PRELIMINARY DRAFT - DO NOT CITE OR QUOTE

APPENDIX B

DESCRIPTION OF SPARK-IGNITED IC ENGINE OPERATION AND EMISSION CONTROLS

I. DESCRIPTION OF SPARK-IGNITED IC ENGINES

The main parts of a piston-type (also known as reciprocating) spark-ignited (SI) internal combustion (IC) engine include pistons, combustion chambers, a crankshaft, and valves or ports. IC engines generate power from the combustion of an air/fuel mixture. The combusted mixture drives the piston, which is connected by a rod to the crankshaft, so that the back-and-forth motion of the piston is converted into rotational energy at the crankshaft. This rotational energy drives power equipment such as pumps, compressors, or electrical generators.

There are several key aspects of engine design and operation that influence emissions and emissions control. These include the basic design of the engine, the manner in which combustion is initiated, the type of fuel used, the introduction of intake air, the air/fuel ratio, and the operational mode of the engine. A brief description of these aspects is given below.

A. Basic Engine Design

Piston-type internal combustion engines are generally classified as either four or two stroke. Four operations occur in all piston-type internal combustion engines: intake, compression, power, and exhaust. Four stroke engines require two revolutions of the crankshaft to complete all four operations, while two stroke engines require only one revolution.

In four stroke engines, a single operation is associated with each movement of the piston. During the intake stroke, the intake valve opens, and gas is drawn into the combustion chamber and cylinder by the downward motion of the piston. Fuel is mixed with air before being introduced into the combustion chamber, and thus the gas drawn into the combustion chamber is an air/fuel mixture. At or shortly after the end of this downward movement, the valves close and the compression stroke begins with the pistons moving upward, compressing the air/fuel mixture. A spark plug ignites the air/fuel mixture. During the power stroke, the hot, high-pressure gases from combustion push the pistons downward. The exhaust stroke begins when the piston nears its full downward position. At that point, the exhaust valves open, and the piston reverses its motion, moving upward to push the exhaust gases out of the combustion chamber. Near the full upward travel of the pistons, the exhaust valves close, the intake valves open, and the intake stroke is repeated.

In a two stroke engine, instead of intake valves, there are one or more ports (i.e., openings) in each cylinder wall that are uncovered as the piston nears its full downward movement. Two stroke engines use either exhaust valves similar to four stroke engines, or exhaust ports located in each cylinder wall across from the intake ports. When the pistons reach their full downward travel, both the intake ports and the exhaust ports or valves are open, and the exhaust gases are swept out by the air/fuel mixture that is transferred into the cylinder through the intake ports. In order to effect this transfer, the intake air must be pressurized. This operation is often referred to as scavenging. The pressurization can result from introducing the air into a sealed crankcase. An air/fuel mixture is pulled into the sealed crankcase through the upward movement of the piston, and is pressurized by the downward movement of the piston. Alternatively, a supercharger or turbocharger can be used to compress the intake air. The compression and power strokes for a two-stroke engine are similar to those for a four-stroke engine.

B. Combustion Initiation

In SI engines, (also called Otto cycle), the fuel is usually mixed with intake air before introduction into the combustion chamber, resulting in a relatively homogeneous air/fuel mixture in the combustion chamber. Once the spark plug initiates combustion, the homogeneous mixture propagates the flame throughout the combustion chamber during the power stroke.

C. Type of Fuel

SI engines can use natural gas, landfill gas, digester gas, field gas, refinery gas, propane, methanol, ethanol, gasoline, or a mixture of these fuels. Natural gas consists almost exclusively of methane. Field gas refers to the raw gas produced from oil or gas production fields and contains varying amounts of hydrogen sulfide which can clog exhaust catalysts and render them ineffective in controlling NOx. Refinery gas refers to the gas generated by oil refinery processing. Field gas and refinery gas consist of mostly methane, but contain more of the heavier gaseous hydrocarbon compounds than natural gas. Landfill gas is generated from the decomposition of waste materials deposited in landfills. Landfill gas can vary from 25 to 60 percent methane, with the remainder being mostly inert gases such as carbon dioxide and nitrogen. Digester gas is generated from the anaerobic digestion of solids at sewage treatment plants. Digester gas is typically about two-thirds methane, while the remaining one-third is mostly inert gases such as carbon dioxide.

Significant amounts of gaseous sulfur compounds may also be present in landfill and digester gas. The sulfur content of the fuel is important, as exhaust catalysts may be adversely affected by high levels of sulfur. In addition, waste gases may contain methylated siloxanes which could poison or mask exhaust catalysts.

D. Introduction of Intake Air

On many engines, the intake air is compressed by a supercharger or turbocharger before it enters the combustion chamber. This compression can increase engine power substantially.

The major parts of a turbocharger consist of a turbine and compressor. Exhaust gases from the combustion chamber which are under high temperature and pressure pass through the exhaust pipe into the turbine, causing the turbine blades to spin. The turbine is connected by a shaft to a compressor. Intake air is directed into the compressor, where it is pressurized before passing through the intake manifold into the combustion chamber. The turbocharger allows the engine to pass a greater mass of air through the combustion chamber, which allows more fuel to be added and more power to be produced. Turbocharging also improves the overall efficiency of an engine.

Superchargers work in a similar fashion to turbochargers, except a mechanical power drive off the engine rather than exhaust gas powers the compressor. Less power is required to run a turbocharger than a comparable supercharger, and therefore turbocharged engines tend to be slightly more efficient than supercharged engines.

Engines not equipped with turbochargers or superchargers are referred to as naturally aspirated. Two stroke engines sometimes use superchargers to displace exhaust with intake air, but this design generally does not result in any significant pressurization of the intake air, and such engines are also classified as naturally aspirated.

E. Air/Fuel Ratio

Another basic engine parameter is the air/fuel ratio. Stoichiometry is defined as the precise air-to-fuel ratio where sufficient oxygen is supplied to completely combust fuel. A stoichiometric air/fuel ratio provides exactly enough oxygen to fully atomize the fuel for complete combustion. Rich of stoichiometry refers to fuel-rich combustion, i.e., operation at any air-to-fuel ratio less than stoichiometry. Lean of stoichiometry refers to fuel-lean combustion, i.e., operation at any air-to-fuel ratio numerically higher than stoichiometry.

Two-stroke, spark-ignited engines are lean-burn, while naturally aspirated, four-stroke SI engines are generally rich-burn. Turbocharged, spark-ignited engines can be either rich-burn or lean-burn, depending on design. Lean-burn engines tend to be more efficient but larger in size and higher in capital cost than rich-burn engines of the same power output. Also, smaller engines tend to be rich-burn, while larger engines tend to be lean-burn.

SI engines exhibit peak thermal efficiency (and also peak NOx emissions) at an air/fuel ratio that is about 6 to 12 percent leaner than stoichiometric. Efficiency (and NOx emissions) decrease if the mixture becomes leaner or richer than this peak efficiency ratio (see Figure B-1). If the mixture is enriched, NOx emissions can be reduced to about 50 percent of their peak value before encountering problems with excessive emissions of CO, VOC, and possibly smoke. If the mixture is leaned from the peak efficiency air/fuel ratio, NOx reductions exceeding 50 percent of peak values are possible.

