Draft
Technical Information
Oil and Gas Sector
Significant Stationary Sources of NOx Emissions

Contents

1.0 Introduction

The oil and gas exploration and production sector is a large, complex industry with a diverse array of equipment and many sources of NOx emissions. Larger sources within the sector, such as refineries and natural gas processing facilities, are reasonably well documented and are generally treated as point sources with the appropriate applicable NOx emissions limitations. However, the oil and gas sector includes many smaller, diffuse NOx emission sources that support the equipment used for the exploration for oil and gas and the subsequent transport of the oil and gas from the source in the ground to the marketplace. Many of these NOx emission sources are well distributed throughout the country, including those used to support oil or gas pipeline transportation. However, in areas were there are concentrations of oil or gas in underground reservoirs, there tends to also be a concentration of drilling operations, pumps, compressors, etc that collectively emit significant levels of NOx emissions and greatly impact air quality. These relatively small, diffuse oil and gas industry NOx emissions sources are the subject of this review.

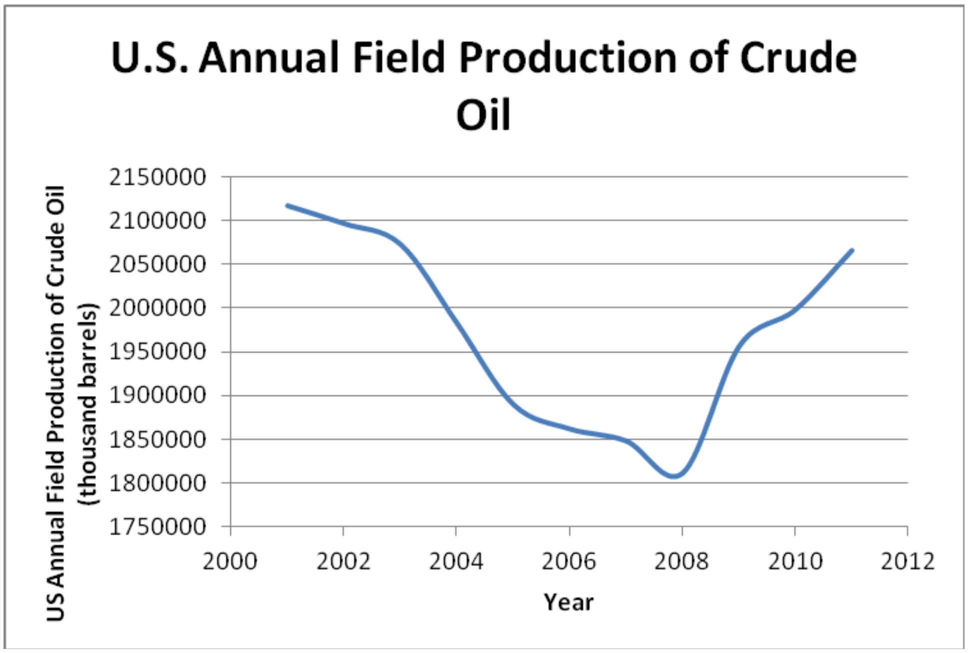
Equipment within the oil and gas sectors can result in the production of significant NOx emissions that contribute to air quality problems locally and in downwind states. While much of the equipment, such as drilling rigs and well pumps and compressors, are concentrated in areas with abundant in-situ supply of oil and/or natural gas, other sources such as refineries, gas processing plants, fuel-fired pipeline gas compressors and pipeline oil pumps are located throughout the country. This equipment operates in a wide variety of modes, with some only operating during initial phases of extracting the product from the ground, some operating almost continuously as long as the source well is productive, and some operating in a variable capacity to meet the demand for the product.

This review attempted to assemble relevant information and technical documentation regarding the combustion devices utilized in the gas and oil sector in the Northeast and Mid-Atlantic states, excluding those sources located in refineries and gas processing facilities, and to present relevant information regarding the possibility of achieving NOx reductions from those sources. The twelve states and District of Columbia that constitute the Ozone Transport Commission (OTC) are developing this document to understand the potential for reductions in emissions of nitrogen oxides (NOx) that may be available from the oil and gas sector. Reductions in NOx emissions are important to assist the OTC states to attain and maintain the ozone national ambient air quality standards.

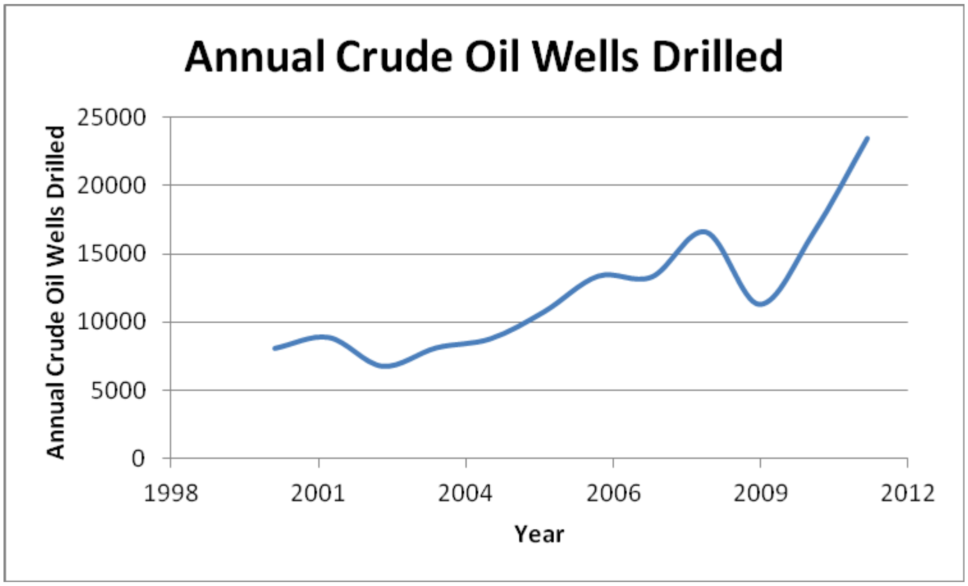
The production and consumption of natural gas have both increased dramatically in recent years, and the rate of both natural gas production and natural gas consumption is projected to continue to increase. As a result, many new sources of NOx emissions have been added to the existing inventory within the OTR (as well as surrounding states), primarily in Pennsylvania and New York. While many of these engines are small, the emissions from these small sources as a group may become an air quality problem if the existing and new equipment is not properly controlled. This document addresses the equipment used in drilling of exploratory wells and production wells for crude oil and natural gas, pumps and compressors to take the product from the well heads to the gathering system, oil and gas heaters near the well head, and pipeline pumps and compressors to transport the product to processing facilities, storage facilities, and to distribution systems. Emissions and emissions controls from the equipment are summarized. The document also provides a sample of state and federal air quality laws and regulations that apply to the oil and natural gas sector.

2.0 US Annual Crude Oil and Natural Gas Production

Crude oil production in the lower 48 states has been in a general decline for a long period of time, including a portion of the last decade. However, the crude oil production has demonstrated an increase in the last few years. In the lower 48 states, the states of Texas, California, and North Dakota have been the largest crude oil producers. Within the Ozone Transport Region (OTR), the states of Pennsylvania and New York are crude oil producers. The following graph shows the US crude oil production over the last decade:

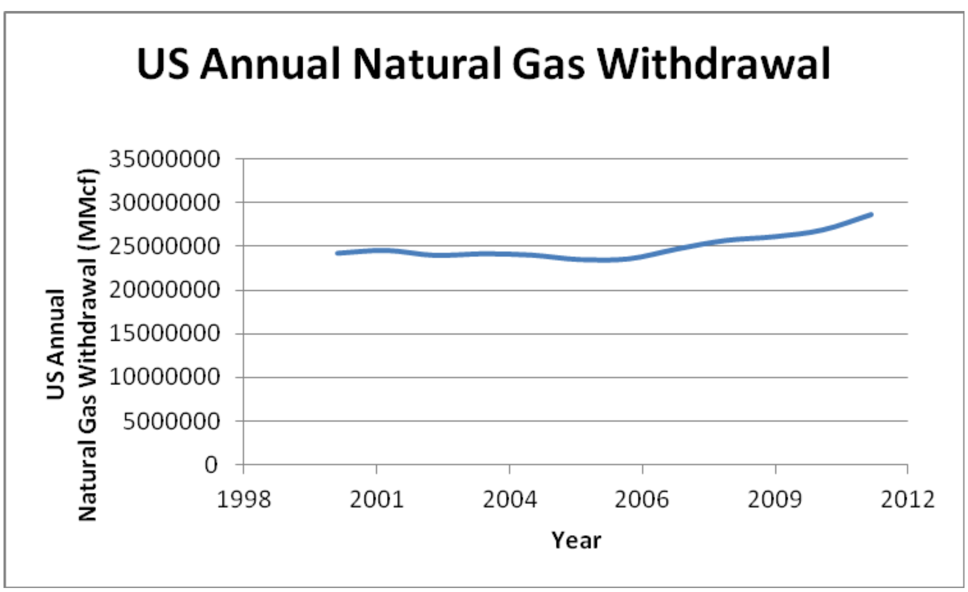


In order to maintain and increase the crude oil production across the US, new crude oil wells have been, and continue to be, drilled in many locations throughout the US. The following graph shows the general increase in crude oil well drilling over the last decade:

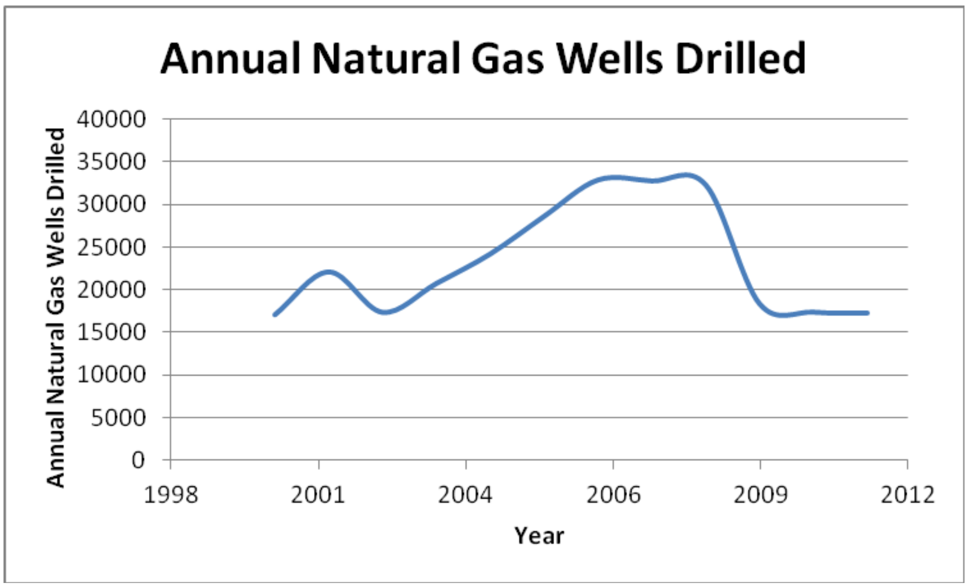


Based on the available data, the U.S. Department of Energy's Energy Information Agency (EIA) noted that in 2009 there were in excess of 960,000 producing oil wells in the US.

