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

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

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

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3.13b SOTA MANUAL FOR STATIONARY SPARK IGNITION RECIPROCATING INTERNAL COMBUSTION ENGINES

3.13b.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).

"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).

"Ethanol" is an alcohol that can be used as a fuel in reciprocating internal combustion engines. Ethanol is naturally produced via fermentation of sugars or yeasts and is commonly used as an additive in gasoline.

"Gasoline" means a complex mixture of volatile hydrocarbons, with or without additives, suitably blended to be used in spark ignition engines. Reformulated gasoline can be blended with different concentrations of ethanol (E10, E15, and E85 – flex fuel) and other additives to meet the requirements of Title 40 of the Code of Federal Regulations, Part 80.

"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.

"Liquified Petroleum Gas (LPG)" means a flammable mixture of hydrocarbons that include individually or as a mixture propane, propylene, butylene, isobutane, and n-butane.

"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.

"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.

3.13b.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 spark ignition (SI) reciprocating internal combustion engines (RICE) with a rating of 157 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. 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

[1] 40 CFR §63.6675

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 natural gas (including compressed natural gas), gasoline, a combination of gasoline and ethanol, or liquified petroleum gas (LPG) from SI 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 Compression Ignition Reciprocating Internal Combustion Engines - Section 3.13b.

3.13b.1.1 Operation of SI 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 4-stroke SI RICE, an air/fuel mixture enters the combustion chamber via a valve. The air/fuel mixture is compressed, then ignited by a spark plug, forming higher-pressure gases. The higher-pressure gases push 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.

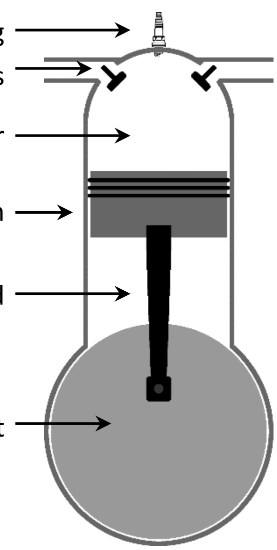

Figure 3.13b - 1: SI RICE Cylinder (4-stroke)

2-stroke and 4-stroke cylinders are composed of similar parts, except for the location of fuel intake and combustion exhaust ports. In a 4-stroke engine, valves open and close at the top of the combustion chamber; in the 2-stroke engine, the piston blocks the fuel intake and combustion exhaust ports during movement. A carburetor or fuel injector is used to disperse the fuel and mix with air.[2]

3.13b.1.2 SI RICE Classifications

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

<u>**Power**</u>

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 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.

[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.

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 SI RICE, the U.S. Environmental Protection Agency (EPA) has estimated the BSFC to be 0.406 lbs./hp-hr for LPG and natural gas and 0.484 for gasoline.[3] Heating values for fuels are provided in 40 CFR, Part 98, Table C-1.

Equation 3.13b-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

SI 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 SI RICE, the intake stroke has the air/fuel mixture entering the combustion chamber. During the compression stroke, the air/fuel mixture is compressed in the combustion chamber. At the beginning of the power stroke, the spark plug fires, igniting the air/fuel mixture. 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 SI RICE 4-stroke operating cycle is illustrated in Figure 3.13b - 2.

[3] *Exhaust Emission Factors for Nonroad Engine Modeling – Spark-Ignition*, U.S. EPA, EPA-420-R-10-019, July 2010.

