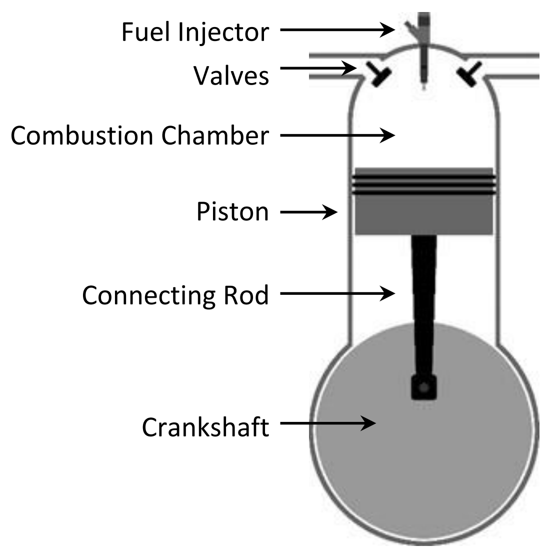

Figure 3.13a - 1: CI RICE Cylinder (4-stroke)

In a CI RICE, the air/fuel mixture self-combusts, as the air heats upon compression between the piston head and the cylinder. When fuel is injected into the cylinder, the compressed air is higher than the autoignition temperature of the fuel, causing the fuel to spontaneously ignite in the cylinder; a separate energy source (i.e., spark plug) is not required to ignite the air/fuel mixture in a CI RICE.[2]

3.13a.1.2 CI RICE Classifications

CI RICE are classified by several parameters: power, operating cycle (number of strokes), air-to-fuel (A/F) ratio, fuel type, charge pressure, and cylinder displacement (size).

Power

Engines are classified by the amount of power that can be generated in units of horsepower (hp) or kilowatts (kW). Brake horsepower (bhp) is measured at the flywheel, a large wheel attached to the

[2] *Compilation of Air Emissions Factors, Volume 1, Chapter 3: Stationary Internal Combustion Sources, Section 3.3: Gasoline and Diesel Industrial Engines,* EPA AP-42, January 1995.

crankshaft of the engine that transfers the rotary motive power of the engine to the equipment that needs powered. The amount of power provided by an engine in 1 hour is expressed in hp-hr or kW-hr.

To convert engine power into different units:

1. Divide the engine hp / bhp by 1.34 hp-hr/kW-hr to convert from hp / bhp to kW; and
2. Multiply the engine kW by 1.34 hp-hr/kW-hr to convert from kW to hp / bhp.

Engines may also be classified by their maximum heat input capacity, usually given in British Thermal Units (Btu) or million Btu (mmBtu). The heat capacity of an engine is not a measure of its power. The fuel heating value and the brake specific fuel consumption (BSFC, a measure of efficiency) of the engine are required to covert mmBtu to hp or kW. For CI RICE combusting diesel fuel, the U.S. Environmental Protection Agency (EPA) established a BSFC of 0.367 pounds per hour (lbs./hour)[3] and diesel fuel has a lower heating value of 128,488 Btu/gallon (or 18,133 Btu/lb.).[4] Heating values for other fuels are provided in 40 CFR, Part 98, Table C-1.

Equation 3.13a-1: Converting maximum heat rating to engine power rating

$$\frac{\text{mmBtu/hr} \times 1{,}000{,}000 \text{ Btu/mmBtu}}{\text{BSFC lbs./hp-hr} \times \text{LHV Btu/lb.}} = \text{hp}$$

Engines used for electricity generation usually list the kW or megawatts (MW) of electricity that can be generated by the alternator attached to the engine, rather than the kW (or MW) of mechanical motive power generated by the engine.

Operating Cycle

CI RICE are designed to operate as either a 2-stroke (rare) or 4-stroke (common) cycle. Each stroke is considered a separate part of the operating cycle. In a 4-stroke CI RICE, the intake stroke has air entering the combustion chamber. During the compression stroke, the air is compressed in the combustion chamber; at the end of the compression stroke, fuel is injected into the combustion chamber and self-ignites. The autoignition of the fuel begins the power stroke, where the expanding, combusting gases force the piston head downwards and generate motive power. For the exhaust stroke, another valve opens, venting the products of combustion from the combustion chamber. The CI RICE 4-stroke operating cycle is illustrated in Figure 3.13a - 2.