Natural gas is produced in 30 of the lower 48 states. Within the OTR, the states of Pennsylvania, New York, and Maryland produce natural gas. Natural gas production has shown an overall increase over the last decade, with an accelerated rate of increase in the last few years. It is interesting to note that during the last few years gas production from conventional (wells drilled vertically into conventional geologic al formations) gas wells and oil wells has actually decreased. However, that reduction in natural gas production from conventional gas wells and oil wells has been compensated for and surpassed by gas production from shale gas wells and coal bed methane wells. Annual US natural gas production for the last decade is shown in the following graph:

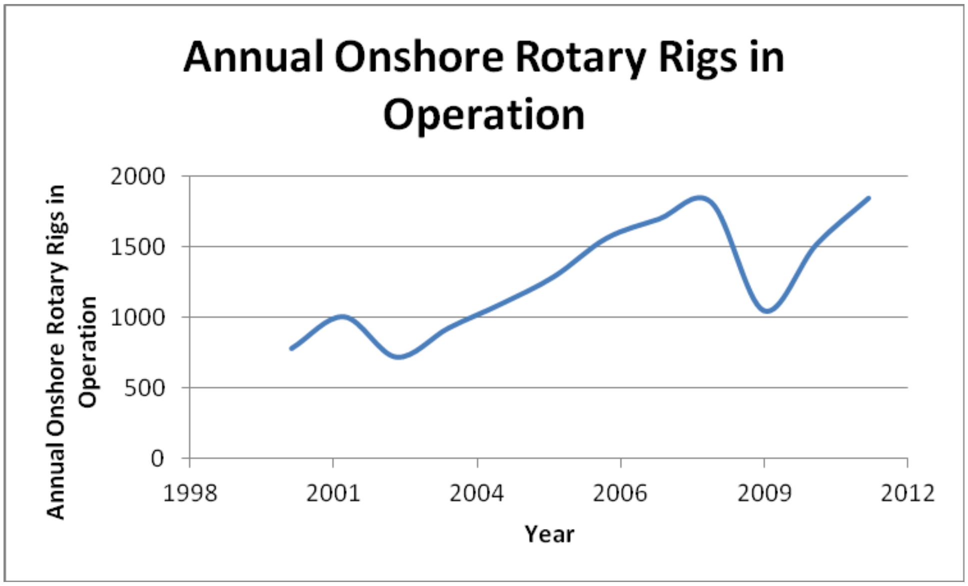


As shown in the following graph, the annual number of natural gas wells being drilled has decreased in the last few years. However, the graph also shows that a significant number of new natural gas wells are continuing to be drilled on an annual basis. While it may seem strange that the natural gas withdrawal has increased but the rate of well drilling has decreased, it should be noted that much of the increase in natural gas production is from shale gas and coal bed methane wells. Shale gas wells and coal bed methane wells are typically deeper and/or longer than conventional gas wells, requiring longer drilling periods, and have, to date, been highly productive.

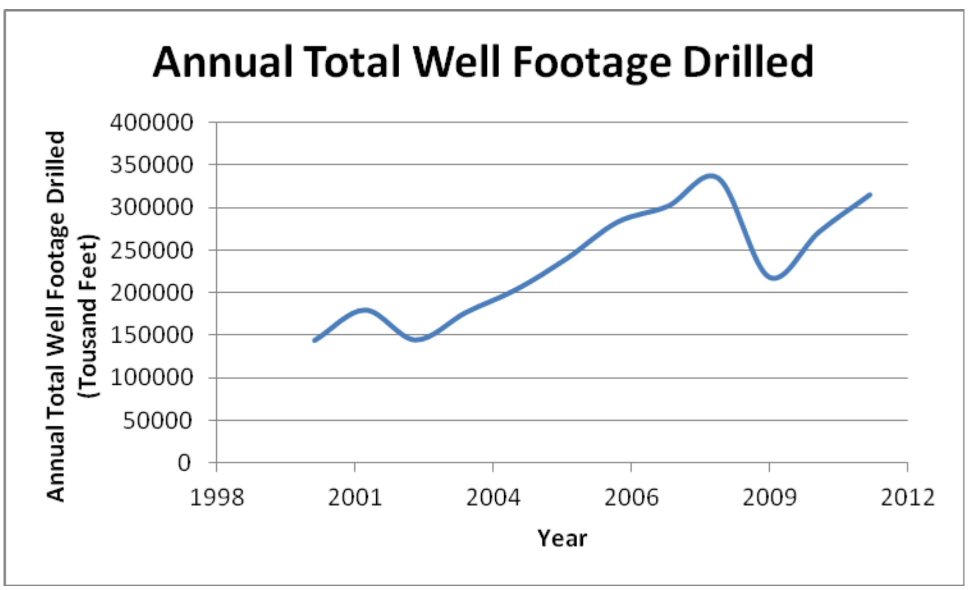


Based on the available data, the EIA noted that in 2009 there were in excess of 1,097,000 producing gas wells in the US.

The combination of increased demand for crude oil and natural gas has caused a general increase in drilling operations. As shown in the following graph, the annual number of well drilling rigs in on-shore operation has generally increased over the last decade.



As would be expected, the general increase in the annual number of well drilling rigs in operation is accompanied by a general increase in the annual total well footage drilled. The following graph shows the total annual well footage drilled over the last decade:



3.0 Oil and Gas Sector NOx Emissions Sources

Within the oil and gas sector, there are many significant NOx emitting sources. Excluding NOx emissions from sources at refineries and gas processing facilities, oil and gas sector NOx emissions sources include the following:

- Diesel and spark ignition reciprocating engines in drilling rig operations (gas and oil sectors).
- Diesel reciprocating engines, spark ignition reciprocating engines, and combustion turbines driving electric generators for power in remote locations and for supporting operation of electric motors (gas and oil sectors).
- Diesel and spark ignition reciprocating engines engine driving hydraulic fracturing pumps, recovery pumps, and water recirculating pumps (oil and gas sectors).
- Gas heating units in well fields working with “wet” gas.
- Oil well heating units.
- Diesel reciprocating engines, spark ignition reciprocating engines, and combustion turbines for well field gas compressors, gas field gathering compressors, and gas pipeline compressors
- Diesel reciprocating engines, spark ignition reciprocating engines, and combustion turbines for wellhead oil pumps, oil field gathering pumps, and oil transportation pipeline pumps.
- Well flairs (oil and gas sectors)

These NOx emissions sources are discussed further below.

3.1 Well Drilling and Completion

A well is created by drilling a hole (diameter dependent upon product and expected flow rate) into the earth with a drilling rig that rotates a drill pipe with a drill bit attached. This drilling process is facilitated by the use of a drill rig which contains all the necessary equipment to pump and circulate the drilling fluid, hoist and turn the drill pipe, control down-hole movement, remove cuttings from the drilling fluid, and generate on-site power for these operations.

After drilling and casing the well, it must be 'completed'. Completion is the process in which the well is enabled to produce oil or gas. Often well completion is performed utilizing a specialized rig or platform, enabling the drilling rig to be moved to a new location to drill another well. Well completion may include preparing the last section of the pipe casing in the reservoir to create a flow path from the reservoir into the piping. After a flow path is made, acids and fracturing fluids may be pumped into the well to fracture, clean, or otherwise prepare and stimulate the reservoir rock to optimally produce hydrocarbons into the wellbore.

In some wells, the natural pressure of the subsurface reservoir is high enough for the oil or gas to flow to the surface. However, this is not always the case, especially in depleted fields where the pressures have been lowered by other producing wells, or in low permeability oil reservoirs. Installing smaller diameter tubing may be enough to help the production, but artificial lift methods, such as downhole pumps or surface pumps or compressors, may also be needed. Many new systems have been introduced for improving well completion in recent years that have cut completion costs and improved production, especially in the case of horizontal wells. Some of these well completion activities have also reduced the amount of gas that is flared by capturing the gas that might otherwise have been flared off and treating and utilizing it as a product.

Sources of NOx emissions from the drilling and completion processes include, but are not limited to, engines driving electric generators that provide electric power supporting the drilling process, engines used to directly power the drilling drive and related pumps and compressors, and flaring of relatively small amount of natural gas as part of well completion. The majority of the engines utilized in this service are diesel reciprocating engines.

Shell operates drilling rigs to support their oil and natural gas development activities. In a presentation, Shell indicated that they have installed SCR on diesel engines that they utilize in drilling rig operations. They indicated that they had been able to achieve greater than 90% reduction in NOx emissions while encountering minimal operational issues.

EIA data indicates that in 2011 there were 1844 on-shore oil and gas drilling rigs in operation in the US, an increase of 330 over 2010 and an increase of 798 over 2009.

EIA data also indicates that there were a combined total of 45,529 oil and gas exploratory and development wells drilled in 2010, an increase of 7,207 wells from those drilled in 2010 and an increase of 12,390 wells from those drilled in 2009. The data indicates that a combined 314,840 thousand feet were drilled in 2011, compared to 271,912 thousand combined feet drilled in 2010 and 218,693 thousand combined feet drilled in 2009.

Because of an overall lack of comprehensive emissions data for NOx sources in the oil and gas sector, and variability due to equipment and site specifics (material being drilled through, well depth, etc), it is difficult to estimate the magnitude of those NOx emissions from well drilling and well completion activities. Some related NOx emissions information was found in a report from the Western Region Air Partnership (WRAP), "An Emissions Inventory of Non-point Oil and Gas Emissions Sources in the Western Region" (presented at the 15th Emission Inventory Conference, New Orleans, May 2006). This report specifically addressed regional emissions from the gas industry, and investigated regional data to estimate NOx emissions factors primarily for natural gas industry operations, with some additional effort to assess oil and methane bed NOx emission factors. The regional data presented in the report indicated a relatively wide range in estimated emission factors, likely due to the site and equipment variability. While the NOx emissions factors presented in the report are based on region specific data, they appear to be realistic values that may be useful in estimating NOx emissions from similar equipment when site or region specific data is not available for other locations. The emissions factors presented in the WRAP report were as follows:

- Drilling: Range of 2.26 tons NOx/well to 9.78 tons NOx/well
- Well Completion: Range of 0.85 tons NOx/well to 1.5 tons NOx/well

Utilizing the above per well NOx emission rates, the additional of 45,529 oil and gas wells is estimated to have resulted in a range of 2011 NOx mass emissions of from 141,596 tons to 513,567 tons (drilling and completion related activities only). (To get some perspective on the magnitude of this value, the NOx emissions represented by the upper end value of the range is larger than the combined 70 highest NOx mass emitting coal-fired electric generating units in the year 2011.)

An emissions inventory of oil and gas sector emissions for 2005 in Texas indicated that oil and gas drilling operations accounted for approximately 56.4% of the onshore oil and gas sector NOx emissions. In that same 2005 Texas emissions inventory, oil and gas well completions accounted for approximately 0.2% of the total oil and gas sector NOx emissions.

A more detailed discussion of the engines used to support well drilling and completion activities, and control of NOx emissions from those engines, is provided in later sections of this document.

3.2 Oil Well Pumps

Pumps are often required to raise oil in an oil well from the oil's underground location to the surface. There are several types of pumping devices that are used to provide artificial lift in an oil field. These include: mechanical lift powered by a motor or engine on the surface; hydraulic lift, where oil or water is pumped down into the well to operate a hydraulic pump; electric submersible pump, where a electric motor driven pump at the bottom of the well is driven is supplied electricity from the surface; and gas lift, where natural gas injected into the piping at intervals lightens the weight of the fluid, helping it rise to the surface. All four of these systems offer advantages and disadvantages for specific situations. Mechanical lift is one of the more commonly used oil well pumping devices.

When located near sources of grid supplied electric power, the oil pumps are generally powered by electric motors. In some more remote areas, the oil pumps may still be powered by electric motors, but utilize electricity generated locally using natural gas engine or diesel engine powered electric generators. In other instances, the oil pumps may be driven directly by natural gas fueled engines or diesel engines. The required output rating of the engines would vary depending on the depth of the well, pumping capacity, etc. However, these engines tend to have a relatively small output rating, generally less than 200 hp.

Once the oil is extracted from the well, it is pumped to a storage tank(s) that may be common to multiple supply wells. The oil is then typically transported from the storage tank by truck or pumped out through a pipeline.

Little data was located that could be used to estimate the NOx emissions from oil well pumps. Documentation of previous estimation efforts were equally absent in the data searches. Variables such as well depth and type of prime mover (reciprocating engine, combustion turbine, electric motor) make it very difficult to make any sort of reasonable estimate of the NOx emissions without some detailed inventory and operational information. Because of the lack of data and/or guidance information, no estimates were made of the potential NOx emissions from oil well pumping activities. However, the NOx emissions from engines used to power the oil pumps are generically addressed in later sections of this document.