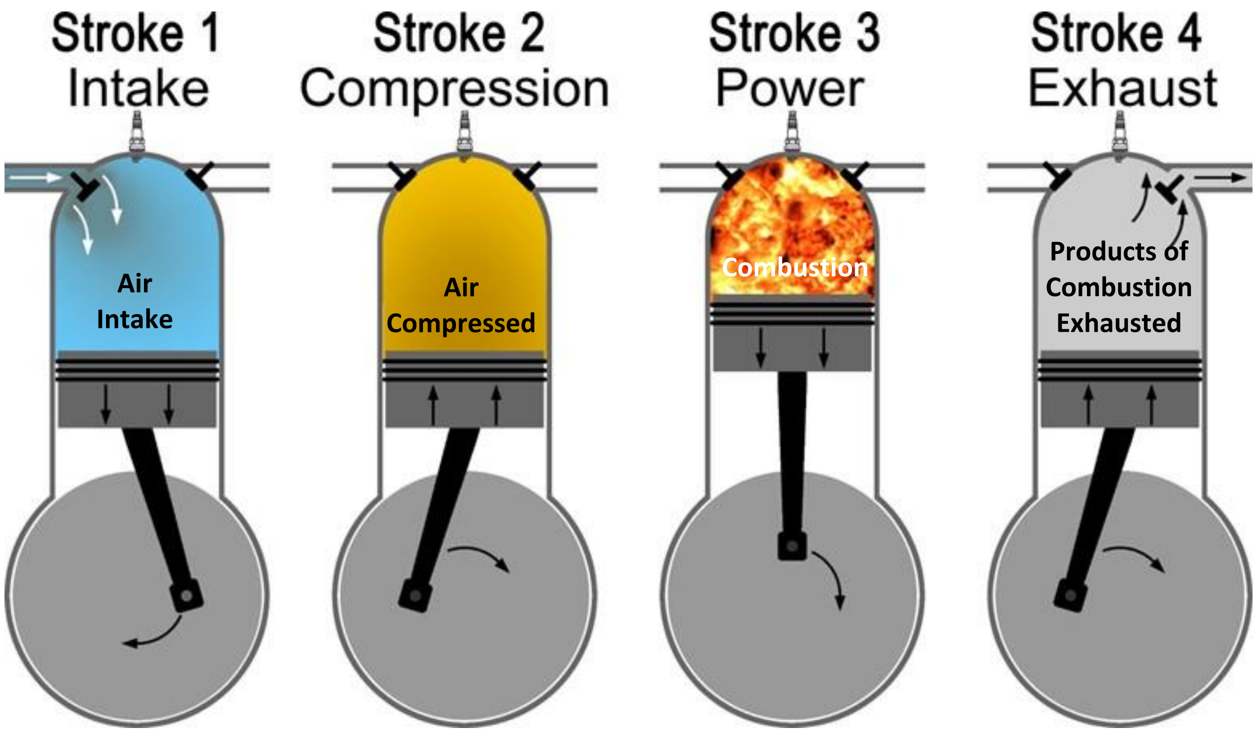

Figure 3.13b - 2: 4-Stroke SI RICE Operating Cycles

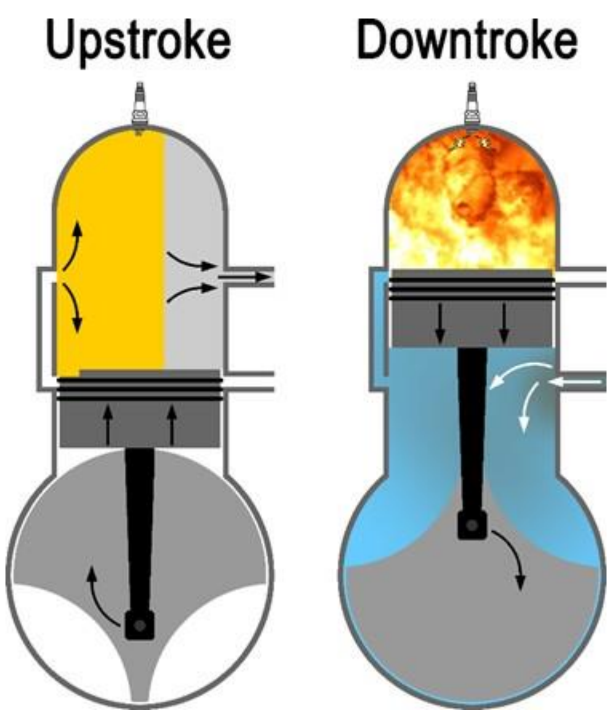

Figure 3.13b - 3: 2-stroke SI RICE Cycles

A 2-stroke SI RICE is illustrated in Figure 3.13b – 3. The SI RICE represented is a piston-controlled inlet port, the most common type of 2-stroke SI RICE. In this type of 2-stroke SI RICE, the downstroke starts with the combustion of the air/fuel mixture in combustion chamber, initiated by a spark. This forces the piston head downwards, turning the crankcase and generating motive power. As the crankshaft turns, it allows the air fuel mixture to enter the crankcase, with the piston head blocking the air/fuel intake and exhaust ports to the combustion chamber. As the piston head moves downwards, the exhaust and air/fuel intake ports are uncovered. The piston head pushes the air/fuel mixture into the combustion chamber, which pushes out the combusted gases through the exhaust port. As the piston head moves downwards, it blocks the air/fuel intake port to the crankcase.

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. A turbocharger or supercharger can produce higher power output without changing the cylinder size or emissions profile.[4]

SI RICE can be either rich burn or lean burn engines, although 2-stroke SI RICE can only be lean burn. Lean burn engines normally emit less NO_X, although rich burn engines can utilize catalysts as add-on control equipment to lower NO_X emissions. Catalysts cannot be used on lean burn engines, as the catalyst requires a reducing (low oxygen) atmosphere, but a lean burn engine exhausts an oxidizing atmosphere.

Fuel Type

SI RICE can use a wide variety of fuels, including gasoline, LPG, natural gas, compressed natural gas (CNG), propane, landfill / digester gas, methanol, and ethanol.

Charge Pressure

Rich burn SI RICE operate at atmospheric pressure (naturally aspirated). A naturally aspirated engine draws filtered air into the combustion chamber through the intake valve during the intake cycle. Lean burn SI RICE use compressed air, usually from a turbocharger, to provide excess air to the SI RICE. 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.[5]

3.13b.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 SI RICE.