[3] *Exhaust and Crankcase Emission Factors for Nonroad Compression-Ignition Engines in MOVES3.0.2*, U.S. EPA, EPA-420-R-21-021, September 2021.
[4] *Alternative Fuels Data Center, Fuel Properties Comparison*, U.S. Department of Energy (DOE), afdc.energy.gov/fuels/properties.

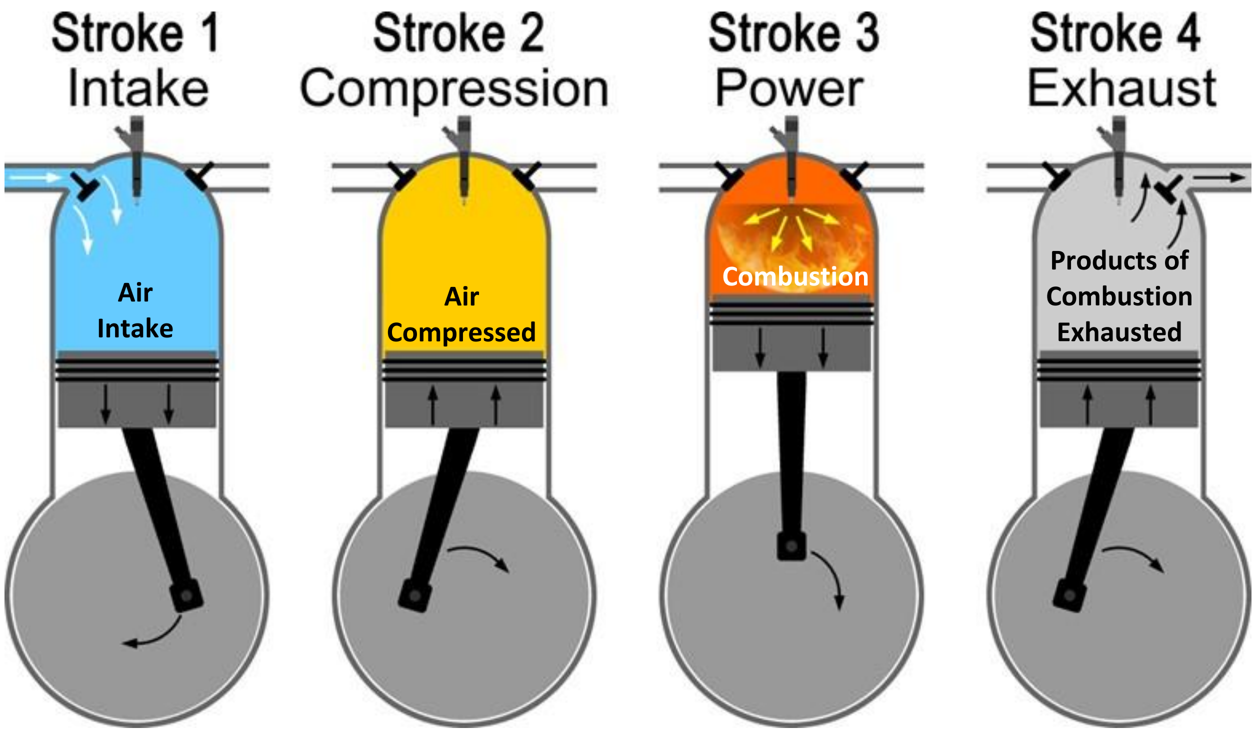

Figure 3.13a - 2: 4-Stroke CI RICE Operating Cycles

A/F Ratio

The A/F Ratio is classified as either rich burn or lean burn. An engine operating at a stoichiometric A/F Ratio of 1.0 has sufficient air to allow the fuel to fully combust. Rich burn engines operate with a stoichiometric or fuel-rich (excess fuel) A/F Ratio of 1.0 or less, which results in a lower concentration of excess oxygen in the exhaust gases(<4%). Lean burn engines operate with a fuel-lean (excess air) A/F Ratio greater than 1.0, which results in higher concentrations of excess oxygen in the exhaust gases (≥8%). Lean burn engines reduce nitrogen oxide (NO_X) emission, since the engine operates at a lower temperature; however, lean burn engines need flame stabilization to promote stable fuel combustion with lower fuel consumption.[5] Since the fuel in a CI RICE self-combusts, CI RICE are only considered lean burn engines.