3.3 Oil Pipeline Pumps

Crude oil is often transported from field gathering locations to downstream locations through pipelines. Industry data indicated that in 2008, pipelines accounted for 71% of all petroleum transportation, up from 67% in 2007. The data indicates that it is estimated that in the US there is in excess of 55,000 miles of crude oil trunk lines connecting regional markets, and estimated that there is from 30,000 miles to 40,000 miles of small crude oil gathering pipelines. Pipelines are also utilized for transportation of refined petroleum products, and industry data estimates indicate that there are approximately 95,000 miles of refined products pipelines in the US.

Pumps are generally required to pump the oil through the pipelines, with pumps generally located at the originating field gathering location and at 20 to 100 mile intervals along the pipeline, depending upon pipeline design, pipeline path geography, and flow requirements. These oil pumps are often driven by electric motors, but some may utilize diesel engines, natural gas fueled reciprocating engines, or combustion turbines to power the pumps when warranted. Little data could be found documenting the size and makeup of the population of oil pipeline pump prime movers.

Little data was located that could be used to estimate the NOx emissions from oil pipeline pumps. Documentation of previous estimation efforts were equally absent in the data searches. Because of the lack of data and/or guidance information, no estimates were made of the potential NOx emissions from oil pipeline pumping activities. However, the NOx emissions from engines used to power the oil pumps are generically addressed in later sections of this document.

3.4 Coal Bed Methane Pumps

In order to facilitate gas extraction from coal bed methane wells, it is often necessary to pump out large amounts of water to reduce the pressure in the coal bed and thereby facilitate methane desorption from the coal. Desorption from the coal allows the methane to be extracted and transported to gathering pipelines. Industry information indicates that the water pumping may occur throughout the useful life of the coal bed methane well, but will tend to experience a reduction with "age" of the well or well field. Coal bed methane pumps are sometime powered by electric motors, but are typically powered by diesel engines or spark ignited reciprocating engines.

Because of an overall lack of comprehensive emissions data for NOx sources in the oil and gas sector, and variability due to equipment and site specifics, it is difficult to estimate the magnitude of NOx emissions from coal bed methane pumping. Some related NOx emissions information was found in a report from the Western Region Air Partnership (WRAP), "An Emissions Inventory of Non-point Oil and Gas Emissions Sources in the Western Region" (presented at the 15th Emission Inventory Conference, New Orleans, May 2006). This report specifically addressed regional emissions from the gas industry, and investigated regional data to estimate NOx emissions factors that included coal bed methane pumping NOx emission factors. The regional data presented in the report indicated a relatively wide range in estimated emission factors, likely due to the site and equipment variability. While the NOx emissions factors presented in the report are based on region specific data, they appear to be realistic values that may be useful in estimating NOx emissions from similar equipment when site or region specific data is not available for other locations. The emissions factors presented in the WRAP report for coal bed methane pumps ranged from 0.06 ton/year/well to 0.60 ton/year/well.

NOx emissions from engines used to power the coal bed methane pumps are generically addressed in later sections of this document.

3.5 Oil Well Heaters

Some oil wells require heating of the crude oil, as the crude oil reaching the surface of a well may contain varying amounts of impurities. The well heaters are used to heat crude oil to separate water, solids such as paraffin, and natural gas from the crude oil. Heat from combustion in the heater's firebox heats the crude oil and helps water droplets and solids settle out so that they can be drained out of the bottom of the heater. The heating of the crude oil also facilitates the separation of natural gas from the crude oil, allowing the gas to rise and be piped off from the top of the heater. The oil is then drawn off for pumping to a pipeline or storage tanks.

Because of an overall lack of comprehensive emissions data for NOx sources in the oil and gas sector, and variability due to equipment and site specifics, it is difficult to estimate the magnitude of NOx emissions from oil well heaters. Some related NOx emissions information was found in a report from the Western Region Air Partnership (WRAP), "An Emissions Inventory of Non-point Oil and Gas Emissions Sources in the Western Region" (presented at the 15th Emission Inventory Conference, New Orleans, May 2006). This report specifically addressed regional emissions from the oil and gas industry, and investigated regional data to estimate NOx emissions factors that included oil well heater NOx emission factors. While the NOx emissions factors presented in the report are based on region specific data, they appear to be realistic values that may be useful in estimating NOx emissions from similar equipment when site or region specific data is not available for other locations. The average NOx emissions factor presented in the WRAP report for oil well heaters is 0.005 lb NOx/barrel produced.

Because of the small size of most oil well heater burners, there may be few commercially available combustion or post-combustion technologies commercially available for NOx reduction.

3.6 Gas Well Heaters

Due to varying amounts of condensates and moisture in the gas coming to the surface, some natural gas wells require treatment near the well head. Heating is often part of this "cleanup" process, generally utilizing natural gas fired heating units. The heating of the natural gas is sometimes required to ensure that the temperature of the natural gas does not drop too low where it could facilitate the formation of a hydrate with any water vapor in the gas stream. Natural gas hydrates are crystalline ice-like solids or semi-solids that can impede the passage of natural gas through valves and pipes.

Because of an overall lack of comprehensive emissions data for NOx sources in the oil and gas sector, and variability due to equipment and site specifics, it is difficult to estimate the magnitude of NOx emissions from gas well heaters. Some related NOx emissions information was found in a report from the Western Region Air Partnership (WRAP), "An Emissions Inventory of Non-point Oil and Gas Emissions Sources in the Western Region" (presented at the 15th Emission Inventory Conference, New Orleans, May 2006). This report specifically addressed regional emissions from the oil and gas industry, and investigated regional data to estimate NOx emissions factors that included gas well heater NOx emission factors. While the NOx emissions factors presented in the report are based on region specific data, they appear to be realistic values that may be useful in estimating NOx emissions from similar equipment when site or region specific data is not available for other locations. The average NOx emissions factor presented in the WRAP report for gas well heaters is 1,752 lb NOx/well/year.

An emissions inventory of oil and gas sector emissions for 2005 in Texas indicated that gas well heaters accounted for approximately 0.5% of the onshore oil and gas sector NOx emissions.

Because of the small size of most gas well heater burners, there may be few commercially available combustion or post-combustion technologies commercially available for NOx reduction from these devices.

3.7 Natural Gas Compressors

The natural gas system in the continental United States is a complex network consisting of equipment and pipelines to gather natural gas from wellheads, transport the raw natural gas to processing facilities as required, transporting the natural gas from processing facilities across potentially large distances to storage facilities and distribution systems, and supplying natural gas to distribution systems that provide the natural gas to the end users.

Compressors are utilized in natural gas fields to boost natural gas wellhead pressure so that the natural gas may be injected into the gathering pipelines to transport it to processing facilities and/or inject the natural gas into the transport pipelines. Compressors are utilized in the transportation network to keep the pipelines pressurized and achieve the desired flow of natural gas. Compressors are also utilized at storage facilities to inject the natural gas into storage and to extract the natural gas from storage and re-inject it back into the transportation or distribution pipelines. Compressors are also sometimes utilized in distribution systems to ensure adequate flow and pressure to the natural gas end users. Most natural gas compressor facilities are normally unmanned, and many are operated from remote facilities to start/stop/modulate output to meet the demands of the associated pipeline systems.

Many natural gas wells require the use of compressors to facilitate extracting the natural gas from the well, boosting the pressure for injecting the natural gas into the field gathering pipeline system, and transporting the natural gas to and from any required field processing facility. Typically, reciprocating engines fueled by raw natural gas are utilized in this service, but other prime movers such as natural gas fueled combustion turbines or electric motors may be utilized in some circumstances. Industry information indicates that compressors utilized in this service tend to run with a relatively constant capacity factor throughout any given calendar year.

Industry literature indicates that the number and size of the compressors utilized in wellhead/gathering systems varies greatly as a result of differences in needed flow capability and pressure boost requirements. The industry information indicates that utilized compressors can range from portable compressor units with 5 HP prime movers to units that have prime mover ratings in excess of 1500 HP. Natural gas fueled reciprocating engines and combustion turbines, along with electric motors, are commonly utilized in this service. Some locations may be remote relative to sources of off-site electric power, prohibiting the use of electric motors for driving gas compressors unless local electric generation is also provided.

Some natural gas gathering systems include a well field processing facility, which performs such functions as removing impurities like water, carbon dioxide or sulfur that might corrode a pipeline, or inert gases, such as helium, that would reduce the energy value of the gas. These well field processing plants also can remove small quantities of propane and butane. These gases may used for chemical feedstocks and other applications. Compressors in this service may be utilized to transport natural gas from the wellheads to the well field processing facility, and then from the ell field processing facility to the main pipeline network.

Because of the relatively small size of some (but certainly not all)of the combustion engines utilized in natural gas field gathering applications, the available data concerning these units is more limited than that available for the generally higher output mainline compressor prime movers. Industry information indicates that some gas compressor engines used in this service are part of a skid mounted assembly, allowing the compressor to be moved with relative ease and thereby providing additional flexibility in meeting the changing demand associated with removing natural gas from any given well or well field. Industry information also indicates that many of the natural gas compressor prime movers used in this service are leased units.

An emissions inventory of oil and gas sector emissions for 2005 in Texas indicated that natural gas compressors of all kinds collectively accounted for approximately 42.9% of the onshore oil and gas sector NOx emissions.

There was a study performed in 2005 to support an investigation of natural gas field gathering engines in Eastern Texas that might provide some more insight into the potential diversity of engines utilized in the natural gas field gathering service. One of the goals of the Texas study was to get a more firm estimate of the inventory of compressors in use in the area in question. That study indicated that there were a number of engine manufacturers represented in the investigation area, along with a significant number of different engine models among the manufactures. The study was able to determine the age for only a very small portion of the engines in the study, but for that group the engine age ranged from 2 years to 25 years old. The output ratings of the engines in the study ranged from 26 HP to 1478 HP, with the majority rated between 50 HP and 200 HP. Some engines were owned by the gas/collection company, but the majority of the engines were leased units. The Texas report indicates that for this particular group of engines, there was little “seasonality” to their operating schedule, but that they seldom ran at full load (generally between 10% and 70% capacity). In the portion of the region covered in the Texas study that were non-attainment areas, the majority of the engines were found to be rich burn engines, with most required to have NSCR NOx emissions controls installed. The report indicates that the engines in the non-attainment areas not requiring NOx emissions controls were primarily 2-stroke engines, engines under 50 HP, and 4-stroke lean burn engines.

Mainline natural gas transmissions pipeline systems utilize compressors at gas compressor stations to maintain system flow and overcome pressure losses due to the movement of the natural gas through the natural gas pipeline system. These compressor stations are typically located at 40 mile to 100 mile intervals along the transmission pipeline, as required by the particular pipeline section duty, to maintain the required flow and pressure. These mainline natural gas compressor facilities will often include multiple gas compressors to add flexibility and reliability in meeting the variable natural gas flow demand. Prime movers for these mainline compressors are typically natural gas fired reciprocating engines and combustion turbines, although there are also a number of electric motor driven gas compressors. In some instances, combustion compressor prime movers and electric motor compressor prime movers are located in the same compressor facilities. The horsepower ratings of the individual combustion compressor prime movers range from less than 300 hp to 15,000 hp and more.

For many mainline natural gas compressor stations, industry data indicated that the gas compressor stations have compressors in operation 24 hrs/day and 365 days/year, although not all compressors may be operating or may not be operating at high capacity. The industry data indicates that on average a compressor unit will tend to experience an annual average capacity factor of approximately 40%. For many mainline natural gas compressor facilities, reciprocating engines are preferred for their ability to adjust their output to meet the pipeline demand. Compressor loading will tend to increase during periods of high natural gas demand, such as cold periods with high heating fuel demand or high electric demand days in the Northeast when natural gas fired electric generation is a significant consumer of natural gas.