3.13b.2.1 Maximum Achievable Control Technology for Stationary SI RICE

SI 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.[6] 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 SI RICE not subject to the MACT standard are addressed in other sections of this SOTA manual.

All SI 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 SI RICE located in an area source of HAP

[4] *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.
[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] Title 40 of the Code of Federal Regulations, Part 63, Subpart ZZZZ.

emissions, the MACT standard requires compliance with the requirements of 40 CFR, Part 60, Subpart JJJJ. For SI RICE located at a major source of HAP emissions, the following emissions limits apply to new or reconstructed SI 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 JJJJ.
2. ≤500 hp 2-stroke lean burn – Comply with 40 CFR, Part 60, Subpart JJJJ;
3. >500 hp 2-stroke lean burn – Formaldehyde ≤12 parts per billion by volume dry (ppbvd) at 15% oxygen (O_2) or a ≥58% reduction in carbon monoxide (CO) emissions;
4. <250 hp 4-stroke lean burn – Comply with 40 CFR, Part 60, Subpart JJJJ;
5. ≥250 hp 4-stroke lean burn – Formaldehyde ≤14 ppbvd at 15% O_2 or a ≥93% reduction in CO emissions;
6. ≤500 hp 4-stroke rich burn – Comply with 40 CFR, Part 60, Subpart JJJJ; and
7. >500 hp 4-stroke rich burn – Formaldehyde ≤350 ppbvd at 15% O_2 OR a ≥76% reduction in formaldehyde emissions OR a ≥30% reduction in total hydrocarbons.

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.*[7]

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

3.13b.2.2 New Source Performance Standards for Stationary SI RICE

EPA has developed new source performance standards (NSPS) in 40 CFR, Part 60, Subpart JJJJ[8] for stationary SI RICE that were constructed, modified, or reconstructed on or after July 1, 2008. It contains emissions limits and control requirements for CO, nitrogen oxides (NO_X), and volatile organic compounds (VOC). The NSPS requires manufacturers to certify certain SI RICE for the life of the engine. The NSPS includes emissions limits for owners or operators of all SI 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.