Fuel Type

CI RICE are limited to using fuels that have an autoignition temperature below the compressed air temperature within the combustion chamber. Diesel fuel is the most common fuel used in CI RICE. Dual-fuel fired CI RICE combust either diesel fuel or a combination of natural gas and diesel fuel. In a dual-fuel fired operation, natural gas is added in the intake cycle with air; a small amount of diesel fuel is added at the end of the compression cycle for autoignition.[6] SOTA standards for RICE combusting solely natural gas can be found in the SOTA Manual for Stationary Spark Ignition Reciprocating Internal Combustion Engines - Section 3.13b.

[5] *Compilation of Air Emissions Factors, Volume 1, Chapter 3: Stationary Internal Combustion Sources, Section 3.2: Natural-Gas Fired Reciprocating Engines,* EPA AP-42, January 1995.

[6] *Alternative Fuels Data Center,* U.S. DOE, afdc.energy.gov/vehicles/conversions_basics.html

Charge Pressure
CI RICE can use air at either atmospheric pressure (naturally aspirated) or compressed via a turbocharger. A naturally aspirated engine draws filtered air into the combustion chamber through the intake valve during the downwards movement of the piston head in the intake cycle. A turbocharger uses exhaust gas from the engine (at a higher temperature) in a turbine to compress the filtered air, forcing more air into the combustion chamber during the intake cycle. A supercharger uses the rotary power from the engine to power a turbine to compress the filtered air, instead of engine exhaust gases. A turbocharger or supercharger can produce higher power output without changing the cylinder size or emissions profile.[7]

Cylinder Displacement
EPA has developed different emissions standards for CI RICE based on cylinder displacement. Displacement is the total volume of air moved by the piston within the engine cylinder. CI RICE with larger cylinder displacement can generate more power, as they have larger combustion chambers that allow combustion of more fuel.[8]

3.13a.2 SOTA Performance Levels

This SOTA Manual includes operational requirements, emissions limitations, and control efficiency requirements for different air contaminants, depending on cylinder displacement and size of the CI RICE.

3.13a.2.1 Maximum Achievable Control Technology for Stationary CI RICE

CI RICE are included in the Maximum Achievable Control Technology (MACT) standard found in 40 CFR, Part 63, Subpart ZZZZ, National Emission Standards for Hazardous Air Pollutants (NESHAP): Stationary Reciprocating Internal Combustion Engines.[9] This MACT standard is considered equivalent to SOTA, pursuant to N.J.A.C. 7:27-8.12(e)(3) for preconstruction permits and N.J.A.C. 7:27-22.35(c) for operating permits. Emissions of other pollutant emissions from CI RICE not subject to the MACT standard are addressed in other sections of this SOTA manual.

All CI RICE are subject to the MACT standard, which contains requirements for both area and major sources of hazardous air pollutant (HAP) emissions of formaldehyde. The MACT standard establishes emissions limits, classified by engine size and date of installation. For all CI RICE located an area source of HAP emissions, the MACT standard requires compliance with the requirements of 40 CFR, Part 60, Subpart IIII. For CI RICE located at a major source of HAP emissions, the following emissions limits apply to new or reconstructed CI RICE installed on or after the date of this SOTA Manual and located at a major source of HAP emissions:

1. ≤500 hp – Limited Use (operated ≤100 hours/year): Comply with 40 CFR, Part 60, Subpart IIII;
2. ≤500 hp: Comply with 40 CFR, Part 60, Subpart IIII; and
3. >500 hp: Formaldehyde ≤580 parts per billion by volume dry (ppbvd) at 15% oxygen (O_2) or a ≥70% reduction in carbon monoxide (CO) emissions.

Note: For new, reconstructed, and rebuilt stationary engines, deviations of emissions or operating limitations that occur within the first 200 hours of operation from engine startup are not violations.[10]

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[7] *Compilation of Air Emissions Factors, Volume 1, Chapter 3: Stationary Internal Combustion Sources, Section 3. 2: Natural-Gas Fired Reciprocating Engines,* EPA AP-42, January 1995.
[8] *Introduction to Diesel Engines.* U.S. Nuclear Regulatory Commission
[9] Title 40 of the Code of Federal Regulations, Part 63, Subpart ZZZZ.
[10] 40 CFR §63.6640(d).

The MACT standard also contains operating, monitoring, recordkeeping, and reporting requirements for all categories of CI RICE.