EIA data indicates that in 2006 there were 1201 natural gas mainline compressor stations in the US, with a combined installed horsepower combined rating in excess of 16.8 million horsepower. The Federal Energy Regulatory Commission (FERC), the approval authority for interstate pipelines projects (including compressor facilities), has records that show that between 2007 through 2010, FERC had approved new compressor facilities or upgrades to existing compressor facilities that are expected to result in the addition of approximately 2.6 million horsepower of compression capability.

Many of the installed reciprocating engines driving mainline natural gas compressors are in excess of 40 years old and therefore pre-date any applicable modern original equipment manufacturer (OEM) installed NOx emissions controls and any otherwise applicable NSPS NOx controls. Little information was readily identifiable regarding the number of these units that may have undergone any NOx emissions reduction modifications as a result of federal or state NOx reduction retrofit requirements and regulations subsequent to the initial unit installation.

In a document titled “ERLE Cost Study of the Retrofit Legacy Pipeline Engines to Satisfy ½ g/BHP-HR NOx”, dated 5/21/2009, prepared by a technical group for the Pipeline Research Council International, it was stated that a gas industry data base of compressor engines identified that there were approximately 5,600 engines on the natural gas pipeline system with a collective rating of approximately 9,150,000 horsepower. The document further indicates that of the engine population, approximately 80% of the rated output was represented by purpose designed low speed two stroke and four stroke integral engines and diesel-derived medium speed engines converted to spark ignition by the engine’s original manufacturer. Of the engines represented in the 80% figure, approximately 78% of the engines were two stroke lean burn engines, approximately 14% were four stroke lean burn engines, and 8% of the engines were four stroke rich burn engines. That same population, on a rated horsepower basis, was made up of approximately 80% two stroke lean burn, approximately 15% four stroke lean burn, and approximately 5% four stroke rich burn.

4.0 Oil and Gas Sector Fuel Fired Prime Movers

Data indicates that with the exception of refineries and central natural gas processing plants, the largest collective sources of NOx emissions from the oil and gas sector are reciprocating engines and combustion turbines. These reciprocating engines and combustion turbines are used to power drilling operations, drive various pumping operations, drive oilwell pumps and pipeline pumps, and drive well head and pipeline natural gas compressors. Further discussion of these NOx emissions sources and potential NOx controls follow.

4.1 Reciprocating Engines - Two Stroke Lean Burn Spark Ignition Engines

In a reciprocating engine, combustion of a compressed fuel-air mixture is used to drive pistons in one or more cylinders, with the linear piston motion converted to rotary motion with a crankshaft. The rotary motion developed by the reciprocating engine may then be utilized to drive natural gas compressors, pumps, mechanical drives, or other rotary loads. Spark ignition engines use a spark (across a spark plug) to ignite the compressed fuel-air mixture to create the motive force.

Two-stroke engines complete the power cycle in a single engine revolution compared to 2 revolutions for 4-stroke engines. With the 2-stroke engine, the air/fuel charge is injected with the piston near the bottom of the power stroke. The ports or valves are all covered or closed, and the piston moves to the top of the cylinder compressing the charge. Following ignition and combustion, the power stroke starts with the downward movement of the piston. Exhaust ports or valves are then uncovered to remove the combustion products, and a new air/fuel charge is ingested. Two-stroke engines may be turbocharged using an exhaust-powered turbine to pressurize the charge for injection into the cylinder. Non-turbocharged engines may be either blower scavenged or piston scavenged to improve removal of combustion products. The air and fuel are mixed inside the power cylinder and fired by either a spark plug or pre-combustion chamber.

Two stroke engines generally are set to operate with a lean mixture to minimize combustion temperatures, and the fuel lean combustion mixtures tend to produce lower combustion temperatures and therefore lower NOx emissions. Some lean burn engines can be modified to operate with very fuel lean mixtures, further reducing NOx emissions, up to the point where engine miss-fire becomes a problem. Some of the combustion improvements discussed below (high energy ignition, pre-chamber combustion, and improved fuel mixing) facilitate the use of very fuel lean mixtures before engine miss-fires are encountered.

There are many 2-stroke spark ignition reciprocating engines utilized in the oil and gas sector, representing a number of different manufacturers, model numbers, and a wide range of engine output ratings.

4.1.1 Two Stroke Lean Burn Spark Ignition Reciprocating Engine NOx Controls

Industry literature indicates that there are a number of methodologies that are commercially available to help control NOx emissions from two-stroke lean burn spark ignition reciprocating engines (2SLB), most of which are related to efforts to acceptably operate with very lean air/fuel mixtures. While most of the technologies are generically applicable to most of the existing two-stroke lean burn engines, application on any specific make/model of engine may present unique circumstances that may affect the effectiveness of the control and the cost of installation on that particular engine.

When an engine's air/fuel mixture is leaned to achieve NOx emissions reductions, the amount of spark required from the ignition system to start combustion is increased. High energy ignition systems are applicable to most lean burn engines that are not already equipped with such a system. The high energy ignition system is generally a conventional open-chamber system with the spark plug (or plugs) generally located with the spark plug protruding from the bottom of the combustion cylinder head into the combustion chamber. High energy ignition systems allow more energy to be delivered to the spark plug(s) with a larger gap, thereby increasing the spark energy delivered to the air/fuel mixture and ensuring proper ignition. High energy ignition systems may be digitally controlled systems that use crankshaft referenced angle encoders to deliver precise, high energy ignition sparks. These high energy ignition systems may have the capability to generate multiple, successive sparks during combustion to ensure proper air/fuel light- off. Modern high energy ignition systems tend to reduce miss-fires and engine detonation, and provide a more stable combustion over an engine's entire operating range. Industry information indicates that a slight NOx emissions reduction, approximately 10%, can be achieved through application of a high energy ignition system on an engine that does not have an existing high energy ignition system.

Another methodology for controlling NOx emissions is by improving the combustion airflow characteristics of the engine. Increasing the airflow tends to produce a leaner air/fuel mixture, reducing the peak combustion temperature which tends to reduce NOx emissions. For some engine designs, this may be accomplished by varying the engine load or increasing the engine speed (if within the manufacturer's limits). The airflow of many engines can be increased by converting non-turbocharged engines to incorporate a turbocharger system, modifying or upgrading existing turbocharger systems on engines already incorporating turbochargers, or other unit-specific means to supply combustion air or scavenge the cylinder of combustion products. Turbocharger additions or upgrades often also require upgrades to the rest of the air intake and exhaust systems to accommodate and optimize the new or upgraded turbochargers. Additionally, a turbocharger installation or upgrade may be optimized through the use of intake/combustion air cooling systems. Industry information indicates that, depending upon the degree of upgrade, NOx emissions reductions of up to 75% may be expected for the addition of properly engineered turbocharger systems with intake /combustion air cooling.

Enhanced air fuel mixing technologies are another method of achieving NOx emissions reductions. The design of some two-stroke engines exhibit problems with the ability to thoroughly mix combustion air and fuel. For these engines, the combustion air and fuel may not be introduced for mixing until each has entered the combustion cylinder. The combustion air and fuel mix as the fuel is "sprayed" into the combustion air already in the cylinder. For some engine designs, the air and fuel mixing results in a non-homogeneous mixture that can cause a sporadic and unstable burning process as the flame burns through the cylinder filled with different regions of differing air/fuel mixtures. To improve the mixing process, the fuel supply system and components can be converted to utilize higher fuel injection pressures that force a more rapid and turbulent interaction between the combustion air and fuel and result in a more homogeneous mixture. Industry information indicates that increasing the pressure at which the fuel is injected, and directing the dispersion of the fuel during injection, can significantly reduce emissions and fuel consumption. Industry information indicates that relative to an older low pressure fuel injection system, a well engineered high pressure fuel injection system may be able to facilitate NOx emissions reductions of up to 90% in some engines.

As mentioned above, leaner air/fuel ratios have a tendency to help reduce NOx emissions. However, as the air/fuel ratio is further leaned to attain lower NOx emission rates, the extremely lean air/fuel mixtures become more difficult, if not impossible, to ignite using a standard open-chamber spark plug ignition system. In these cases, a combustion pre-chamber (typically less than 10 percent of the volume of the main chamber) may be installed in the power cylinder head and fitted with a conventional spark plug in the pre-chamber. The fuel supply system is modified to inject fuel into the pre-chamber as well as the main power chamber. During the intake process, the pre-chamber is charged with a richer air/fuel mixture than the main combustion chamber. This richer pre-chamber combustion mixture is more easily ignited by the sparkplug. As the pre-chamber combustion mixture burns, the pressure of the combustion pushes the burning mixture into the main combustion chamber, igniting the main combustion chamber's lean air/fuel mixture. Industry information indicates that the use of ignition pre-chambers may facilitate NOx reductions capabilities of up to 90% in some engines.

Modern electronic engine controls also may be utilized to facilitate the NOx reduction benefits of the above modifications. This is especially true for varying engine load or speed conditions, varying ambient conditions, or startup/shutdown conditions. Some of these devices are air/fuel ratio controllers. Some of these air/fuel ratio controllers utilize mathematical models to monitor certain engine parameters and atmospheric conditions to determine the correct air/fuel mixture for the operating conditions. By tracking and maintaining the "optimal" air/fuel mixture, the engine runs clean and more efficiently. In this way, the engine is more capable of maintaining NOx emissions compliance even with changing operating conditions and ambient condition changes.

Selective catalytic reduction (SCR) is a post-combustion NOx control that utilizes a catalyst and a reducing agent to reduce the concentration of NOx in the exiting combustion gasses. The reagent, typically ammonia or urea, is injected into the exhaust stream of the engine. Once in the exhaust, the ammonia (or urea that decomposes to produce ammonia in the exhaust stream) that passes over a catalyst to turn NOx into water, nitrogen and CO_2. Catalyst selection is somewhat based on the expected temperature range of the engine exhaust, and is sized to achieve the desired amount of NOx reduction. The reagent injection system is comprised of a storage tank, reagent injector(s), reagent pump, pressure regulator and electronic controls to accurately meter the quantity of reagent injected as a function of engine load, speed, temperature and NOx emissions. Industry information indicates that the use of SCR for NOx control may facilitate NOx reductions of up to 95%.

2-Stroke Lean Burn Spark Ignition Engine NOx Control Retrofit Technology	Potential NOx Reduction
High Energy Ignition System	10%
Intake Air Upgrade (turbocharger, etc)	75%
Improved Mixing (high pressure fuel injection)	90%
Pre-Combustion Chamber Ignition System	90%
SCR Catalyst	50% - 95%

4.1.2 Example Existing Rules and Regulations – 2SLB

California's South Coast Air Quality Management District (SCAQMD) has established Rule 1110.2, Emissions from Gaseous and Liquid Fueled Engines, the latest revision of the rule dated July 2010. Rule

1110.2 regulates NOx emissions from new and existing stationary spark or compression ignition internal combustion engines with a nameplate rating of 50 hp or greater. (This rule, 1110.2, may be accessed from http://aqmd.gov/rules/download.html)

NOx emission limits noted in SCAQMD Rule 1110.2 applicable to existing stationary spark and compression ignition engines include:

Nameplate - Bhp≥500	36 ppmvd NOx (*approximately 0.5 g/bhp-hr*)
Nameplate - Bhp<500	45 ppmvd NOx (*approximately 0.6 g/bhp-hr*)
Effective July 1, 2010	
Nameplate - Bhp≥500	11 ppmvd NOx (*approximately 0.15 g/bhp-hr*)
Nameplate - Bhp<500	45 ppmvd NOx (*approximately 0.6 g/bhp-hr*)
Effective July 1, 2011	
Nameplate - All	11 ppmvd NOx (*approximately 0.15 g/bhp-hr*)

(Note that SCAQMD Rule 1110.2 contains exemptions for units that operate less than 500 hrs/yr or burn less than 100 MMBTU/yr.) (Note that the rule makes no distinction for rich burn, lean burn, etc stationary engines.)

The state of Colorado's Air Quality Control Commission has established NOx emissions limitations for stationary internal combustion reciprocating engines in its Regulation 7, Control of Ozone Via Ozone Precursors (Emissions of Volatile Organic Compounds and Nitrogen Oxides).
Colorado's Regulation 7 has no NOx emissions limitations applicable to lean burn engines.