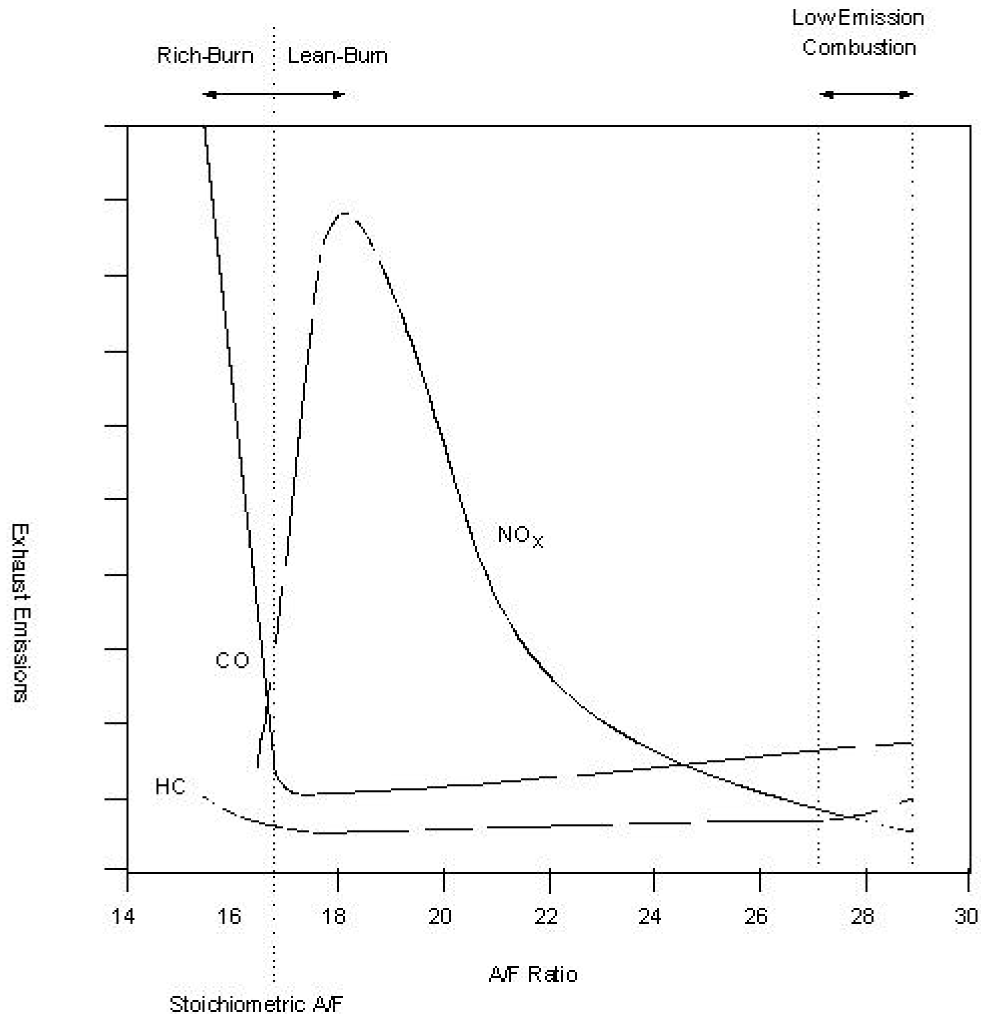

Figure B-1: The Effect of Air-to-Fuel Ratio on NOx, CO, and HC Emissions
(Provided by GRI)

As the mixture is leaned, at some point the engine will have difficulty in initiating combustion of the lean air/fuel mixture. One of the more popular methods of overcoming ignition difficulties with lean mixtures is to incorporate a precombustion chamber into the engine head. A precombustion chamber is a small combustion chamber which contains the spark plug. A rich mixture is introduced into the precombustion chamber, which is ignited by the spark plug. Passageways from the precombustion chamber to the main combustion chamber allow the flame front to pass into and ignite the lean mixture in the main combustion chamber.

Another method used to assist combustion of lean mixtures (especially in smaller engines) is to redesign the intake manifold and combustion chamber to promote more thorough mixing, so that a more uniform air/fuel mixture is present in the combustion chamber. A third method is to use an improved ignition system that sparks either more frequently or continuously.

F. Operational Mode

Reciprocating IC engines can be used in several operational modes. In many cases, they are used continuously under a constant power load, shutting down only when there is a breakdown, or when maintenance or repair work is required. Other engines operate cyclically, changing their power output on a regular, frequent schedule. One of the more common cyclic applications is an oil well pump, where an engine may operate at load for a time period varying from several seconds to about 20 seconds, followed by an equal amount of time operating at idle.

Some engines may operate continuously, but for only part of the year. In many cases, this intermittent operation is seasonal. In other cases, engines are portable, and are used only for a specific, short-term need. In still other cases, engines are used infrequently, for emergency purposes. Such engines may operate for no more than a few hours per year during an emergency, and are also tested routinely, typically for less than an hour once a week. Other engines may operate in modes that combine the characteristics of cyclic and continuous operations.

The operational mode of the engine is an important consideration when adopting control regulations. The operational mode may impact operating parameters such as exhaust gas temperature, which often must be taken into account when designing and applying controls. The operational mode may also affect the impact of emissions on air quality. For instance, an engine that operates only during summer, which is the peak ozone season, will have a much greater impact on ambient air quality violations than an engine with the same annual emissions that operates year round.

II. DESCRIPTION OF IC ENGINE CONTROLS

Combustion of fossil fuels results in emissions of criteria pollutants and their precursors (i.e., NOx, CO, particulate matter, VOC, and sulfur oxides (SOx)). Controls for one pollutant sometimes increases the emissions of one or more other pollutants. If this occurs, controls can often be used for these other pollutants which will fully mitigate the increase. SOx is generally controlled by limiting the sulfur content of the fuel and is not discussed further in this proposed determination, except as it affects emissions of other pollutants.

The following discussion of controls emphasizes the control of NOx. NOx emissions from stationary engines are generally far greater than for the other four pollutants.

NOx is generated in internal combustion engines almost exclusively from the oxidation of nitrogen in the air (thermal NOx) and from the oxidation of fuel-bound nitrogen (fuel NOx). The generation of fuel NOx varies with the nitrogen content of the fuel and the air/fuel ratio. The generation of thermal NOx varies with the air/fuel ratio, flame temperature, and residence time. Most fuels used in IC engines have relatively low fuel-bound nitrogen, so the principal NOx generation mechanism is thermal NOx. Even in cases where a high nitrogen content fuel such as crude oil or residual fuel oil is used, thermal NOx generation is generally far greater than fuel NOx generation due to the high combustion temperatures present.

There are probably more different types of controls available to reduce NOx from IC engines than for any other type of NOx source. These controls can be placed into one of four general categories: combustion modifications, fuel switching, post combustion controls, and replacement with a low emissions engine or electric motor. These controls are discussed in the following sections.

A. Combustion Modifications

Combustion modifications can reduce NOx formation by using techniques that change the air/fuel mixture, reduce peak temperatures, or shorten the residence time at high temperatures. The most frequently used combustion modifications include retarding the ignition, leaning the air/fuel ratio, adding a turbocharger and aftercooler, and adding exhaust gas recirculation.

Emissions of CO, particulate matter, and VOC are generally the result of incomplete combustion. They can be controlled by combustion modifications that increase oxygen, temperature, residence time at high temperatures, and the mixing of air and fuel. Note, however, that many of these modifications tend to increase NOx emissions. Care must be taken when applying these modifications to assure that reductions in one pollutant do not result in an unacceptable increase in other pollutants. These pollutants can also be controlled by post combustion controls such as oxidation catalysts and particulate traps.

1. Ignition Timing Retard

Applicability: This technique can be used on all spark-ignited (SI) engines. The technique has been widely used on motor vehicle engines, but is less popular on stationary source engines.

Principle: The ignition is retarded in SI engines by delaying the electrical pulse to the spark plug. As a result, the spark plug fires later, resulting in more of the combustion taking place as the piston begins its downward movement. This reduces both the magnitude and duration of peak temperatures.

Typical Effectiveness: NOx reductions for ignition timing retard are approximately 15 to 30 percent.

Limitations: SI engines are more sensitive than CI engines to operational problems associated with timing retard, and SI engines with excessive retard tend to misfire and exhibit poor transient performance.