3.13a.2.2 New Source Performance Standards for Stationary CI RICE

EPA has developed new source performance standards (NSPS) in 40 CFR, Part 60, Subpart IIII[11] for stationary CI RICE that were constructed, modified, or reconstructed after July 11, 2005. It contains emissions limits and control requirements for CO, non-methane hydrocarbons (NMHC), nitrogen oxides (NO_X), and particulate matter (PM). The NSPS requires manufacturers to certify CI RICE with a displacement of <30 liters per cylinder for the life of the engine. The NSPS includes emissions limits for owners or operators of all CI RICE. Engine certifications are available on the EPA website at https://www.epa.gov/compliance-and-fuel-economy-data/annual-certification-data-vehicles-engines-and-equipment.

Since the emissions limits in the CI RICE NSPS are less stringent than the emissions limits determined to be SOTA in Section 3.13a.2.3, they are not included in this manual.

3.13a.2.3 Other SOTA Performance Levels for Stationary CI RICE

The SOTA performance levels for SO_2 applicable during steady state operations while combusting gaseous fuels or liquid fuels are provided below:

1. SO_2 emissions limits for any stationary CI RICE using #2 fuel oil (diesel fuel) with a Saybolt Universal Seconds viscosity of 45 or less at 100 °F: 0.00160 lbs. SO_2/MMBtu or a fuel sulfur content of 15.0 parts per million by weight (ppmw).[12]

The SOTA performance levels for ammonia (NH_3), CO, NO_X, total suspended particulate (TSP), and volatile organic compounds (VOC; expressed in non-methane hydrocarbons - NMHC) applicable during steady state operations are provided in Tables 3.13a.2-1 and 3.13a.2-2.

TABLE 3.13a.2-1
SOTA Steady State Performance Levels for Stationary CI RICE ≥198 bhp and <751 bhp[13]

Pollutant	≥198 bhp and <751 bhp	≥148 kW and <560 kW†	Alternative Compliance Option
CO	0.45 grams/bhp-hr	0.60 grams/kW-hr	90% reduction
NO_X	0.15 grams/bhp-hr	0.20 grams/kW-hr	90% reduction
TSP	0.01 grams/bhp-hr	0.02 grams/kW-hr	85% reduction
NMHC	0.02 grams/bhp-hr	0.03 grams/kW-hr	N/A
NH_3 Slip	10 ppmvd @15% O_2	10 ppmvd @15% O_2	N/A

[11] Title 40 of the Code of Federal Regulations, Part 60, Subpart IIII.
[12] N.J.A.C. 7:27-9.2
[13] *Analysis of Stationary Reciprocating Internal Combustion Engines Permits Emissions Limits and Control Requirements*, SC&A, Inc., June 2023.

†*Engines used for electricity generation usually list the kW or MW of electricity that can be generated by the alternator attached to the engine, rather than the kW (or MW) of mechanical motive power generated by the engine.*

TABLE 3.13a.2-2
SOTA Steady State Performance Levels for Stationary CI RICE ≥751 bhp[14]

Pollutant	≥751 bhp	≥560 kW†	Alternative Compliance Option
CO	0.45 grams/bhp-hr	0.60 grams/kW-hr	90% reduction
NO_X	0.15 grams/bhp-hr	0.20 grams/kW-hr	90% reduction
TSP	0.01 grams/bhp-hr	0.02 grams/kW-hr	85% reduction
NMHC	0.02 grams/bhp-hr	0.03 grams/kW-hr	N/A
NH_3 Slip	10 ppmvd @15% O_2	10 ppmvd @15% O_2	N/A

†*Engines used for electricity generation usually list the kW or MW of electricity that can be generated by the alternator attached to the engine, rather than the kW (or MW) of mechanical motive power generated by the engine.*

The emissions limits specified in this SOTA manual do not apply outside of steady state operating conditions. SOTA technology for startup, shutdown, and fuel switching is determined using the case-by-case approach, pursuant to N.J.A.C. 7:27-8.12 and N.J.A.C. 7:27-22.35.

3.13a.3 Control Technologies

Reductions in CO, NO_X, and VOC emissions can be achieved using combustion control technologies or flue gas treatment (post-combustion control technologies). SO_2 is primarily controlled by regulating the fuel sulfur content.