However, Colorado's Regulation 7 does include NOx emissions limitations applicable to lean burn engines that are new, modified, or relocated stationary natural gas fueled reciprocating internal combustion engines, as follows:

Engine Nameplate	**Manufacture Date**	**NOx Emissions Limit**
Nameplate-100≤Bhp<500	Effective January 1, 2008	2 g/bhp-hr
	Effective January 1, 2011	1 g/bhp-hr
Nameplate Bhp≥500	Effective July 1, 2007	2 g/bhp-hr
	Effective July 1, 2010	1 g/bhp-hr

(This Colorado rule may be viewed at http://www.cdphe.state.co.us/regulations/airregs/5CCR1001-9.pdf)

The Texas Commission on Environmental Quality revised its permit by rule (revision date February 17, 2012) for the oil and gas industry sources in Texas, §106.352 Oil and Gas Handling and Production Facilities. The Texas rule provides NOx emissions limitations for the various types of oil and gas sector sources, including NOx emissions limitations for 2-stroke lean burn spark ignition engines. The relevant emissions limitations in the rule include the following:

Engine Type	Manufacture Date	NOx Emissions Limit
Two stroke, lean burn SI– BHP≥ 500	Mfg before 9/23/1982	8g/bhp-hr
	Mfg before 6/18/92 & BHP<825	8g/bhp-hr
	9/23/1982≤Mfg<6/18/1992&BHP>825	5g/bhp-hr
	6/18/1992≤Mfg<6/1/2010	2g/bhp-hr (exc 5 g/bhp-hr at reduced speed and torque 80%<>100%)
	Mfg on or after 6/1/2010	1/g/bhp-hr

(This Texas rule can be reviewed at: http://www.tceq.texas.gov/assets/public/permitting/air/NewSourceReview/oilgas/og-easy-2012.pdf).

Additionally, Texas Administrative Code, Combustion Control at Major Industrial, Commercial, and Institutional Sources in Ozone Non-Attainment Areas, Beaumont-Port Arthur Ozone NonAttainment Area Major Sources, Rule §117.105, Emission Specifications for Reasonably Available Control Technology (RACT), provides NOx emissions limitations for natural gas fueled lean burn spark ignition reciprocating engines as follows:

Gas Fueled Lean Burn SI Engine ≥ 300 bhp	3.0 g/bhp-hr

Pennsylvania has recently proposed a revision to its General Permit for Natural Gas Production and Processing Facilities (GP-5). The proposed GP-5 will apply to all spark ignition internal combustion engines and other air contamination sources at natural gas production and processing facilities. In the proposed GP-5, existing rich and lean burn engines with a nameplate rating of less than or equal to 100 horsepower, but less than 1500 horsepower, will be required to continue to meet the existing GP-5 NOx emissions limit of 2 g/bhp-hr. When the currently proposed GP-5 becomes effective, new and reconstructed engines will be required to meet the following NOx emissions limits:

Configuration	NOx Limit
New and reconfigured Lean Burn Engine ≤ 100hp	2 g/bhp-hr
New and reconfigured Lean Burn Engine 100< hp ≤ 637	1 g/bhp-hr
New and reconfigured Lean Burn Engine > 637hp	0.5 g/bhp-hr

The USEPA established NOx emissions limitations for natural gas fueled lean burn spark ignition engines in 40 CFR Part 60, Subpart JJJJ (NSPS) (1/18/08 73 FR 3567). The applicable NOx emissions limits for lean burn natural gas-fueled, spark ignition engines are as follows:

Engine Type	Output Rating	Manufacture Date	NOx Emissions Limit
SI Nat. Gas Lean Burn	500≥HP<1350	mfg after 7/1/2008	2.0 g/HP-hr
SI Nat. Gas Lean Burn	500≥HP<1350	mfg after 7/1/2010	1.0 g/HP-hr

4.1.3 Discussion of NOx Reduction Capability – Combustion Modifications

With regards to combustion related NOx reduction retrofits for 2-stroke lean natural gas fueled spark ignition engines, the literature suggests that there are often significant differences in design characteristics between 2SLB engine manufacturers' designs such that applicability and effectiveness of generic NOx combustion controls is highly variable. Variability also potentially exists from installation to installation due to equipment clearances, etc.

Additionally, these combustion related modifications/upgrades may also offer the possibility of improving the 2-stroke lean burn reciprocating engine's efficiency and range of operation.

There are a number of manufacturers and suppliers that provide components, systems, and services to support combustion related NOx emission reductions from two stroke lean burn engines. Some of these organizations include the following:

- Windrock offers an autobalance system that automatically balances the cylinder-to-cylinder combustion in multi-cylinder slow speed integral engines such as Cooper-Bessemer, Clark/Dresser, Ingersoll-Rand, Worthington, and other two- or four-stroke engines with individual cylinder fuel adjustment valves. The system constantly adjusts fuel flow to each power cylinder in order to maintain peak firing pressures to ± 5% of engine average during differing ambient conditions, varying speeds and changing loads. Eliminating unbalanced operation across all operating conditions enables the engine to run with the minimum possible NOx and facilitates the positive results of other NOx reduction modifications. For additional information see: http://www.cookcompression.com/files/comm_id_68/GMJournal_Q32009_AutoBalance.pdf

- Dresser-Rand, a reciprocating engine OEM, offers a retrofit NOx emission technology system for a number of engine models. While somewhat dependent upon the specific model, the retrofit NOx emission reduction system may include a screw-in combustion pre-chamber high energy ignition system, earlier fuel injection timing and directional fuel injection for improved air/fuel mixing, improved controls for more precise fuel injection and engine timing, and improved air flow to further lean the mixture when applicable. Dresser-Rand also offers more extensive NOx reduction systems for retrofit, which depending upon engine model may include new cylinder heads with pre-combustion chambers, new main fuel gas injection valves, high efficiency turbochargers, larger turbocharger combustion air intercooler with plenums, new fuel management system, air/fuel ratio controller, new spark controller, new cams and/or camshaft on four-stroke engines, and a high-energy ignition system. Industry literature indicates that Dresser-Rand offers related retrofit NOx reduction controls for TVC, TCVA, TCVD, TLA, TLAD, LA, HLA, HLA/T, BA, HBA, HBA/T, RA, HRA, and HRA/T two stroke engines (Clark, Dresser-Clark). The literature also indicates that NOx emission guarantees of between 2.5 g/bhp-hr and 3.0 g/bhp-hr have been provided with these NOx reduction technologies, and that those guarantees have been consistently met or improved upon. For additional information see: http://dresser-rand.com/service/engineeredsolutions/revamps/recip.php , http://www.dresser-rand.com/techpapers/tp014.pdf

- Cameron offers a NOx reduction system for Ajax two stroke lean burn engines. Cameron's exhaust expansion chamber for the Ajax engine features diverging and converging sections of pipe using exhaust pulsations to optimize the scavenging of the power cylinders while providing a substantial increase in fresh air trapped in the cylinder. The results are improved performance and cooler combustion, which reduce the NOx levels up to 60%. For additional information see: (http://cameronscompressionsystems.blogspot.com/2009/10/ajax-integral-engine-compressors.html) (http://www.coopercameron.com/images/File/AJAX_brochure-vf2.pdf)

- Cameron also offers retrofit NOx reduction systems for many Cooper Bessemer engines. Depending upon the model, the retrofits may include electronic fuel injection, pre-chambers with electronic check valves, and improved intake and exhaust systems. For certain models Cameron may also redesign the cylinder head to allow for leaner combustion and improving combustion stability. For additional information see: http://cameronscompressionsystems.blogspot.com/2009/10/cooper-bessemer.html

An internet search identified a couple of documents discussing the results of NOx reduction combustion control projects or studies for two stroke lean burn engines, including some limited cost estimates. The information from this search is discussed below:

- In a 2011 presentation, Available Emission Reduction Technology for Existing Large Bore Slow Speed Two Stroke Engines, Cameron discussed its ability and experience in retrofitting low-NOx combustion modifications for large bore 2-stroke lean burn engines. In the document Cameron discussed a recent (2010) retrofit project that incorporated the use of high pressure fuel injection, turbocharging, pre-combustion chambers, and cylinder head modifications to attain a NOx emissions rate of 0.5 g/bhp-hr with an operating range of 80% for both engine speed and torque output. In this presentation Cameron further provided estimates for the cost of achieving similar NOx emission rates for several makes, models and output ratings of two stroke lean burn engines. The engines identified by Cameron in this estimation ranged from 200hp 6-cylinder engines to 11,000hp 20-cylinder engines. The estimated project costs ranged, depending upon make/model/output, from $4.3 million per engine to $1.9 million per engine, or from a low of $162,500 per cylinder to a high of $466,667 per cylinder, or from a low of $245 per rated hp to a high of $1400 per rated hp. This information shows the variability associated with NOx reduction efforts required for the various makes/models/outputs of the large bore two stroke engines.

- In a document titled "ERLE Cost Study of the Retrofit Legacy Pipeline Engines to Satisfy ½ g/BHP-HR NOx", dated 5/21/2009, prepared by a technical group for the Pipeline Research Council International, the results were discussed of an evaluation of the costs to attain NOx emission rates of 0.5 g/bhp-hr for legacy natural gas fueled 2-stroke lean burn engines used in pipeline compressor service. For the evaluation, three of the most representative make/models of 2-stroke lean burn integral compressor engines (2250 hp Cooper GMVH-10, 2000 hp Clark TLA-6, 2500hp Cooper GMW-10) were selected for evaluation. The evaluation concluded that there were no technology gaps and that each of the three makes/models evaluated were capable of attaining a NOx emissions limitation of 0.5 g/bhp-hr using a combination of improvements and retrofits related to air supply, fuel supply, ignition, electronic controls, and engine monitoring. The document also provided an estimate of the cost range to achieve the 0.5 g/bhp-hr NOx emission rate for each of the subject engines, as follows:

Engine	Output	First Unit Upgrade Cost	Follow On Unit Upgrade Cost
Cooper GMVH-10	2250 hp	\$2,050,000 - \$2,150,000	\$1,850,000 - \$1,950,000
Clark TLA-6	2000 hp	\$2,850,000 - \$2,950,000	\$2,550,000 - \$2,650,000
Cooper GMW-10	2500 hp	\$3,250,000 - \$3,350,000	\$2,950,000 - \$3,050,000

(Source: http://www.coresymposium.com/2010Core/EngineCostStudy.pdf)

The information suggests that most 2-stroke lean burn engines would be responsive to combustion and airflow modifications (potentially including installation/upgrade of turbochargers and inter-cooling, pre-chamber ignition or high energy ignition, improved fuel injection control, air/fuel ratio control, etc). All of the mentioned retrofit combustion related NOx controls may not be commercially available for all manufacturers and models of 2-stroke lean burn engines. It appears that the actual achievable NOx emission rate, in terms of g/bhp-hr, would tend to be engine design specific. Additionally, site specific installation issues may be greatly problematic or not cost effective. These engine and site specific issues are not altogether different than issues encountered with other types of emissions reduction technologies and projects. These types of issues can usually be addressed by providing appropriate flexibility in any rulemaking that includes consideration of site specific issues.

The available information suggests that combustion related modifications have the potential to achieve from 60% to 90% reduction in NOx emissions from two stroke lean burn spark ignited reciprocating engines, depending upon the make/model configuration of the engine. This suggests an approximate range of NOx emissions rate of 3.0 g/bhp-hr to 0.5 b/bhp-hr, depending upon the make/model configuration of the engine. The higher rates of NOx emissions reductions, and lower g/bhp-hr rate NOx emissions, are potentially achievable on some of the larger two stroke lean burn engines where NOx reduction systems are available that include layered combustion controls such as improved airflow, improved fuel-air mixing, improved ignition, and upgraded controls. The higher emission rates would tend to be more representative of the two stroke lean burn spark ignited reciprocating engine design and some larger units where layered NOx reduction packages have not been commercialized.