Other Effects: Ignition timing retard will result in greater fuel consumption and higher exhaust temperatures, which could cause excessive exhaust valve wear. The maximum power output of the engine is also reduced, but this reduction is generally minor.

Costs: This method has relatively low capital and operating costs. The cost of adjusting timing to retard the ignition should be less than $300.

2. Air/Fuel Ratio Changes

Applicability: This technique can be used on all SI engines, and has been used extensively on a wide variety of engines.

Principle: NOx formation is a strong function of the air/fuel ratio as shown in Figure B-1. Emissions of CO and VOC are also strong functions of the air/fuel ratio. Stoichiometry is achieved when the air/fuel ratio is such that all the fuel can be fully oxidized with no residual oxygen remaining. NOx formation is highest when the air/fuel ratio is slightly on the lean side of stoichiometric. At this point, both CO and VOC are relatively low. Adjusting the air/fuel ratio toward either leaner or richer mixtures from the peak NOx formation air/fuel ratio will reduce NOx formation. In the case of leaner mixtures, the excess air acts as a heat sink, reducing peak temperatures, which results in reduced NOx formation. The excess air also allows more oxygen to come into contact with the fuel, which promotes complete combustion and reduces VOC and CO emissions. As the mixture continues to be leaned out, the reduced temperatures may result in a slight increase in CO and VOC emissions. For extremely lean mixtures, misfiring will occur, which increases VOC emissions dramatically.

Operating the engine on the lean side of the NOx formation peak is often preferred over operating rich because of increased fuel efficiencies associated with lean operation. When adjusting the air/fuel ratio, once an engine is leaned beyond the peak NOx air/fuel ratio, there is approximately a 5 percent decrease in NOx for a 1 percent increase in intake air. However, this rate of decrease in NOx becomes smaller as the mixture becomes leaner. Leaning the mixture beyond the optimal air/fuel ratio associated with peak fuel efficiency will result in increased fuel consumption. Compared to the most efficient air/fuel ratio, there is a fuel consumption penalty of about 3 percent when an engine is leaned sufficiently to reduce NOx by 50 percent. Fuel consumption increases exponentially if the mixture is leaned further.

NOx formation will also decrease if the mixture is richened from the peak NOx air/fuel ratio. However, the effect on NOx is generally not as great as that associated with leaning the mixture. With richer mixtures, the available oxygen preferentially combines with the fuel to form carbon dioxide (CO_2) and water (H_2O), leaving less oxygen available to combine with nitrogen to form NOx. A mixture richer than stoichiometric will result in incomplete combustion. Nearly all the oxygen will then combine with the fuel, emissions of CO and VOC will increase, and reductions in peak temperatures will reduce NOx formation. There is a very rapid exponential increase in CO and VOC emissions as the mixture becomes richer than stoichiometric.

The use of very lean air/fuel ratios may result in ignition problems. For this reason, techniques designed to improve ignition are often combined with lean air/fuel ratios to control NOx emissions and avoid increases in VOC emissions. These other techniques are described on the following pages.

Typical Effectiveness: When leaning of the mixture is combined with other techniques such as clean burn retrofit, NOx reductions greater than 80 percent are achievable, along with reductions in CO and VOC emissions. If extremely lean mixtures are used in conjunction with engine derating, NOx reductions well above 80 percent (less than 65 ppmv) are achievable. For extremely lean mixtures the resulting reduced temperatures will tend to inhibit oxidation, which will increase CO and VOC emissions to some degree.

For rich mixtures, the NOx reduction potential is not as great as reductions for lean mixtures. As the mixture is richened, emissions of CO and VOC increase to unacceptable levels before the NOx decreases to levels achieved by leaning the mixture.

Limitations: If the air/fuel mixture is richened excessively, emissions of CO and VOC increase dramatically. If the air/fuel ratio is leaned excessively, the flammability limit may be exceeded, resulting in misfiring. When an engine misfires (i.e., fails to fire), uncombusted fuel enters the exhaust, which dramatically increases VOC emissions.

Other Effects: None known.

Costs: Changing the air/fuel ratio of a SI engine should cost no more than $300. There is generally a fuel penalty for rich-burn engines that are richened, but leaning the mixture may reduce fuel consumption. These fuel effects vary with the engine and the degree of change in the air/fuel mixture.

3. Clean Burn Retrofit

Applicability: This control technology can be used on all SI engines, and has had wide applications on a variety of engines.

Principle: This method is used to enhance the effectiveness of the air/fuel ratio method described previously. As indicated previously in the discussion of air/fuel ratio changes, leaning the air/fuel mixture from the optimal NOx producing ratio will reduce NOx formation. The leaner the mixture, the lower the NOx emissions. However, to obtain substantial reductions in NOx emissions, engine modifications are needed to assure that the fuel will ignite and to minimize any fuel consumption penalties. A number of engine manufacturers and NOx control equipment manufacturers offer retrofit kits for some makes and models of lean-burn and rich-burn engines that allow these engines to operate on extremely lean mixtures to minimize NOx emissions. These retrofits are often referred to as "clean burn" retrofits.

On smaller engines, the cylinder head and pistons can be redesigned to promote improved swirl patterns which result in thorough mixing. On larger engines, the use of a precombustion chamber (also referred to as a prechamber) is needed to ignite the lean mixture. Combustion begins in the smaller prechamber, which contains the spark plug and a rich air/fuel mixture. Combustion propagates into the larger main chamber, which contains a lean air/fuel mixture. The resulting peak temperatures are lower due to: 1) the rich ignition mixture, 2) heat transfer losses as combustion proceeds into the main chamber, and 3) the dilution effects of the excess air.

Many precombustion chamber retrofits consist of replacing the existing engine heads with new heads. However, some low cost prechamber retrofits are designed to use the existing engine's head, with the prechambers fitted into the existing spark plug hole. Other prechamber retrofits consist of a modified spark plug instead of a separate prechamber. The modified spark plug has a small, built-in fuel nozzle which injects fuel toward the spark plug electrode.

In order to achieve these leaner air/fuel ratios, additional amounts of air must be introduced into the engine when using a given amount of fuel. For naturally aspirated engines, a turbocharger often must be added to provide the additional air. In other cases, the existing turbocharger may have to be replaced or modified to increase the air throughput.

Other equipment may also be used in a clean burn retrofit, such as a high energy ignition system to eliminate or minimize misfiring problems associated with lean operation, a new or modified aftercooler, and an air/fuel ratio controller. This equipment is described in more detail on the following pages.

Typical Effectiveness: For natural gas-fired engines, in almost all cases NOx emissions can be reduced to less than 130 parts per million (ppm) (i.e., greater than an 80 percent reduction over uncontrolled levels) with little or no fuel penalty. If engine parameters are adjusted and carefully controlled and the maximum power output of the engine is derated, sustained emissions below 65 ppm are achievable.

Limitations: NOx reductions of roughly 80 percent over uncontrolled levels are achievable with little or no fuel penalty. However, if the engine is leaned further to reduce emissions by more than about 80 percent, the fuel penalty increases exponentially. In some cases, a turbocharger may be needed to provide increased air flow, but a properly sized turbocharger may not be available for a retrofit. In other cases, the available retrofit parts may not allow the engine to produce the same maximum power, and the engine must be derated. Beyond a certain degree of leaning (and NOx reduction), misfiring will become a problem.

In some cases, it may be cheaper to replace an existing engine with a new clean burn engine, rather than install a clean burn retrofit kit. This is especially true if the retrofit kit has to be developed for that particular make and model of engine, or if the existing engine is old, inefficient, or unreliable.

Other Effects: At extremely lean air/fuel ratios, VOC and CO emissions tend to increase slightly. Once the air/fuel mixture is sufficiently lean, misfiring may occur, in which case VOC emissions can increase substantially.