3.13a.3.1 Combustion Control Technologies

Combustion control technologies modify combustion parameters, changing the combustion chemistry (lower temperature, excess oxygen, and reduced residence time). NO_X is formed from nitrogen in the fuel (Fuel NO_X) and atmosphere (thermal NO_X) combining with excess oxygen in the combustion chamber. CO and NMHC / VOC are formed by incomplete combustion of the fuel.

A/F Ratio Adjustment – Lean Burn
A/F ratio adjustment is not a feasible control technique for CI RICE; however, a CI RICE with the wrong A/F ratio will generate smoke and excess engine heat.[15]

Exhaust Gas Recirculation (EGR)
A portion of engine exhaust gases can be recirculated back into the engine as combustion air. Since the exhaust gases contain a lower oxygen content, (as some of the oxygen was converted to CO_2 during the

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[14] *Analysis of Stationary Reciprocating Internal Combustion Engines Permits Emissions Limits and Control Requirements*, SC&A, Inc., June 2023.
[15] *Compilation of Air Emissions Factors, Volume 1, Chapter 3: Stationary Internal Combustion Sources, Section 3.3: Gasoline and Diesel Industrial Engines,* EPA AP-42, January 1995.

power stroke), this lowers the oxygen available for further combustion, decreasing thermal NO_X formation and combustion temperatures. EGR is accomplished with an EGR valve, which regulates the flow of exhaust gases into intake air. An EGR can be equipped with a heat exchanger to cool the exhaust gases, further lowering combustion temperature. Since exhaust air passed through the EGR valve, carbon deposits can buildup on the valve over time, reducing airflow through the EGR valve, causing black smoke and an increase in NMHC / VOC in the exhaust gases.

Fuel Additives

Materials are added to diesel fuel to reduce formation of TSP. Fuel additives work in conjunction with diesel oxidation catalyst and diesel particulate filters to capture TSP. Addition of certain catalysts (platinum and cerium) facilitates the production of a carbon-rich soot that can be more easily combusted during the passive regeneration cycle of a diesel particulate filter.

Ignition Timing

By moving the ignition event later in the compression stroke, the combustion chamber temperature will be reduced during fuel combustion, decreasing thermal NO_X formation. In CI RICE, this is achieved by changing the timing for fuel injection. The manufacturer establishes optimal ignition timing for certified CI RICE via an electronic fuel injection system.[16]

Low Emission Combustion (LEC)

LEC is combustion of a very fuel lean mixture, with the lean fuel mixture acting as a heat sink that lowers cylinder temperature, decreasing thermal NO_X formation. LEC engines are lean burn engines that are equipped with improved combustion chambers to enhance air-fuel mixing and improved ignition systems. LEC is not used on diesel RICE but may be used in dual-fuel CI RICE to reduce the amount of diesel consumed. Typically, an air-fuel mixture with 75-100% excess air is utilized within a pre-combustion chamber; newer designs have an “open” combustion chamber that can provide 50% excess air. Turbochargers / superchargers and aftercoolers are used to provide the additional combustion air to a specially designed combustion chamber within the cylinder. A HEIS is required to ignite air-fuel charge in LEC engines.

Low Sulfur Fuel

Reducing the sulfur content of diesel fuel reduces SO_2 and PM emissions. #2 Fuel Oil (Diesel Fuel) sale in New Jersey is considered Ultra-Low Sulfur Diesel (ULSD) Fuel with the sulfur content restricted to 15.0 ppmw or less.[17]

Turbocharger After-Cooling

An aftercooler or intercooler reduces the temperature of compressed air from a turbocharger / supercharger before it enters the engine. The reduced cylinder temperature lowers thermal NO_X formation.

Water / Methanol Injection

Water or a water / methanol mixture can be injected into the combustion chamber with the fuel. The energy required to convert the water to steam reduces the combustion temperature and the steam produces additional downwards thrust on the piston head. Water injection reduces thermal NO_X

[16] *Compilation of Air Emissions Factors, Volume 1, Chapter 3: Stationary Internal Combustion Sources, Section 3.3: Gasoline and Diesel Industrial Engines,* EPA AP-42, January 1995.
[17] N.J.A.C. 7:27-9.2

formation and increases engine power. The use of a water / methanol mixture reduces combustion temperature and provides an additional fuel to increase power production.

3.13a.3.2 Add-On Control Technologies

Add-on control technologies are devices designed to reduce air pollution after it has been generated by the engine. These control technologies are placed in the exhaust stream, between the engine exhaust and the exhaust outlet (stack).