The same information indicates that there is a wide range of estimated costs for installation of combustion related controls with a target NOx emissions rate of 0.5 g/bhp-hr. The estimated range of cost is from \$245 per rated horsepower to \$1475 per rated horsepower. The range in cost appears to be affected both by the make/model/configuration of the engine and the output rating of the engine.

4.1.4 Discussion of NOx Reduction Capability – Post Combustion Modifications

With regards to post-combustion related NOx reduction retrofits for 2-stroke lean burn natural gas fueled spark ignition engines, the literature suggests that selective catalytic reduction (SCR) is technically feasible to achieve significant NOx emission rate reductions from 2SLB engines, but that there are problems that make SCR installation questionable. The first issue is that the 2SLB engine operation is very sensitive to changes in exhaust pressure, which could be problematic with the retrofit of SCR on existing engines. However, this issue can be alleviated for most units through proper design and sizing of airflow and exhaust components.

Some industry information suggests that the two stroke lean burn spark ignition engine's range of exhaust temperature may be too low for proper SCR operation. In a presentation titled "Challenges in Retrofitting Selective Catalytic Reduction (SCR) Systems to Existing Stationary Natural Gas Fired Engines" that was presented at the October 5, 2011 Gas Machinery Conference, it was stated that applying SCR to pipeline engines is not feasible because the exhaust temperatures are below the operating window for SCR or at a level where the SCR effectiveness is reduced, that the exhaust temperature is below the temperature for reliable decomposition of urea into ammonia, and the effectiveness of SCR has not been demonstrated on the slow speed, large bore, low exhaust temperatures typical of gas pipeline engines. For additional information see: http://www.gmrc.org/ckfinder/userfiles/files/GMC%20Conf/Final%20Papers/Challenges%20in%20Retrofitting%20SCR%20Systems.pdf

However, there are a number of organizations that market SCR systems that indicate that their catalysts are capable of effectively operating over a wide range of exhaust gas temperature. Such catalysts would serve to offer considerable flexibility for application to varying makes/models of two stroke lean burn engines, as well as providing flexibility for effective NOx reduction over a range of operating conditions for those engines.

Another stated issue is that many compressor facilities are unmanned and that SCR installations have not been demonstrated in unmanned facilities. Other industry information indicates that while it may be true that there are currently few SCRs in unmanned facilities, with modern software based controls and supervisory control and data acquisition (SCADA) type communication technologies there does not appear to be any technical barrier to operating the SCR related controls and auxiliaries successfully from a remote location.

Another industry concern that has been stated is that SCRs have not been demonstrated on combustion devices with variable loads. However, SCR manufactures indicate that they offer catalysts that are effective over wide temperature ranges characteristic of a range in engine operating load. Modern controls also have the ability to closely regulate fuel and air flows to ensure combustion gas oxygen and temperature levels at expected levels and to regulate reagent flow, all serving to ensure proper SCR function over a broad range of load.

In a document titled "ERLE Cost Study of the Retrofit Legacy Pipeline Engines to Satisfy ½ g/BHP-HR NOx", dated 5/21/2009, prepared by a technical group for the Pipeline Research Council International, the results were discussed of an evaluation of the costs to attain NOx emission rates of 0.5 g/bhp-hr for legacy natural gas fueled 2-stroke lean burn engines used in pipeline compressor service. For the evaluation, three of the most representative make/models of 2-stroke lean burn integral compressor engines (2250 hp Cooper GMVH-10, 2000 hp Clark TLA-6, 2500hp Cooper GMW-10) were selected for evaluation. The evaluation concluded that there were no technology gaps and that each of the three makes/models evaluated were capable of attaining a NOx emissions limitation of 0.5 g/bhp-hr using a combination of improvements and retrofits related to air supply, fuel supply, ignition, electronic controls, and engine monitoring. The document also briefly discusses using SCR as an alternative to the layered combustion related improvements/retrofits. The document discussed that SCR is a high cost alternative to the combustion related improvements/retrofits, primarily due to the high cost of ongoing

reagent consumption. For additional information see:
(http://www.coresymposium.com/2010Core/EngineCostStudy.pdf)

Even though some industry sources indicate that SCR is not a practical or proven NOx reduction technology for two stroke lean burn engines, there are a number of manufacturer's and suppliers that offer SCR systems that may be used on two stroke lean burn engines. Some of the manufacturer and supplier information is provided below:

- Johnson Matthey markets urea based SCR systems that reduce NOx emissions from lean burn natural gas fueled engines by 90% or more. Johnson Matthey offers catalysts with a broad effective operating temperature range to achieve NOx reductions earlier in an engine operating cycle and across a wide engine operating range. For additional information see: (http://ect.jmcatalysts.com/site.asp?siteid=836&pageid=888&furtherid=946)

- Miratech Corporation offers a SCR based NOx reduction system that is advertised to be applicable to lean burn engines used in natural gas compression applications. Miratech indicates that NOx reductions of up to 99% are achievable with their SCR system. For additional information see: http://www.miratechcorp.com/images/data/attachments/0000/0019/SCR_Systems.pdf

- CleanAir Systems offers a SCR system that they advertise as being applicable to lean burn natural gas fired engines, including those utilized for gas compression. CleanAir indicates that their SCR catalyst allows NOx reduction operation in a wide range of temperatures, from approximately 300 degF to approximately 1000 degF. (CleanAir Systems was acquired by Caterpillar in 2010, and is now called CleanAir Systems, A Caterpillar Company.) Their lean burn engine SCR product is now being referred to as E-Pod SCR. CleanAir indicates that their lean burn engine capable SCR achieves up to 95% reduction in NOx emissions across a wide range of exhaust temperatures. For additional information see: http://www.cleanairsys.com/products/hybrids/index.htm

Information from the Manufacturers of Emission Controls Association (MECA) indicated that there have been some limited examples of SCR being retrofit on two stroke lean burn engines as part of demonstration test programs, but that the results of these test programs have never been published. MECA indicated that there have been several demonstrations conducted by independent laboratories where SCR was retrofitted on such two-stroke, lean-burn natural gas spark ignited reciprocating engines that achieved >90% reduction in NOx. It was indicated that SCR retrofits were a challenge on some two stroke lean burn engines because of the relatively low exhaust temperatures on some of the older 2-stroke engines. However, MECA indicated that more modern SCR systems operate over a much broader operating range, and some of MECA's members have formulated catalysts specifically for these large two-stroke engines and demonstrated their effectiveness down to exhaust temperatures as low as 250^{o}C and as high as 550^{o}C. MECA stated that a NOx emissions rate of around 0.5 g/bhp-hr would more closely represent the 90% NOx removal capability of SCR achieving a 90% reduction in NOx emissions from two stroke lean burn spark ignited reciprocating engines.

It also appears that installation of SCR may be a beneficial NOx control technology on two stroke lean burn spark ignition reciprocating engines that have previously been modified with combustion related controls to moderately reduce the engine's NOx emission rate. The "reduced engine out" NOx emission rate, combined with the NOx control capability o f SCR, may achieve NOx emission rates of 0.5 g/bhp-hr or less.

From the available information it appears that SCR systems potentially applicable to two stroke lean burn reciprocating engines are available from several suppliers. It also appears that one of the main drawbacks at this time is that there are no public demonstration projects or completed projects in commercial operation to prove the viability of SCR in this service.

From the available information it appears that the use of SCR for NOx control does not appear to be technically infeasible generically, but that individual two stroke lean burn reciprocating engine characteristics and installations may be greatly problematic or not cost effective. This "site specific" issue is not altogether any different than other types of emission reduction technologies, and can usually be addressed by providing appropriate flexibility in any rulemaking that includes consideration of site specific issues.

Without the benefit of information from actual installations or comprehensive engineering evaluations, it is difficult to definitively identify a range of NOx emissions reduction possible from installation of SCR on two stroke lean burn spark ignition reciprocating engines. The information from SCR suppliers and MECA suggests that, for two stroke lean burn reciprocating engines, SCR may be capable of achieving approximately 90% reduction in NOx emissions, giving a potential range of NOx emissions rates of 0.5 g/bhp-hr to 1.0 g/bhp-hr.

Likewise, without the benefit of information from actual installations or comprehensive engineering evaluations, it is difficult to provide any range of costs regarding installation of SCR on the variety of two stroke lean burn spark ignited reciprocating engines. However, the "ERLE Cost Study of the Retrofit Legacy Pipeline Engines to Satisfy ½ g/BHP-HR NOx" document provided some capital cost information related to the installation of SCR on two stroke lean burn engines with the intent of approaching a NOx emissions rate of 0.5 g/bhp-hr. (The document points out that some combustion related NOx emission reductions may be required to help the primary SCR NOx control to achieve an overall 0.5 g/bhp-hr NOx emission rate.) For the nominal 2000 hp to 2500 hp two stroke lean burn reciprocating engines evaluated in the ERLE document, the document indicates that capital cost estimates for SCR would be in the range of $740,000 to $890,000. The document also estimated annual reagent costs in excess of $120,000 for these SCR systems.

4.1.5 Two Stroke Lean Burn Spark Ignition Reciprocating Engine NOx Control Summary

Industry information indicates that there are technically feasible, commercially available NOx reduction technologies applicable to natural gas fueled, spark ignited, lean burn reciprocating engines. The information suggests that most of these engines would be responsive to combustion and airflow modifications (potentially including installation/upgrade of turbochargers and inter-cooling, pre-chamber ignition or high energy ignition, improved fuel injection control, air/fuel ratio control, etc). The industry information also indicates that there are technically feasible, commercially available post-combustion (SCR) NOx reduction systems available for use on these same engines. However, some of the combustion related and post combustion NOx controls may not be commercially available for all manufacturers and models of two stroke lean burn spark ignited reciprocating engines.

From the industry information it appears that the actual achievable NOx emission rate, in terms of g/bhp-hr, would tend to be engine design specific. Additionally, site specific installation issues may impact controls installation such that the installations are operationally problematic or not cost effective. These engine design and site specific issues are not altogether different than issues encountered with other types of emissions reduction technologies and projects, and can usually be addressed by providing appropriate flexibility in any rulemaking that includes consideration of site specific issues.

The information therefore seems to support NOx emission rate limits of as low as 0.5 g/bhp-hr for many two-stroke lean burn spark ignition reciprocating engines with a nameplate rating of 250 hp or above, providing that there is consideration of individual engine design and site specific flexibility provisions. For two stoke lean burn engines with nameplate ratings below 250 hp, the available industry information indicates NOx emission rate limits of around 3 g/bhp-hr for some of the existing popular make/model combinations. Again, this could be addressed with appropriate rule or regulation consideration of individual engine design and site specific flexibility provisions.

Very little information was found regarding the cost of purchase and installation of combustion related and post-combustion NOx controls for two stroke lean burn engines. The following summarizes the limited information:

Type of NOx Control	**Engine Size Range (hp)**	**Estimated Range of NOx Reduction (%)**	**Estimated Range of NOx Emissions Rate (g/bhp-hr)**	**NOx Control Estimated Costs ($)**
Layered Combustion	100 - 250	60 - 90	3 - 0.5	182,000 - 456,000
Layered Combustion	2000 - 2500	90	0.5	2,175,000 - 3,554,000
SCR	2000 - 2500	90	0.5	1,050,000 - 1,210,000

(Note: Estimated control costs are initial capital cost estimates only. Costs are based on information from “ERLE Cost Study of the Retrofit Legacy Pipeline Engines to Satisfy ½ g/BHP-HR NOx” document, adjusted for CPI.)

It should be noted that the range of costs, especially for the combustion related NOx control modifications, is more representative of the diversity of the modifications that might be required to attain the NOx emission rate limits rather than a function of the nameplate rating of the engine. This is due to the fact that some engines may require complete new turbocharger systems with related auxiliaries, while some may require relatively modest modifications to existing induction systems, some may require new precombustion chamber (PCC) combustion ignition systems while others may require only minor improvements, etc. These differences can exist across the range of four stroke lean burn engine nameplate ratings.