Costs: For the installation of precombustion chamber heads and related equipment on large (~ 2,000 horsepower) engines, capital costs are about $400,000 per engine, and installation costs are about $200,000. Costs are lower for smaller engines. In terms of dollars per rated brake horsepower (bhp), costs are about $250/bhp for the large engines, and tend to be higher than this for smaller engines.

For prechambers fitted inside the existing spark plug hole, capital costs are about $15,000 to $20,000 for engines in the 300 to 400 horsepower range. Capital costs for engines in the 2,000 horsepower range can exceed $200,000.

4. <u>Ignition System Improvements</u>

Applicability: This control technology can be used on all SI engines. It has been applied to only a limited number of engines and engine types.

Principle: This method is used in conjunction with the use of lean air/fuel ratios to reduce NOx emissions. It allows leaner mixtures to be used without misfiring problems. As indicated previously, the leaner the air/fuel ratio, the lower the NOx emissions. However, at some point in leaning the mixture, lean misfire begins to occur, and further NOx reductions are impractical. In most engines during ignition, a nonuniform air/fuel mixture passes by the spark plug. In standard ignition systems, the spark plug's firing duration is extremely short. If the spark plug fires when this mixture is too lean to support combustion, a misfire occurs. If the spark plug fires multiple times, or for a longer period of time, there is a greater chance that the proper air/fuel mixture will pass by the spark plug and ignite the mixture. Improved ignition systems generally use a higher voltage to fire the spark plug, in addition to multiple or continuous sparking of the spark plug. This allows the use of leaner air/fuel ratios, resulting in lower NOx emissions.

Typical Effectiveness: Emission reductions from a combination of leaning of the air/fuel mixture and use of a continuous sparking ignition system approach but are generally less than a precombustion chamber retrofit. NOx emissions can generally be reduced to about 200 ppm.

Limitations: If the air/fuel ratio is leaned excessively, misfiring can occur. As with all methods involving leaning, the engine's maximum power rating may have to be reduced unless a turbocharger is retrofitted to naturally aspirated engines or the existing turbocharger is modified or replaced to increase the throughput of combustion air. In many cases, a separate retrofit kit must be developed for each make and model of engine, and only a few kits have been developed so far.

Other Effects: At extremely lean air/fuel ratios, VOC and CO emissions tend to increase slightly. If the air/fuel mixture is leaned excessively, misfiring may occur, in which case VOC emissions can increase substantially.

Costs: Costs are about two-thirds that of a precombustion chamber retrofit involving head replacement. For large engines (~ 2000 horsepower), costs can be in excess of $200,000.

5. <u>Turbocharging or Supercharging and Aftercooling</u>

Applicability: This control method can be used on almost any engine and is widely used.

Principle: Turbochargers and superchargers compress the intake air of an engine before this air enters the combustion chamber. Due to compression, the temperature of this air is increased. This tends to increase peak temperatures, which increases the formation of NOx. However, the heat sink effect of the additional air in the cylinder, combined with the increased engine efficiency from turbocharging or supercharging, generally results in a minor overall decrease in NOx emissions per unit of power output. On the other hand, turbocharging or supercharging can significantly increase the maximum power rating of an engine, which increases the maximum mass emissions rate for NOx. Due to the high density of oxygen in the combustion chamber, turbocharging or supercharging makes the combustion process more effective, which tends to reduce emissions of CO and VOC.

On turbocharged or supercharged engines, the intake air temperature can be reduced by aftercooling (also known as intercooling or charge air cooling). An aftercooler consists of a heat exchanger located between the turbocharger or supercharger and combustion chamber. The heat exchanger reduces the temperature of the intake air after it has been compressed by the supercharger or turbocharger. Cooling the intake air reduces peak combustion temperatures, and thereby reduces NOx emissions. The cooling medium can be water, either from the radiator or from a source outside of the engine, or the cooling medium can be ambient air. The use of radiator water generally results in the least amount of cooling, while the use of outside water or ambient air results in the most cooling of the intake air. Using either a cooler source of water or ambient air for the aftercooler can reduce the intake air temperature to as low as 90 ^{o}F.

The cooling effects of the aftercooler increases the density of the intake air, which results in a leaner air/fuel mixture in SI engines if no additional fuel is introduced. For engines already using lean air/fuel mixtures, this leaner mixture will lower NOx emissions further.

Typical Effectiveness: NOx reductions from aftercooling range from about 3 to 35 percent. The percentage reduction is roughly proportional to the reduction in temperature. Reductions in VOC and CO emissions also occur.

Limitations: Turbochargers or superchargers may not be available for some engines. In addition, some internal engine parts may have to be replaced or strengthened when adding a supercharger or turbocharger.

Other Effects: Use of a supercharger or turbocharger increases the efficiency and maximum power rating of an engine. Use of an aftercooler further increases the efficiency of an engine, and can also increase the maximum power rating. At low loads and excessive temperature reductions, an aftercooler can cause longer ignition delays, which increase emissions of VOC and particulate matter. This emissions increase can be minimized if an aftercooler bypass is used to limit cooling at low loads.

Costs: The cost of retrofitting a naturally aspirated engine with a turbocharger and related equipment varies from engine to engine. These costs vary not only because different sizes of turbochargers are used for different engines, but also because different engines may require more extensive internal modifications.

For natural gas engines, costs of a turbocharger retrofit are typically $30,000 to $40,000 for engines in the 800 to 900 horsepower range. For natural gas engines in the 1,100 to 1,300 horsepower range, costs can vary from $35,000 to $150,000.

In some cases, replacement of an existing engine with a new, low NOx emitting turbocharged engine may result in lower overall costs than retrofitting the existing engine with a turbocharger or supercharger. Although the capital cost of the new engine will generally be greater than the retrofit cost for the existing engine, the new engine will reduce overall costs due to increased efficiency, reduced down time, and reduced maintenance and repair costs.

Except in cases where an engine's usage factor is very low, the improved fuel efficiency associated with the use of turbochargers, superchargers, and aftercoolers generally results in a cost savings.

6. Exhaust Gas Recirculation

Applicability: Exhaust gas recirculation, or EGR, can be used on all engine types. It has been widely used on gasoline motor vehicle engines, but has been used infrequently on engines used in other applications.

Principle: EGR can be external or internal. In the case of external EGR, a portion of the exhaust gas is diverted from the exhaust manifold and routed to the intake manifold before reentering the combustion chamber. For internal EGR, an engine's operating parameters (such as valve timing or supercharger pressure) are adjusted so that a greater amount of exhaust remains in the cylinder after the exhaust stroke.

EGR reduces NOx emissions by decreasing peak combustion temperatures through two mechanisms: dilution and increased heat absorption. Dilution of the fuel/air mixture slows the combustion process, thereby reducing peak temperatures. In addition, exhaust gases contain significant amounts of carbon dioxide and water vapor, which have a higher heat capacity than air. This means that, compared to air, carbon dioxide and water vapor can absorb greater amounts of heat without increasing as much in temperature.

Typical Effectiveness: NOx reductions are limited to about 30 percent before operation of the engine is adversely affected.

Limitations: EGR will reduce an engine's peak power. This may be a serious problem for engines required to operate at or near their peak power rating. The EGR system must be designed and developed for each make and model of engine. An EGR retrofit kit is not available for most engines.

Other Effects: EGR reduces engine efficiency. For example, fuel efficiency decreases about 2 percent for a 12 percent decrease in NOx emissions.

Costs: Costs are typically greater than for timing retard, but less than a turbocharger retrofit.

7. Prestratified Charge

Applicability: This control technology is applicable to spark-ignited rich-burn engines. This method converts rich-burn engines into lean burn engines. It has been used on a number of different engines, but is not as widely used as some of the most popular controls, such as clean burn or NSCR catalysts.