Catalytic Absorption System Without Ammonia Injection
This system utilizes a single catalyst for the removal of both CO and NO_X emissions. The previous metal catalyst works by simultaneously oxidizing CO to carbon dioxide (CO_2), NO to NO_2, and then absorbing NO_2 onto its surface via a potassium carbonate coating on the absorber. 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, the catalyst must be regenerated, as it no longer is reacting with NO_X. The regeneration cycle is accomplished by passing a dilute H_2 reducing gas across the surface of the catalyst in the absence of the oxygen.

Closed Crankcase Ventilation System
The cover on the crankcase collects air pollution and vents it to a control device to remove TSP and oil mist.

Diesel Oxidation Catalyst (DOC)
A DOC consists of a previous metal coating on a honeycomb structure. As the hot exhaust gas flows through the honeycomb, the catalyst oxidizes CO to CO_2 and NHMC / VOC to CO_2 and water. TSP reduction is between 20 and 40%; CO reduction is between 10 and 60%; and NMHC / VOC reduction is between 40 and 75%.[18]

Diesel Particulate Filter (DPF) or Diesel Particulate Trap (DPT)
A DPF captures TSP (soot) inside of a porous membrane. Disposable DPF are replaced and disposed of as a solid waste after saturation; they have a much shorter operational life than a regenerable DPF. Regenerable DPF are made of ceramic or metals that can be regenerated and reused. Passive regeneration occurs during engine operation; as the exhaust gas temperature increases while the engine operates, carbon within the collected soot is oxidized into CO_2. Other, non-carbon particulates within the soot captured in the DPF must be addressed through active regeneration. There are several options for active regeneration, where the DPF is oxidized to remove carbon within the captured soot:

1. Fuel is oxidized in the DOC or an electric heater is used to generate a high temperature in the DPF.
2. Catalysts are used on the DPF to oxidize the soot at a lower temperature.
3. Fuel additives (catalysts) oxidize the soot at a lower temperature.
4. Using a valve to throttle the exhaust and raising the temperature within the DPF.

Both forms of regeneration result in the buildup over time of metal oxide particles within the DPF that cannot be combusted, eventually requiring DPF cleaning every 6-12 months. DPF are effective at reducing

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[18] *Technical Bulletin: Diesel Oxidation Catalyst General Information*, U.S. EPA, EPA-420-F-10-031, May 2010, www.epa.gov/sites/default/files/2016-03/documents/420f10031.pdf.

TSP by 85 to 90% and NMHC / VOC and CO by 70 to 90%. Some DPF generate NO_2 during filter regeneration at lower temperatures.[19]

Lean NO_X Catalyst

A reducing agent (usually unburnt fuel) is added to the exhaust stream to facilitate reduction of NO_X into nitrogen and water vapor in a catalyst. The operation is similar to selective catalytic reduction (SCR), with the hydrocarbons acting as the reducing agent to facilitate the conversion of NO_X to nitrogen and water vapor.

Ozone Injection

Ozone is injected into the exhaust gas to further oxidize nitrogen oxides into dinitrogen pentoxide (N_2O_5). A wet or caustic scrubber is used to remove the highly water-soluble N_2O_5 from the exhaust stream. The exhaust gases must be cooled to 350ºF to optimize NO_X oxidation, inhibit ozone dissociation, and reduce evaporation within the wet scrubber. A heat recovery steam generator or economizer is used to reduce exhaust gas temperatures. Ozone is generated onsite using an ozone generator.

Selective Non-Catalytic Reduction (SNCR)

SNCR can be used in lean burn engines and is only effective within a narrow, high temperature range. Ammonia or urea is injected into the exhaust, reducing NO_X to nitrogen and water vapor. The exhaust gases must be at a temperature greater than 1,550ºF and require a residence time between the ammonia / urea and exhaust gas of at least 1 second. Additional fuel is usually required to heat the engine exhaust to the high temperature required for SNCR to work effectively. Additional combustion of the exhaust gases (afterburner) can also reduce emissions of CO, TSP, NMHC / VOC.[20]

More ammonia / urea is added to the exhaust gas than needed, so some of this ammonia passes through the catalyst unreacted (ammonia slip); ammonia slip of 10 ppm is considered reasonable. Additional catalysts can be used to reduce ammonia slip.