Stationary SI RICE combusting gasoline that are subject to 40 CFR, Part 60, Subpart JJJJ can only combust gasoline with a sulfur content of 95 parts per million (ppm).[9] Since the emissions limits in the SI RICE NSPS are less stringent than the emissions limits determined to be SOTA in Section 3.13b.2.3, they are not included in this manual.

3.13b.2.3 Other SOTA Performance Levels for Stationary SI RICE

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 3.13b.2-1 through 3.13b.2-2.

[7] 40 CFR §63.6640(d).
[8] Title 40 of the Code of Federal Regulations, Part 60, Subpart JJJJ.
[9] 40 CFR §1090.205(c)

TABLE 3.13b.2-1
SOTA Steady State Performance Levels for Stationary Lean Burn SI RICE[10]

Pollutant	≥157 bhp	≥117 kW†	Alternative Compliance Option
CO	0.40 grams/bhp-hr	0.54 grams/kW-hr	58% reduction (2-stroke) 93% reduction (4-stroke)
NO_X	0.15 grams/bhp-hr	0.20 grams/kW-hr	90% reduction
TSP	0.01 grams/bhp-hr	0.01 grams/kW-hr	80% reduction[11]
NMHC	0.14 grams/bhp-hr	0.19 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.

TABLE 3.13b.2-2
SOTA Steady State Performance Levels for Stationary Rich Burn SI RICE[12]

Pollutant	≥157 bhp	≥117 kW†	Alternative Compliance Option
CO	0.40 grams/bhp-hr	0.54 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	0.01 grams/kW-hr	80% reduction[13]
NMHC	0.14 grams/bhp-hr	0.19 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.

[10] *Analysis of Stationary Reciprocating Internal Combustion Engines Permits Emissions Limits and Control Requirements*, SC&A, Inc., June 2023.
[11] *The Effects of Secondary Air Injection on Particulate Matter Emissions*, Massachusetts Institute of Technology, February 2014.
[12] *Analysis of Stationary Reciprocating Internal Combustion Engines Permits Emissions Limits and Control Requirements*, SC&A, Inc., June 2023.
[13] *The Effects of Secondary Air Injection on Particulate Matter Emissions*, Massachusetts Institute of Technology, February 2014.

3.13b.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.

3.13b.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

Increasing the A/F ratio in lean burn SI RICE decreases NO_X emissions. Extra air dilutes the combustion gases, lowering peak flame temperature and reducing thermal NO_X formation. Although increasing A/F ratio decreases generation of thermal NO_X, there is an increase in CO and VOC emissions. Increasing the A/F ratio can reduce the power generated by the engine; to avoid de-rating the engine, combustion air must be increased at a constant fuel flow. This is achieved with the use of a turbocharger and an automatic A/F ratio controller. A/F ratio adjustment has limited utility in naturally aspirated engines and engines with fuel injectors outside of the cylinder (in the intake manifold plenum), as the A/F ratio cannot be established or monitored within each cylinder.

The A/F ratio is typically increased from a normal level of 50% excess air to 240% excess air. The A/F ratio upper limit is constrained by the misfiring due to flame instability. To maintain acceptable engine performance at super lean conditions, high energy ignition systems (HEIS) have been developed that promote flame stability at very lean conditions.

A/F Ratio Adjustment – Rich burn

Increasing the A/F ratio in rich burn engines limits oxygen availability in the cylinder, decreasing NO_X emissions but increasing CO and VOC emissions. The A/F ratio cannot exceed 1.0 in a rich burn engine. Installation of an automatic A/F ratio controller is required to monitor and adjust to changing load and other operating conditions and maintain an optimum A/F ratio.

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 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 gasoline to change its combustion properties. The most common gasoline additive is ethanol, which is added to gasoline to provide oxygen and promote fuel combustion. Oxygenated fuel decreases CO emissions, as there is more oxygen available during combustion; however, ethanol contains less energy per unit of volume than gasoline, reducing engine efficiency.