Principle: Rich-burn engines are typically four stroke naturally aspirated engines with no intake/exhaust overlap. The major components of a prestratified charge (PSC) retrofit are the air injectors. These injectors pulse air into the intake manifold in such a fashion that layers or zones of air and the air/fuel mixture are introduced into the combustion chamber. Once inside the combustion chamber, the top zone, near the spark plug, contains a rich air/fuel mixture. The bottom zone is an air layer. The most recent version of the PSC system operates off of engine vacuum, which allows the system to automatically compensate for varying power outputs.

The PSC technique is very similar in concept to a precombustion chamber. Both have a rich fuel mixture near the spark plug, and a lean mixture elsewhere in the combustion chamber. NOx emissions are low for PSC for the same reasons they are low for prechamber designs.

Typical Effectiveness: PSC can achieve greater than 80 percent control of NOx for power outputs up to about 70 or 80 percent of the maximum (uncontrolled) power rating using air injection only.

Limitations: In order for the engine to generate more than 70 or 80 percent of the maximum (uncontrolled) power rating, the air injection rate must be reduced. This results in a richer fuel mixture, which increases NOx emissions. To maintain high NOx control at high power outputs, a turbocharger may have to be added or the existing turbocharger may have to be modified or replaced to increase air throughput. Maximum emission reductions, even with use of a turbocharger, are generally lower than can be accomplished with the use of an NSCR catalyst.

Other Effects: Fuel efficiency may be improved because PSC effectively converts a rich-burn engine into a lean-burn engine.

Costs: For engines in the 300 to 900 horsepower range, retrofit costs are typically about $30,000. For engines in the 1100 to 1600 horsepower range, retrofit costs are about $40,000. However, costs can double if a turbocharger is added. Retrofits for even larger engines where a turbocharger is added can cost as much as $160,000 to $190,000.

B. Fuel Switching

NOx emissions from IC engines can be reduced by switching to fuels that burn at lower temperatures, such as methanol.

1. <u>Methanol</u>

Applicability: This control method is applicable to all engine types. Although a number of motor vehicle engines have been converted to methanol fuel, very few stationary source engine conversions have taken place.

Principle: NOx emissions are generally lower for methanol than for other fuels for several reasons. Methanol has a higher heat of vaporization than other fuels, and thus the process of vaporization cools the air/fuel mixture significantly, resulting in lower peak temperatures. Methanol, being a partially oxygenated fuel, burns with a lower flame temperature, which also reduces peak temperatures. Methanol fuel consists of only one type of molecule, which makes it easier to optimize the combustion process in comparison to fuels consisting of a wide variety of molecules, such as gasoline or diesel. Methanol and natural gas combustion produces almost no particulate matter.

For rich-burn methanol engines, a relatively inexpensive three-way catalyst like that used in gasoline-engined motor vehicles can be installed to control NOx. Methanol can also be used as a fuel for lean-burn spark-ignited engines. Methanol has a wider range of flammability than many other fuels, allowing a leaner mixture to be used, resulting in greater NOx reductions than is possible with other fuels.

Methanol can be used as a replacement fuel for gaseous and gasoline fueled engines with only relatively minor engine modifications.

Typical Effectiveness: NOx reductions from the conversion of an engine to methanol fuel depend on the pre-conversion engine and fuel type. NOx reductions range from about 30 percent for the conversion of a natural gas engine. Reductions are even greater when the conversion is accompanied by the addition of a catalyst.

Limitations: A retrofit kit must be developed for each make and model of engine. Currently, there are very few conversion kits available. The fuel and engine system must use materials that are resistant to the corrosive action of methanol. Special lubricants must be used to avoid excessive engine wear. Incomplete combustion of methanol produces formaldehyde, but the use of an oxidation catalyst can reduce formaldehyde emissions to low levels.

Other Effects: None for SI engines.

Costs: Conversion costs for an automotive engine are on the order of $1,000. Costs for converting stationary gasoline engines to methanol are expected to be similar. The largest cost element is often is the fuel price differential between methanol and the fuel it replaces (e.g., natural gas or gasoline). Included in this price differential are transportation, storage, and refueling costs associated with the use of methanol.

C. Post Combustion Controls

Post combustion controls generally consist of catalysts or filters that act on the engine exhaust to reduce emissions. Post combustion controls also include the introduction of agents or other substances that act on the exhaust to reduce emissions, with or without the assistance of catalysts or filters.

1. <u>Oxidation Catalyst</u>

Applicability: This control method is applicable to all engines. For stationary engines, oxidation catalysts have been used primarily on lean-burn engines. Rich-burn engines tend to use 3-way catalysts, which combine nonselective catalytic reduction (NSCR) for NOx control and an oxidation catalyst for control of CO and VOC. The oxidation catalyst has been used on lean-burn engines for nearly 30 years. Oxidation catalysts are used less frequently on stationary engines. In the United States, only about 500 stationary lean-burn engines have been fitted with oxidation catalysts.

Principle: An oxidation catalyst contains materials (generally precious metals such as platinum or palladium) that promote oxidation reactions between oxygen, CO, and VOC to produce carbon dioxide and water vapor. These reactions occur when exhaust at the proper temperature and containing sufficient oxygen passes through the catalyst. Depending on the catalyst formulation, an oxidation catalyst may obtain reductions at temperatures as low as 300 or 400 ^{o}F, although minimum temperatures in the 600 to 700 ^{o}F range are generally required to achieve maximum reductions. The catalyst will maintain adequate performance at temperatures typically as high as 1350 ^{o}F before problems with physical degradation of the catalyst occur. In the case of rich-burn engines, where the exhaust does not contain enough oxygen to fully oxidize the CO and VOC in the exhaust, air can be injected into the exhaust upstream of the catalyst.

Typical Effectiveness: The effectiveness of an oxidation catalyst is a function of the exhaust temperature, oxygen content of the exhaust, amount of active material in the catalyst, exhaust flow rate through the catalyst, and other parameters. Catalysts can be designed to achieve almost any control efficiency desired. Reductions greater than 90 percent for both CO and VOC are typical. Reductions in VOC emissions can vary significantly and are a function of the fuel type and exhaust temperature.

Limitations: A sufficient amount of oxygen must be present in the exhaust for the catalyst to operate effectively. In addition, the effectiveness of an oxidation catalyst may be poor if the exhaust temperature is low, which is the case for an engine at idle. Oxidation catalysts, like other catalyst types, can be degraded by masking, thermal sintering, or chemical poisoning by sulfur or metals. If the engine is not in good condition, a complete engine overhaul may be needed to ensure proper catalyst performance.

Sulfur, which can be found in fuels and lubricating oils, is generally a temporary poison, and can be removed by operating the catalyst at a sufficiently high temperatures. However, high temperatures can damage the substrate material. Other ways of dealing with sulfur poisoning include the use of low sulfur fuels or scrubbing of the fuel to remove the sulfur. Besides being a catalyst poison, sulfur can also be converted into sulfates by the catalyst before passing through the exhaust pipe. Catalysts can be specially formulated to minimize this conversion, but these special formulations must operate over a relatively narrow temperature range if they are to effectively reduce VOC and CO and also suppress the formation of sulfates. For engines operated over wide power ranges, where exhaust temperatures vary greatly, special catalyst formulations are not effective.

Metal poisoning is generally more permanent, and can result from the metals present in either the fuel or lubricating oil. Specially formulated oils with low metals content are generally specified to minimize poisoning, along with good engine maintenance practices. Metal poisoning can be reversed in some cases with special procedures. Many catalysts are now formulated to resist poisoning.

Masking refers to the covering and plugging of a catalyst's active material by solid contaminants in the exhaust. Cleaning of the catalyst can remove these contaminants, which usually restores catalytic activity. Masking is generally limited to engines using landfill gas, diesel fuel, or heavy liquid fuels, although sulfate ash from lubricating oil may also cause masking. Masking can be minimized by passing the exhaust through a particulate control device, such as a filter or trap, before this material encounters the catalyst. In the case of landfill gas, the particulate control device can act directly on the fuel before introduction into the engine.