4.2 Reciprocating Engines - Four Stroke Lean Burn Spark Ignition Engines

In a reciprocating engine, combustion of a compressed fuel-air mixture is used to drive pistons in one or more cylinders, with the linear piston motion converted to rotary motion with a crankshaft. The rotary motion developed by the reciprocating engine may then be utilized to drive natural gas compressors, pumps, mechanical drives, or other rotary loads. Spark ignition engines use a spark (across a spark plug) to ignite the compressed fuel-air mixture to create the motive force.

Four-stroke spark ignition reciprocating engines use a separate engine revolution for the intake/compression stroke and the power/exhaust stroke. Four-stroke engines complete the combustion cycle in two revolutions of the crankshaft. Each of the piston's four strokes has an important function in the engine cycle (intake, compression, power and exhaust). These engines have intake and exhaust valves to introduce combustion air into the cylinder and exhaust combustion gases from the cylinder. Most four-stroke spark ignition reciprocating engines use open-chamber spark plugs to ignite the air/fuel mixture, and can be configured to operate as rich- or lean burn, depending on the air/fuel mixture. These reciprocating engines may be either naturally aspirated, using the suction from the piston to entrain the air charge, or utilize a supercharger or turbocharger to pressurize the inlet air/fuel charge.

Lean-burn four-stroke spark ignition engines usually have a fuel injection system that injects the fuel near the intake valves or in the power head. They use either open-chambered spark plugs or pre-combustion chamber ignition systems to assure ignition of the lean mixture. Lean burn spark ignited reciprocating engines are often fitted with a mechanically driven blower or turbocharger to supply the required combustion air. Lean burn engines have higher oxygen levels in the combustion chamber (and exhaust), which decreases the combustion temperature and thereby reducing the amount of NOx that is formed during combustion. Because the air-to-fuel ratio is lean with fuel, less fuel is used, which results in decreased combustion temperatures, decreased engine power, and increased engine efficiency relative to a rich burn engine.

Some lean burn four-stroke spark ignited reciprocating engines can be modified to operate with very fuel lean mixtures, further reducing NOx emissions, up to the point where engine misfire becomes a problem. Combustion improvements such as high energy ignition, pre-chamber combustion, and improved fuel mixing may be incorporated on four-stroke engines to facilitate the use of very fuel lean mixtures before engine misfires are encountered.

There are many four stroke lean burn (4SLB) spark ignition reciprocating engines in service, representing a number of different manufacturers, model numbers, and a range of output ratings.

4.2.1 Four Stroke Lean Burn Spark Ignition Engine NOx Controls

Industry literature indicates that there are a number of methodologies that are commercially available to help control NOx emissions from four-stroke lean burn spark ignition reciprocating engines, most of which are related to efforts to acceptably operate with very lean air/fuel mixtures. While most of the technologies are generically applicable to most of the existing four-stroke lean burn reciprocating engines, application on any specific make/model of engine may present unique circumstances that may affect the effectiveness of the control and the cost of installation on that particular engine.

When an engine's air/fuel mixture is leaned to achieve NOx emissions reductions, the amount of spark energy required from the ignition system to start combustion is increased. High energy ignition systems are applicable to most lean burn engines that are not already equipped with such a system. The high energy ignition system is generally a conventional open-chamber system with the spark plug (or plugs) generally located with the spark plug protruding from the bottom of the combustion cylinder head into the combustion chamber. High energy ignition systems allow more energy to be delivered to the spark plug(s) with a larger gap, thereby increasing the spark energy delivered to the air/fuel mixture and ensuring proper ignition. High energy ignition systems may be digitally controlled systems that use crankshaft referenced angle encoders to deliver precise, high energy ignition sparks. These high energy ignition systems may have the capability to generate multiple, successive sparks during combustion to ensure proper air/fuel light- off. Modern high energy ignition systems tend to reduce misfires and engine detonation, and provide a more stable combustion over an engine's entire operating range. Industry information indicates that a slight NOx emissions reduction, approximately 10%, can be achieved through application of a high energy ignition system on an engine that does not have an existing high energy ignition system.

Another methodology for controlling NOx emissions is by improving the combustion airflow characteristics of the engine. Increasing the airflow tends to produce a leaner air/fuel mixture, reducing the peak combustion temperature which tends to reduce NOx emissions. For some engine designs, this may be accomplished by varying the engine load or increasing the engine speed (if within the manufacturer's limits). The airflow of many engines can be increased by converting non-turbocharged engines to incorporate a turbocharger system, modifying or upgrading existing turbocharger systems on engines already incorporating turbochargers, or other unit-specific means to supply combustion air or scavenge the cylinder of combustion products. Turbocharger additions or upgrades often also require upgrades to the rest of the air intake and exhaust systems to accommodate and optimize the new or upgraded turbochargers. Additionally, a turbocharger installation or upgrade may be optimized through the use of intake/combustion air cooling systems. Industry information indicates that, depending upon the degree of upgrade, NOx emissions reductions of up to 75% may be expected for the addition of properly engineered turbocharger systems with intake /combustion air cooling.

Enhanced air-fuel mixing technologies are another method of achieving NOx emissions reductions. The design of some four-stroke engines exhibit problems with the ability to thoroughly mix combustion air and fuel. For these engines, the combustion air and fuel may not be introduced for mixing until each has entered the combustion cylinder. The combustion air and fuel mix as the fuel is "sprayed" into the combustion air already in the cylinder. For some engine designs, the air and fuel mixing results in a non-homogeneous mixture that can cause a sporadic and unstable burning process as the flame burns through the cylinder filled with different regions of differing air/fuel mixtures. To improve the mixing process, the fuel supply system and components can be converted to utilize higher fuel injection pressures that force a more rapid and turbulent interaction between the combustion air and fuel and result in a more homogeneous mixture. Industry information indicates that increasing the pressure at which the fuel is injected, and directing the dispersion of the fuel during injection, can significantly reduce emissions and fuel consumption. Industry information indicates that relative to an older low pressure fuel injection system, a well engineered high pressure fuel injection system may be able to facilitate NOx emissions reductions of up to 90% in some engines.

As mentioned above, leaner air/fuel ratios have a tendency to help reduce NOx emissions. However, as the air/fuel ratio is further leaned to attain lower NOx emission rates, the extremely lean air/fuel mixtures become more difficult, if not impossible, to ignite using a standard open-chamber spark plug ignition system. In these cases, a combustion pre-chamber (typically less than 10 percent of the volume of the main chamber) may be installed in the power cylinder head and fitted with a conventional spark plug in the pre-chamber. The fuel supply system is modified to inject fuel into the pre-chamber as well as the main power chamber. During the intake process, the pre-chamber is charged with a richer air/fuel mixture than the main chamber. This richer pre-chamber combustion mixture is more easily ignited by the sparkplug. As the pre-chamber combustion mixture burns, the pressure of the combustion pushes the burning mixture into the main power chamber, igniting the main power chamber's lean air/fuel mixture. Industry information indicates that the use of ignition pre-chambers may facilitate NOx reductions capabilities of up to 90% in some four stroke spark ignited reciprocating engines.

Modern electronic engine controls also may be utilized to facilitate the NOx reduction benefits of the above modifications. This is especially true for varying engine load or speed conditions, varying ambient conditions, or startup/shutdown conditions. One type of control device is referred to as an air/fuel ratio controller. Some of these air/fuel ratio controllers utilize mathematical models to monitor certain engine parameters and atmospheric conditions to determine the correct air/fuel mixture for the operating conditions. By tracking and maintaining the "correct" air/fuel mixture, the engine runs clean and more efficiently. In this way, the engine is more capable of maintaining NOx emissions compliance even with changing operating conditions and changes in ambient conditions.

Another potential NOx reduction technology for four-stroke lean burn spark ignited reciprocating engines is the use of exhaust gas recirculation (EGR). EGR systems utilize hardware changes to recirculate engine exhaust gases into the combustion chamber of the engine as an inert substitute for the excess air normally supplied in lean burn reciprocating engine operation. EGR allows the combustion chamber to operate as if it were a rich burn engine and, since no excess oxygen is present in the exhaust, a much less expensive nonselective reduction catalyst (NSCR) can be used when post-combustion NOx controls are needed to meet the most stringent NOx emissions standards. NOx emissions rates from an EGR and NSCR equipped engine can be as low as, or lower than, a lean burn engine equipped with a selective catalytic reduction (SCR) system. Several independent companies have installed retrofit systems on existing natural gas engines and have reported some success in meeting very low emissions requirements during initial and limited field testing. Engine performance and fuel efficiency are reported to be the equivalent of standard lean burn engines yet are still able to utilize NSCR for meeting stringent NOx emissions limitations. This NOx control strategy has yet to achieve widespread acceptance in a retrofit application.

Selective catalytic reduction (SCR) is a post-combustion NOx control that utilizes a catalyst and a reducing agent to reduce the concentration of NOx in the exiting combustion gasses. The reagent, typically ammonia or urea, is injected into the exhaust stream of the engine. Once in the exhaust, the ammonia (or urea that decomposes to produce ammonia in the exhaust stream) passes over a catalyst to turn NOx into water, nitrogen and CO_2. Catalyst selection is somewhat based on the expected temperature range of the engine exhaust, and is sized to achieve the desired amount of NOx reduction. The reagent injection system is comprised of a storage tank, reagent injector(s), reagent pump, pressure regulator and electronic controls to accurately meter the quantity of reagent injected as a function of engine load, speed, temperature and NOx emissions. Industry information indicates that the use of SCR for NOx control may facilitate NOx reductions of up to 95%.

4-Stroke Lean Burn Spark Ignition Engine **NOx Control Retrofit Technology**	**Potential NOx Reduction**
High Energy Ignition System	10%
Intake Air Upgrade (turbocharger, etc)	60% - 70%
Improved Mixing (high pressure fuel injection)	90%
Pre-Combustion Chamber Ignition System	90%
SCR Catalyst	50% - 95%

4.2.2 Example Existing Rules and Regulations – 4SLB

California - California's South Coast Air Quality Management District (SCAQMD) has established Rule 1110.2, Emissions from Gaseous and Liquid Fueled Engines, the latest revision of the rule dated July 2010. Rule 1110.2 regulates NOx emissions from new and existing stationary spark or compression ignition internal combustion engines with a nameplate rating of 50 hp or greater. (This rule, 1110.2, may be accessed from http://aqmd.gov/rules/download.html)

NOx emission limits noted in SCAQMD Rule 1110.2 applicable to existing stationary spark and compression ignition engines include:

Nameplate - Bhp≥500	36 ppmvd NOx (*approximately 0.5 g/bhp-hr*)
Nameplate - Bhp<500	45 ppmvd NOx (*approximately 0.6 g/bhp-hr*)
Effective July 1, 2010	
Nameplate - Bhp≥500	11 ppmvd NOx (*approximately 0.15 g/bhp-hr*)
Nameplate - Bhp<500	45 ppmvd NOx (*approximately 0.6 g/bhp-hr*)
Effective July 1, 2011	
Nameplate - All	11 ppmvd NOx (*approximately 0.15 g/bhp-hr*)

(Note that SCAQMD Rule 1110.2 contains exemptions for units that operate less than 500 hrs/yr or burn less than 100 MMBTU/yr.) (Note that the rule makes no distinction for rich burn, lean burn, etc stationary engines.)

Colorado - The state of Colorado's Air Quality Control Commission has established NOx emissions limitations for stationary internal combustion reciprocating engines in its Regulation 7, Control of Ozone Via Ozone Precursors (Emissions of Volatile Organic Compounds and Nitrogen Oxides).
Colorado's Regulation 7 has no NOx emissions limitations applicable to existing lean burn engines.