High Energy Ignition Systems (HEIS)

With traditional spark plug ignition, the duration of the spark is comparatively short, occurring over one degree (1º) of crankshaft rotation. If the air-fuel mixture within the cylinder when the spark occurs is not exact, there little to no combustion occurs. With HEIS or plasma ignition, a fuel-rich mixture is ignited in a small ignition cell located within the cylinder head, and the spark plug provides a continuous electrical discharge for 10-90º of crankshaft rotation. The flame from the ignition cell expands throughout the cylinder, providing a uniform ignition source. HEIS ensures more complete combustion will occur, even in very fuel-lean conditions. HEIS can be used only in 2-stroke and 4-stroke, lean burn, natural gas fired SI RICE. The reduction in NO_X from HEIS can be accompanied by an increase in power output and increased fuel economy.

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 SI RICE, this is achieved by changing the timing of the spark. The manufacturer establishes optimal ignition timing for certified SI RICE via ignition timing using an onboard computer.

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. 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 gasoline reduces SO_2 and PM emissions. EPA has issued national standards limiting the sulfur content of gasoline to 95 ppm.[14]

Pre-stratified Charge Combustor (PSC)

PSC combustion is a technology for injecting the air-fuel mixture into the intake manifold in 4-stroke natural gas SI RICE in distinct “slugs.” Each slug becomes a separate (stratified) layer of a specific air-fuel mixture when drawn into the cylinder. By varying the air-fuel mixture, a fuel rich, easily ignitable mixture is introduced around the spark plug, while the overall air-fuel mixture within the combustion chamber is fuel lean. This allows combustion to occur at a lower temperature, producing less thermal NO_X and reducing misfire occurrence at the lower flammability limit for the fuel. Pre-stratified charges may increase CO and VOC emissions. The maximum NO_X reduction is limited to the maximum air content of the stratified charge without affecting engine power (derating) and balanced against increased CO and VOC emissions.

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.

[14] 40 CFR §1090.205(c)

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

3.13b.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.

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.

Non-Selective Catalytic Reduction (NSCR)

NSCR is a technology used only on rich burn SI RICE. It uses a three-way catalyst to promote the reduction of NO_X to nitrogen and water and the oxidation of CO and VOC to CO_2 and water. NSCR requires an oxygen sensor and automatic A/F ratio controller to maintain an appropriate A/F ratio for the catalysts to operate. Ammonia can be produced as a by-product, particularly as the catalyst ages.

The exhaust passes over a catalyst, usually a noble metal (platinum, rhodium, or palladium), which chemically reduces the NO_X to nitrogen and water and some VOC to CO_2 and water. Typical exhaust temperatures for effective removal of NO_X are 800-1200ºF. After passing through the reduction catalyst, additional air may be added before passing through an oxidation catalyst for control of CO and VOC emissions. The CO and VOC are oxidized to form CO_2 and water.

Engines operating with NSCR require A/F ratio control to maintain a highly reducing atmosphere to increase the effectiveness of the reduction catalyst. This is accomplished with an A/F ratio controller.[15]

[15] *Compilation of Air Emissions Factors, Volume 1, Chapter 3: Stationary Internal Combustion Sources, Section 3.4: Natural Gas-fired Reciprocating Engines,* EPA AP-42, January 1995.

Oxidation Catalyst

An oxidation catalyst is used on rich burn SI RICE to lower the emissions of CO and VOC. A low oxygen atmosphere is required for effective catalyst operation, so this technology is limited to rich burn SI RICE. Air is mixed with engine exhaust prior to the oxidation catalyst, which is made of precious metals like platinum and palladium. The CO and VOC are oxidized to form CO_2 and water. The operating temperature for an oxidation catalyst is between 500-1100ºF.

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.

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 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.[16]

[16] *Compilation of Air Emissions Factors, Volume 1, Chapter 3: Stationary Internal Combustion Sources, Section 3.4: Natural Gas-fired Reciprocating Engines,* EPA AP-42, January 1995.

3.13b.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.[17]

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.

3.13b.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 JJJJ, “Standards of Performance for Stationary Spark 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.

3.13b.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.

[17] *Alternative Fuels Data Center,* U.S. Department of Energy (DOE), afdc.energy.gov/fuels