Thermal sintering is caused by excessive heat and is not reversible. However, it can be avoided by incorporating over temperature control in the catalyst system. Many manufacturers recommend the use of over temperature monitoring and control for their catalyst systems. In addition, stabilizers such as CeO_2 or La_2O_3 are often included in the catalyst formulation to minimize sintering. High temperature catalysts have been developed which can withstand temperatures exceeding 1800 ^oF for some applications. This temperature is well above the highest IC engine exhaust temperature that would ever be encountered. Depending on the design and operation, peak exhaust temperatures for IC engines range from 550 to 1300 ^oF.

Other recommendations to minimize catalyst problems include monitoring the pressure drop across the catalyst, the use of special lubricating oil to prevent poisoning, periodic washing of the catalyst, the monitoring of emissions, and the periodic laboratory analysis of a sample of catalyst material.

Other Effects: A catalyst will increase backpressure in the exhaust, resulting in a slight reduction in engine efficiency and maximum rated power. However, when conditions require an exhaust silencer, the catalyst can often be designed to do an acceptable job of noise suppression so that a separate muffler is not required. Under such circumstances, backpressure from the catalyst may not exceed that of a muffler, and no reduction in engine efficiency or power occur. Often, engine manufacturers rate their engines at a given backpressure, and as long as the catalyst does not exceed this backpressure, no reduction in the engine's maximum power rating will be experienced.

Costs: Typical costs for an oxidation catalyst are 10 to 12 dollars per horsepower, or slightly less than a nonselective catalytic reduction (NSCR) catalyst. The cost for catalyst wash service has been reported as $300 to $600 per cubic foot of catalyst material.

2. Nonselective Catalytic Reduction (NSCR)

Applicability: This control method is applicable to all rich-burn engines, and is probably the most popular control method for rich-burn engines. The first wide scale application of NSCR technology occurred in the mid- to late-1970s, when 3-way NSCR catalysts were applied to motor vehicles with gasoline engines. Since then, this control method has found widespread use on stationary engines. NSCR catalysts have been commercially available for stationary engines for over 15 years, and over 3,000 stationary engines in the U.S. are now equipped with NSCR controls. Improved NSCR catalysts, called 3-way catalysts because CO, VOC, and NOx are simultaneously controlled, have been commercially available for stationary engines for over 10 years. Over 1,000 stationary engines in the U.S. are now equipped with 3-way NSCR controls.

The dual bed NSCR catalyst is a variation of the 3-way catalyst. The dual bed contains a reducing bed to control NOx, followed by an oxidizing bed to control CO and VOC. Dual bed NSCR catalysts tend to be more effective than 3-way catalysts, but are also more expensive, and have not been applied to as many engines as 3-way catalysts. Improved 3-way catalysts can approach the control efficiencies of dual bed catalysts at a lower cost, and for this reason dual bed catalysts have lost popularity to 3-way catalysts.

Principle: The NSCR catalyst promotes the chemical reduction of NOx in the presence of CO and VOC to produce oxygen and nitrogen. The 3-way NSCR catalyst also contains materials that promote the oxidation of VOC and CO to form carbon dioxide and water vapor. To control NOx, CO, and VOC simultaneously, 3-way catalysts must operate in a narrow air/fuel ratio band (15.9 to 16.1 for natural gas-fired engines) that is close to stoichiometric. An electronic controller, which includes an oxygen sensor and feedback mechanism, is often necessary to maintain the air/fuel ratio in this narrow band. At this air/fuel ratio, the oxygen concentration in the exhaust is low, while concentrations of VOC and CO are not excessive.

For dual bed catalysts, the engine is run slightly richer than for a 3-way catalyst. The first catalyst bed in a dual bed system reduces NOx. The exhaust then passes into a region where air is injected before entering the second (oxidation) catalyst bed. NOx reduction is optimized in comparison to a 3-way catalyst due to the higher CO and VOC concentrations and lower oxygen concentrations present in the first (reduction) catalyst bed. In the second (oxidation) bed, CO and VOC reductions are optimized due to the relatively high oxygen concentration present. Although the air/fuel ratio is still critical in a dual bed catalyst, optimal NOx reductions are achievable without controlling the air/fuel ratio as closely as in a 3-way catalyst.

Typical Effectiveness: Removal efficiencies for a 3-way catalyst are greater than 90 percent for NOx, greater than 80 percent for CO, and greater than 50 percent for VOC. Greater efficiencies, below 10 parts per million NOx, are possible through use of an improved catalyst containing a greater concentration of active catalyst materials, use of a larger catalyst to increase residence time, or through use of a more precise air/fuel ratio controller.

For dual bed catalysts, reductions of 98 percent for both NOx and CO are typical.

The previously mentioned reduction efficiencies for catalysts are achievable as long as the exhaust gases are within the catalyst temperature window, which is typically 700 to 1200 ^{o}F. For many engines, this temperature requirement is met at all times except during startup and idling.

The percentage reductions are essentially independent of other controls that reduce the NOx concentration upstream of the catalyst. Thus, a combination of combustion modifications and catalyst can achieve even greater reductions.

Limitations: As with oxidation catalysts, NSCR catalysts are subject to masking, thermal sintering, and chemical poisoning. In addition, NSCR is not effective in reducing NOx if the CO and VOC concentrations are too low. NSCR is also not effective in reducing NOx if significant concentrations of oxygen are present. In this latter case, the CO and VOC in the exhaust will preferentially react with the oxygen instead of the NOx. For this reason, NSCR is an effective NOx control method only for rich-burn engines.

When applying NSCR to an engine, the sulfur content of the fuel gas must be limited to about 800 ppm by weight. The sulfur content of natural gas and LPG is well below 800 ppm, but some oil field gases and waste gases exceed this level. Sulfur tends to collect on the catalyst, which causes deactivation. This is generally not a permanent condition, and can be reversed by introducing higher temperature exhaust into the catalyst or simply by heating the catalyst. Even if deactivation is not a problem, the water content of the fuel gas must be limited when significant amounts of sulfur are present to avoid deterioration and degradation of the catalyst from sulfuric acid vapor.

For dual bed catalysts, engine efficiency suffers slightly compared to a 3-way catalyst due to the richer operation of engines using dual bed catalysts.

In cases where an engine operates at idle for extended periods or is cyclically operated, attaining and maintaining the proper temperature may be difficult. In such cases, the catalyst system can be designed to maintain the proper temperature, or the catalyst can use materials that achieve high efficiencies at lower temperatures. For some cyclically operated engines, these design changes may be as simple as thermally insulating the exhaust pipe and catalyst.

Most of these limitations can be eliminated or minimized by proper design and maintenance. For example, if the sulfur content of the fuel is excessive, the fuel can be scrubbed to remove the sulfur, or the catalyst design or engine operation can be modified to minimize the deactivation effects of the sulfur. Poisoning from components in the lube oil can be eliminated by using specially formulated lube oils that do not contain such components. However, NSCR applications on landfill gas and digester gas have generally not been successful due to catalyst poisoning and plugging from impurities in the fuel.

Other Effects: A very low oxygen content in the exhaust must be present for NSCR to perform effectively. To achieve this low oxygen content generally requires richening of the mixture. This richening tends to increase CO and VOC emissions. However, use of a 3-way catalyst can reduce CO and VOC emissions to levels well below those associated with uncontrolled engines.

Another effect of NSCR is increased fuel consumption. This increase is very slight when compared to an uncontrolled rich-burn engine. However, when compared to a lean-burn engine, a rich-burn engine uses 5 to 12 percent more fuel for the same power output. If a rich-burn engine uses a dual bed catalyst, a further slight increase in fuel consumption is generally experienced.