Selective Catalytic Reduction (SCR)

SCR is an increasingly common control technique for controlling NO_X emissions in lean burn engines. Ammonia or urea (also known as diesel exhaust fluid – DEF) is directly injected into the exhaust gas and then passed over a catalyst (catalytic converter). The exhaust air is filtered to remove particulates, then ammonia or urea is added to the exhaust stream. For an SCR system using urea, a hydrolysis catalyst converts the urea to ammonia. The next catalyst causes the ammonia / urea to react with NO_X, converting the NO_X to nitrogen and water. A catalyst allows a chemical reaction to take place at a lower temperature than would be required without it. The SCR catalyst is usually either a base metal (titanium or vanadium) or a zeolite-based material.

Exhaust temperatures greater than the upper limit of the catalyst (850ºF) will cause the NO_X to pass through the catalyst unreacted. More ammonia / urea is added to the exhaust gas than needed, so some of this ammonia passes through the catalyst unreacted (ammonia slip); ammonia slip of 10 ppm is considered reasonable. Additional catalysts can be used to reduce ammonia slip. Low sulfur fuels must be

[19] *Technical Bulletin: Diesel Particulate Filter General Information*, U.S. EPA, EPA-420-F-10-029, May 2010.

[20] *Compilation of Air Emissions Factors, Volume 1, Chapter 3: Stationary Internal Combustion Sources, Section 3.3: Gasoline and Diesel Industrial Engines,* EPA AP-42, January 1995.

used in an SCR, as SO_2 in the exhaust stream is also chemical altered in the catalyst, forming sulfuric acid mist and sulfur particulate matter.[21]

3.13a.3.3 Alternate Technologies

Alternative Fuels

Alternatives to fossil-fuels are available for use in RICE. These alternative fuels may be sourced from renewable resources (corn-based ethanol) or may be considered wastes (landfill gas). Alternative fuels are defined in the Energy Policy Act of 1992 to include: biodiesel, renewable natural gas (landfill gas), hydrogen, P-series fuels, gasoline / ethanol blends (E85 or flex-fuel), methanol, ethanol, or other fuels derived from biological materials.

Alternative fuels have similar emissions profiles to fossil fuels; however, they have lower net CO_2 emissions. Combusting fossil fuels generates CO_2, transferring carbon that was previously stored underground into our atmosphere. Combusting alternative fuels returns the CO_2 to the atmosphere that was previously extracted by the crops used to produce the alternative fuels. Although they generate CO_2 emissions, alternative fuels cause no net change in carbon emissions.

Using wastes as an alternative fuel alleviates the need to dispose of the waste material and provides the added benefit of generating power. Additional SOTA standards for the combustion of landfill gas can be found in the SOTA Manual for Equipment Used to Vent Municipal Solid Waste Landfills - Section 3.18.

Energy Efficiency

Greater energy efficiency reduces emissions of all air contaminants, including CO_2, a greenhouse gas. For electric generation, the energy efficiency of the process is related to the heat rate of the engine, (expressed in terms of MMBtu per Megawatt-hour (MW-hr)), with a lower heat rate indicating a more efficient RICE. The heat rate must be reported in the permit application. Energy efficiency programs are encouraged to increase the use of otherwise wasted thermal energy and to ensure that engine use is limited to appropriately sized, higher efficiency engines.

3.13a.4 Technical Basis

Information from the following sources were used as the basis for developing this SOTA Manual:

A. Title 40 of the Code of Federal Regulations, Part 60, Subpart IIII, “Standards of Performance for Stationary Compression Ignition Internal Combustion Engines.”

B. Title 40 of the Code of Federal Regulations, Part 63, Subpart ZZZZ, “National Emission Standards for Hazardous Air Pollutants: Stationary Reciprocating Internal Combustion Engines.”

C. SC&A, Inc. Analysis of Stationary Reciprocating Internal Combustion Engines Permits Emissions Limits and Control Requirements, June 16, 2023.

3.13a.5 Recommended Review Schedule

This SOTA Manual will be reviewed periodically and revised if new collection and control technologies that minimize emissions become available, and any time a new MACT standard or standard of performance for new or existing sources is published.

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[21] *Compilation of Air Emissions Factors, Volume 1, Chapter 3: Stationary Internal Combustion Sources, Section 3.3: Gasoline and Diesel Industrial Engines,* EPA AP-42, January 1995.