Costs: The total installed cost of an NSCR system on an existing engine varies with the size of the engine. The catalyst will cost about 8 to 15 dollars per horsepower, while air/fuel ratio controllers vary in cost from about $3,500 to $7,000. Installation and labor costs generally range from $1,000 to $3,000. For an 80 horsepower engine, total costs for installation may range from $5,000 to $11,000. For an 1,100 horsepower engine, installed costs of $20,000 to $25,000 are typical.

3. Hybrid System

Applicability: This control method can be applied to all engines. This control method was conceived by Radian Corporation, and has been developed by AlliedSignal and Beaird Industries. There has been one field prototype demonstration in San Diego, and it appears that the system has been offered commercially. However, there are no commercial applications of this technique.

Principle: The hybrid system is a modification of the dual bed NSCR system. The hybrid system adds a burner in the engine exhaust between the engine and the dual bed catalysts. The burner is operated with an excess amount of fuel so that oxygen within the engine exhaust is almost completely consumed, and large amounts of CO are generated. The exhaust then passes through a heat exchanger to reduce temperatures before continuing on to a reducing catalyst. The NOx reduction efficiency of the reducing catalyst is extremely high due to the high CO concentration (the CO acts as a reducing agent to convert NOx into nitrogen gas. The exhaust next passes through another heat exchanger, and air is added before the exhaust passes through an oxidation catalyst. The oxidation catalyst is extremely efficient in reducing CO and VOC emissions due to the excess oxygen in the exhaust.

Typical Effectiveness: NOx concentrations as low as 3 to 4 ppm are achievable with this system. Concentrations of CO and VOC are typical of systems using oxidation catalysts.

Limitations: When the oxygen content of the engine's exhaust is high, such as for lean-burn engines, the burner must use a large amount of fuel to consume nearly all the oxygen and generate sufficient amounts of CO. Therefore, use of this method on lean-burn engines is only practical in cogeneration applications, where heat generated by the burner can be recovered and converted to useful energy.

Other Effects: For rich-burn engines, this method has a fuel penalty of about one to five percent. However, for lean-burn engines, the fuel penalty could be equal to the uncontrolled engine's fuel consumption.

Costs: Costs are several times greater than for a simple NSCR catalyst. Capital costs were reported in 1993 as $150,000 for a 470 brake horsepower engine.

4. <u>Selective Catalytic Reduction (SCR)</u>

Applicability: This method was patented in the U.S. in the 1950s, and there have been over 700 applications of SCR to combustion devices worldwide. Some of these applications include stationary IC engines. However, most of these applications are external combustion devices such as boilers. SCR systems for IC engines have been commercially available for a number of years, but there have only been a few dozen SCR retrofits of IC engines. SCR is applicable to all lean-burn engines, including diesel engines.

Principle: The exhaust of lean-burn engines contains high levels of oxygen and relatively low levels of VOC and CO, which would make an NSCR type of catalyst ineffective at reducing NOx. However, an SCR catalyst can be highly effective under these conditions. Oxygen is a necessary ingredient in the SCR NOx reduction equation, and SCR performs best when the oxygen level in the exhaust exceeds 2 to 3 percent.

Differing catalyst materials can be used in an SCR catalyst, depending on the exhaust gas temperature. Base metal catalysts are most effective at exhaust temperatures between 500 and 900 ^{o}F. Base metal catalysts generally contain titanium dioxide and vanadium pentoxide, although other metals such as tungsten or molybdenum are sometimes used. Zeolite catalysts are most effective at temperatures between 675 to over 1100 ^{o}F. Precious metal catalysts such as platinum and palladium are most effective at temperatures between 350 and 550 ^{o}F.

In SCR, ammonia (or, in some cases, urea) is injected in the exhaust upstream of the catalyst. The catalyst promotes the reaction of ammonia with NOx and oxygen in the exhaust, converting the reactants to water vapor and nitrogen gas. Ammonia injection can be controlled by the use of a NOx monitor in the exhaust downstream of the catalyst. A feedback loop from the monitor to the ammonia injector controls the amount injected, so that NOx reductions are maximized while emissions of ammonia are minimized. To eliminate the use of a costly NOx monitor, some applications use an alternative system that measures several engine parameters. Values for these parameters are then electronically converted into estimated NOx concentrations.

Typical Effectiveness: The NOx removal efficiency of SCR is typically above 80 percent when within the catalyst temperature window.

Limitations: SCR can only be used on lean burn engines. Relatively high capital costs make this method too expensive for smaller or infrequently operated engines.

Some SCR catalysts are susceptible to poisoning from metals or silicon oxides that may be found in the fuel or lubricating oil. Poisoning problems can be minimized by using specially formulated lubricating oils that do not contain the problem metals, the use of fuels with low metals or silicon oxides content, or the use of zeolite catalysts which are not as susceptible to poisoning.

If platinum or palladium is used as an active catalyst material, the sulfur content of the exhaust must be minimized to avoid poisoning of the catalyst. In addition, for all types of SCR catalysts, high sulfur fuels will result in high sulfur oxides in the exhaust. These sulfur compounds will react with the ammonia in the exhaust to form particulate matter that will either mask the catalyst or be released into the atmosphere. These problems can be minimized by using low sulfur fuel, a metal-based SCR system specially designed to minimize formation of these particulate matter compounds, or a zeolite catalyst.

Ammonia gas has an objectionable odor, is considered an air pollutant at low concentrations, becomes a health hazard at higher concentrations, and is explosive at still higher concentrations. Safety hazards can occur if the ammonia is spilled or there are leaks from ammonia storage vessels. These safety hazards can be minimized by taking proper safety precautions in the design, operation, and maintenance of the SCR system. Safety hazards can be substantially reduced by using aqueous ammonia or urea instead of anhydrous ammonia. If a concentrated aqueous solution of urea is used, the urea tank must be heated to avoid recrystallization of the urea. In addition, if too much ammonia is injected into the exhaust, excessive ammonia emissions may result. These emissions can be reduced to acceptable levels by monitoring and controlling the amount of ammonia injected into the exhaust.

SCR may also result in a slight increase in fuel consumption if the backpressure generated by the catalyst exceeds manufacturer's limits.

Other Effects: None known.

Costs: SCR is one of the higher cost control methods due to the capital cost for the catalyst, the added cost and complexity of using ammonia, and the instrumentation and controls needed to carefully monitor NOx emissions and meter the proper amount of ammonia. Estimated costs, however have been declining over the past several years. Currently, costs are estimated to be about $50 to $125 per horsepower.

Engines operated at a constant load may be able to eliminate the NOx monitor and feedback ammonia metering system. In such cases, proper instrumentation must be used to monitor ammonia and NOx when the SCR system is set up. Frequent checks are also needed to assure that the setup does not change. Such a system was purchased in 1996 for a 1,300 horsepower diesel engine at a cost of approximately $100,000.

5. Lean NOx Catalyst

Applicability: This control method can be used on any lean-burn engine, although development work has concentrated on diesel engines. This control method is still in the development stage and is not commercially available, but may be available in a few years.

Principle: A number of catalyst materials can be used in the formulation of lean NOx catalysts. The constituents are generally proprietary. NOx reductions are generally minimal unless a reducing agent (typically raw fuel) is injected upstream of the catalyst to increase catalyst performance to acceptable levels. Depending on the catalyst formulation, this method can reduce NOx, CO, and VOC simultaneously.

Typical Effectiveness: Claims for NOx control efficiencies have ranged from 25 to 50 percent. Steady state testing on a diesel-fueled engine yielded NOx reductions of 17 to 44 percent.

Limitations: Use of a reducing agent increases costs, complexity, and fuel consumption. The reducing agent injection system must be carefully designed to minimize excess injection rates. Otherwise, emissions of VOC and particulate matter can increase to unacceptable levels. Tests have shown that lean NOx catalysts produce significant amounts of nitrous oxide (N_2O), and that this production increases with increasing NOx reduction efficiencies and reducing agent usage. This method is not commercially available, and is still in the development and demonstration stage.

Other Effects: None known.

Costs: Since no systems have been sold commercially, costs are unknown, but would probably exceed those for NSCR.

6. NOxTech

Applicability: This control method, formerly known as RAPRENOX, is applicable to lean-burn engines. This technology can be applied to lean-burn gaseous fueled engines. However, this technology is relatively new, and there have only been a few commercial applications.

Principle: NOxTech uses a gaseous phase autocatalysis process to reduce NOx and other pollutants. There is no catalyst. In this method a reagent and fuel are injected into a reactor vessel with the exhaust stream of the engine. The fuel combusts and increases the exhaust temperature to a range of 1,400 to 1,550 ^oF, where reactions between nitric oxide (NO) and the reagent generate N_2, CO_2, and H_2O. The reactor vessel is a large chamber which increases the residence time of the constituent gases at high temperature. In the past, cyanuric acid has been the reagent. More recent literature indicates that either urea or ammonia is used.

Typical Effectiveness: NOx emission reductions of 80 to 90 percent are typical, and the system can be designed to reduce NOx by well over 90 percent. This control method also removes 80 percent or more of CO, VOCs, and PM as well with minimal reagent slip.

Limitations: With a recovery heat exchanger in the reactor, the fuel penalty is about 5 to 10 percent. There are versions which do not have the heat exchanger. In these versions, significant amounts of fuel are used to heat the exhaust. Although this technology may be economically attractive for cogeneration applications where the energy used to heat the exhaust is recovered, the economics are less favorable for applications where the exhaust heat is not recovered. This technology may not be economically attractive when an engine's power output remains below 50 percent of full power. At low power outputs, exhaust temperatures are low, and greater amounts of fuel must be used to achieve the required exhaust temperature. The size of the reaction chamber may make applications difficult where there is a lack of room.

Other Effects: None known.

Costs: In general, the capital costs for this system are much lower than SCR, but operating costs are significantly higher. Start-up costs are estimated to be in the range of $100 to $200 per kilowatt.

7. Urea Injection

Applicability: This control method is applicable to all lean-burn engines and is also known as selective noncatalytic reduction. It has been used on several boilers to control NOx, but there have been no applications to internal combustion engines.

Principle: Urea injection is very similar to cyanuric acid injection, as both chemicals come in powder form, and both break down at similar temperatures to form compounds which react with nitric oxide. Differences are that a high temperature heating system is not required for urea injection. Instead, the urea is usually dissolved in water, and this solution is injected into the exhaust stream.

Typical Effectiveness: Unknown.

Limitations: The temperature window for urea is higher than the highest exhaust temperature of nearly all engines. Therefore, due to cost-effectiveness considerations, practical applications of urea injection are limited to engines in cogeneration applications. Specifically, these applications are limited to situations where supplemental firing is applied to the engine's exhaust to increase its temperature, and the exhaust heat is recovered and used.

Other Effects: Unknown.

Costs: Unknown.

8. NOx Adsorber Technology (SCONOx)

Applicability: This NOx control method is applicable to diesel-fueled and lean burn engines and is just entering the commercialization phase. It has been installed on gas turbines, boilers, and steam generators previously. The first U.S. application of NOx adsorber technology on a mobile source is the Honda Insight which is a hybrid vehicle. Multiple companies and organizations are engaged in the development of the NOx adsorber technology. This discussion will focus on SCONOx.

Principle: This system uses a single catalyst for the removal of NOx, VOC, and CO emissions. This is a three step process in which initially the catalyst simultaneously oxidizes NO, hydrocarbon, and CO emissions. In the second phase, NO_2 is absorbed into the catalyst surface through the use of a potassium carbonate coating. Unlike SCR, this technology does not require a reagent such as ammonia or urea in reducing emissions. Finally, the catalyst undergoes regeneration periodically to maintain maximum NOx absorption. The SCONOx system requires natural gas, water, and electricity and operates at temperatures ranging from 300° to 700° F.

The catalyst is regenerated by passing a dilute hydrogen reducing gas across its surface in the absence of oxygen. The gases react with the potassium nitrites and nitrates to form potassium carbonate which is the absorber coating on the surface of the catalyst. The exhaust from the regeneration process is nitrogen and steam. This catalyst has multiple sections of catalyst. At any given time, a certain percentage of the sections are in the oxidation/absorption cycle while the remaining catalyst sections are being regenerated. In IC engine applications, one regeneration approach has been to de-sorb the adsorber by running the engine in a fuel rich mode and passing the exhaust through a three way catalyst to reduce the NOx.

Typical Effectiveness: Since this technology is just entering commercialization data is very limited. Feasibility testing conducted by the manufacturer on a diesel engine rated less than 100 horsepower indicated that NOx reductions greater than 90 percent can be achieved. The manufacturer intends to conduct further testing on a demonstration basis. As part of its demonstration for California Environmental Technology Certification, this technology had NOx emissions of 2 ppmv (approximately 98.6 control) on a natural gas-fired gas turbine.

Limitations: The system is sensitive to trace amounts of sulfur in the exhaust. In certifying this technology with a gas turbine, it has been reported that the system achieves it lowest NOx levels by adding a sulfur scrubber to the natural gas fuel. From this statement, it would seem logical that the use of low sulfur diesel fuel would be recommended on IC engines.

Other Effects: Since a reagent is not required as with SCR, there will be no emissions of ammonia which is a toxic compound which can cause health effects. The catalyst is regenerated using hydrogen gas which is generated onsite through the use of a reformer. Hydrogen is flammable and could be a potential safety hazard.

Costs: At this stage of development/commercialization, the cost for a single prototype is estimated to be about $100,000. It is expected that mass production would drop prices substantially.

D. Replacement

Another method of reducing NOx is to replace the existing IC engine with an electric motor, or a new engine designed to emit very low NOx emissions. In some instances, the existing engine may be integral with a compressor or other gear, and replacement of the engine will require the replacement or modification of this other equipment as well.

Applicability: This control method is applicable to all engines.

Principle: Rather than applying controls to the existing engine, it is removed and replaced with either a new, low emissions engine or an electric motor.

Typical Effectiveness: New, low emissions engines can reduce NOx by a substantial amount over older, uncontrolled engines. Potential NOx reductions of over 60 percent can be realized by replacing existing SI engines with new certified low emission engines fueled by natural gas or propane.

Another approach is to replace an engine with an electric motor. An electric motor essentially eliminates NOx emissions associated with the removed engine, although there may be minor increases in power plant emissions to supply electricity to the electric motor.

Limitations: In remote locations or where electrical infrastructure is inadequate, the costs of electrical power transportation and conditioning may be excessive. Similarly, the cost of replacing an engine with a natural gas fired unit could be prohibitive if a natural gas pipeline is not in reasonably close proximity to the engine. In cases where the existing engine operates equipment integral to the engines (such as some engine/compressors that share a common crankshaft), both the engine and integral equipment often must be replaced.

Certified Engines: Another issue to consider is associated with new engines certified to an on road or off road emission standard. A certified engine's NOx emission units is given in g/bhp-hr and is an average of the NOx concentrations measured under different operating conditions of a given test cycle. So the certified engine's NOx emissions could be higher or lower than its certification value depending on the operating mode under which the engine is being tested. In addition, on road test cycles are typically transient in nature which matches the duty cycle of a mobile source whereas an off road cycle is steady state in nature. There is the possibility that the emissions measured using ARB Test Method 100 or U.S. EPA Test Method 7E on a certified engine in a stationary application may not match the engine's NOx certification numbers due to the differences between test cycles and the engine's operational duty cycle.

Other Effects: None known.

Costs: Costs of engine replacement with an electric motor or new low emissions engine are highly variable, and depend on the size of the engine, the cost of electricity, electrical power availability, accessibility of natural gas pipelines, useful remaining life for the existing engine, and other factors.