However, Colorado's Regulation 7 does include NOx emissions limitations applicable to lean burn engines that are new, modified, or relocated stationary natural gas fueled reciprocating internal combustion engines, as follows:

Engine Nameplate	**Manufacture Date**	**NOx Emissions Limit**
Nameplate-100≤Bhp<500	Effective January 1, 2008	2 g/bhp-hr
	Effective January 1, 2011	1 g/bhp-hr

Nameplate Bhp≥500	Effective July 1, 2007	2 g/bhp-hr
	Effective July 1, 2010	1 g/bhp-hr

(This Colorado rule may be viewed at http://www.cdphe.state.co.us/regulations/airregs/5CCR1001-9.pdf)

Texas - The Texas Commission on Environmental Quality revised its permit by rule (revision date February 17, 2012) for the oil and gas industry sources in Texas, §106.352 Oil and Gas Handling and Production Facilities. The Texas rule provides NOx emissions limitations for the various types of oil and gas sector sources, including NOx emissions limitations for 4-stroke lean burn spark ignition engines. The relevant emissions limitations in the rule include the following:

Engine Type	**Manufacture Date**	**NOx Emissions Limit**
Four stroke, lean burn SI-BHP<500	Mfg before 7/1/2008	2g/bhp-hr
	(After 1/1/2030, no 4SLB SI engine NOx emissions shall exceed 2 g/bhp-hr regardless of manufacture date.)	
Four stroke, lean burn SI-BHP≥500	Mfg before 9/23/1982	5g/bhp-hr (exc 8 g/bhp-hr at reduced speed and torque 80%<>100%)
	Mfg before 6/18/92 & BHP<825	5g/bhp-hr (exc 8 g/bhp-hr at reduced speed and torque 80%<>100%)
	9/23/1982≤Mfg<6/18/1992&BHP>825	5g/bhp-hr
	6/18/1992≤Mfg<6/1/2010	2g/bhp-hr (exc 5 g/bhp-hr at reduced speed and torque 80%<>100%)
	Mfg on or after 6/1/2010	1/g/bhp-hr
	(After 1/1/2030, no 4SLB SI engine NOx emissions shall exceed 2 g/bhp-hr regardless of manufacture date.)	

(This Texas rule can be reviewed at:
http://www.tceq.texas.gov/assets/public/permitting/air/NewSourceReview/oilgas/og-easy-2012.pdf).

Additionally, Texas Administrative Code, Combustion Control at Major Industrial, Commercial, and Institutional Sources in Ozone Non-Attainment Areas, Beaumont-Port Arthur Ozone NonAttainment Area Major Sources, Rule §117.105, Emission Specifications for Reasonably Available Control Technology (RACT), provides NOx emissions limitations for natural gas fueled lean burn spark ignition reciprocating engines as follows:

Gas Fueled Lean Burn SI Engine ≥ 300 bhp	3.0 g/bhp-hr

Pennsylvania has recently proposed a revision to its General Permit for Natural Gas Production and Processing Facilities (GP-5). The proposed GP-5 will apply to all spark ignition internal combustion engines and other air contamination sources at natural gas production and processing facilities. In the proposed GP-5, existing rich and lean burn engines with a nameplate rating of less than or equal to 100 horsepower, but less than 1500 horsepower, will be required to continue to meet the existing GP-5 NOx emissions limit of 2 g/bhp-hr. When the currently proposed GP-5 becomes effective, new and reconstructed engines will be required to meet the following NOx emissions limits:

Configuration	**NOx Limit**
New and reconfigured Lean Burn Engine ≤ 100hp	2 g/bhp-hr
New and reconfigured Lean Burn Engine 100< hp ≤ 637	1 g/bhp-hr
New and reconfigured Lean Burn Engine > 637hp	0.5 g/bhp-hr

The USEPA established NOx emissions limitations for natural gas fueled lean burn spark ignition engines in 40 CFR Part 60, Subpart JJJJ (NSPS) (1/18/08 73 FR 3567). The applicable NOx emissions limits for lean burn natural gas-fueled, spark ignition engines are as follows:

Engine Type	**Output Rating**	**Manufacture Date**	**NOx Emissions Limit**
SI Nat. Gas Lean Burn	500≥HP<1350	mfg after 7/1/2008	2.0 g/HP-hr
SI Nat. Gas Lean Burn	500≥HP<1350	mfg after 7/1/2010	1.0 g/HP-hr

4.2.3 Discussion of 4-Stroke Lean Burn NOx Reduction Capability – Combustion Controls

With regards to the NOx reduction capabilities of combustion modifications for four stroke lean burn spark ignited reciprocating engines, the literature suggests that there are often significant differences in design characteristics between four stroke lean burn reciprocating engine manufacturers' designs such that applicability and effectiveness of generic NOx combustion controls is highly variable. Variability also potentially exists from installation to installation due to equipment clearances, etc. The information suggests that most four stroke lean burn spark ignited reciprocating engines would be responsive to combustion and airflow modifications (potentially including installation/upgrade of turbochargers and inter-cooling, pre-chamber ignition or high energy ignition, improved fuel injection control, air/fuel ratio control, etc).

These (or some of these) modifications/upgrades may represent a generic NOx reduction strategy with the potential of reducing NOx emission rates by up to 90% from uncontrolled by facilitating operation with very lean fuel air mixtures. All of the mentioned retrofit NOx controls may not be commercially available for all manufacturers and models of gas compressor four stroke lean burn engines. The actual achievable NOx emission rate, in terms of g/bhp-hr, would tend to be engine design specific. These modifications/upgrades also offer the possibility of improving the four stroke lean burn spark ignited reciprocating engine's efficiency.

There are a number of manufacturers and suppliers that provide components, systems, and services to support combustion related NOx emission reductions from four stroke lean burn engines. Some of these organizations include the following:

- Windrock offers an autobalance system that automatically balances the cylinder-to-cylinder combustion in multi-cylinder slow speed integral engines such as Cooper-Bessemer, Clark/Dresser, Ingersoll-Rand, Worthington, and other two- or four-stroke engines with individual cylinder fuel adjustment valves. The system constantly adjusts fuel flow to each power cylinder in order to maintain peak firing pressures to ± 5% of engine average during differing ambient conditions, varying speeds and changing loads. Eliminating unbalanced operation across all operating conditions enables the engine to run with the minimum possible NOx and facilitates the positive results of other NOx reduction modifications. For additional information see: http://www.cookcompression.com/files/comm_id_68/GMJournal_Q32009_AutoBalance.pdf

- Attainment Technologies company markets gas recirculation systems for NOx control for lean burn spark ignited reciprocating engines. (Gas recirculation as a NOx control for these engines is also being offered by some original equipment manufacturers (OEMs).) With this process, instead of high levels of excess air, re-circulated and cooled exhaust gas is used as a heat sink in the combustion process. High, lean burn reciprocating engine compression ratios can be used without engine knock complications. Engine performance and fuel efficiency is equivalent to a standard lean burn engine. The advantage compared to traditional lean burn reciprocating engines is the availability of NSCR as an emission after-treatment. This is possible, since there is no excess oxygen in the exhaust stream. Attainment Technologies' literature indicates that retrofitted lean burn engines have achieved NOx emission rates of 0.1 g/bhp-hr in testing using the Attainment Technologies NOx reduction systems. For additional information see: http://www.attainmenttech.com/solutions.html

- Dresser-Rand, a reciprocating engine OEM, offers a retrofit NOx emission technology system for many engine models, including four stroke lean burn spark ignited reciprocating engines. While somewhat dependent upon the specific model, the retrofit NOx emission reduction system may include a screw-in combustion pre-chamber high energy ignition system, earlier fuel injection timing and directional fuel injection for improved air/fuel mixing, improved controls for more precise fuel injection and engine timing, and improved air flow to further lean the mixture when applicable. Dresser-Rand also offers more extensive (and expensive) NOx reduction systems for retrofit, which depending upon engine model may include new cylinder heads with pre-combustion chambers, new main fuel gas injection valves, high efficiency turbochargers, a larger turbocharger combustion air intercooler with plenums, a new fuel management system, an air/fuel ratio controller, a new spark controller, new cams and/or camshaft on four-stroke engines, and a high-energy ignition system. Industry literature indicates that Dresser-Rand offers related NOx controls for KVS, KVSR, KVR, KVT, SVS, TVS, and TVR four stroke engines (Dresser-Rand, Ingersoll-Rand). The literature also indicates that NOx emission guarantees of between 2.5 g/bhp-hr and 3.0 g/bhp-hr have been provided with these NOx reduction technologies, and that those guarantees have been consistently met or improved upon. For additional information see: http://dresser-rand.com/service/engineeredsolutions/revamps/recip.php, http://www.dresser-rand.com/techpapers/tp014.pdf

- Dresser Rand also indicates that they have considerable experience in the retrofit of NOx emissions controls across a broad range of existing legacy natural gas compression lean burn reciprocating engines. Their products and systems include a high-pressure fuel injection system, a real-time engine and compressor monitoring platform, high delivery ratio turbochargers designed for the performance requirements of emission reduction packages, a low emissions reduction (LEC) kit and a variety of products designed to reduce emissions while expanding the operating envelope, model-based control strategies that provide operational flexibility, adaptive air/fuel ratio controllers, and catalytic exhaust emissions control systems. Dresser Rand indicates that they have experience in working with a number of engine makes and models, including Caterpillar (3500 Series and 3600 Series), Cooper Bessemer (GMW, GMWA, GMV, GMVH, V-250, W-330, LSV, Quad 12), Clark (BA, HBA, TLA, TCV, TCVA, TCVC, TCVD), Ingersoll Rand (KVG,KVS Series, KVTR, KVGR, LVG, PVG, PSVG, SVG), Nordberg (FSE), White Superior (825, 2416), Wartsilla (18V34SG), Waukesha (3521, 5790, 7042), and Worthington (UTC, UTC-T, Mainliner (ML), Mainliner (MLV)). For additional information see: http://www.dresser-rand.com/service/engineeredsolutions/enginuity/solutions/emissions.php

- Compression Components Texas (CCT) advertises a retrofit kit for Caterpillar G3516 natural gas fueled four stoke lean burn spark ignited reciprocating engines that enable the engine to meet a 0.15 g/hp-hr NOx emission rate limit with little or no loss in engine power. The CCT kit is comprised of a group of combustion related improvements/upgrades and does not incorporate any post-combustion controls. For additional information see: http://www.compressioncomponentstx.com/-/Low_NOx.html

- Caterpillar offers new lean burn spark ignited reciprocating engines with a wide range of output ratings up to approximately 5000 HP with a broad operating speed range. Caterpillar advertises that many of these engines are capable of achieving NOx emissions limits of 0.5 g/bhp-hr without post-combustion NOx emission controls. For additional information see: http://catoilandgas.cat.com/products/engines

- Dresser Waukesha offers new 12 cylinder and 16 cylinder versions of its 275GL lean burn engine for the gas compression market. The engines are reported to be able to achieve NOx emission rates of less than 0.5 g/bhp-hr, and are rated at 3,625 hp for the 12 cylinder version and 4,835 hp for the 16 cylinder version. For additional information see: http://www.pipelineandgasjournal.com/12-16-cylinder-versions-low-emission-compressor-engine-unveiled

In 2007 the Illinois Environmental Protection Agency prepared its "Technical Support Document for Controlling Emissions from Stationary Reciprocating Internal Combustion Engines and Turbines". This document reviewed NOx emissions control capabilities and estimated cost effectiveness for a number of NOx controls for lean burn reciprocating engines. Included in this evaluation for lean burn spark ignited reciprocating engines is the installation of a low emissions control (LEC), layered NOx control system. The document indicates that LEC has the capability of reducing NOx emissions from lean burn engines by approximately 80% to 93%. The following summarizes the lean burn spark ignited reciprocating engine evaluation:

Type of Control	Nameplate Rating (HP)	Total Capital Cost (2004 $)
Low Speed LB Layered Comb	500 – 11,000	751,600 – 4,249,700
Med Speed LB Layered Comb	500 – 11,000	130,300 – 2,149,300

For additional information see: http://www.epa.state.il.us/air/rules/rice/tsd-rice.pdf

The industry information suggests that most four stroke lean burn spark ignited reciprocating engines would be responsive to combustion and airflow modifications (potentially including installation/upgrade of turbochargers and inter-cooling, pre-chamber ignition or high energy ignition, improved fuel injection control, air/fuel ratio control, etc). All of the combustion related NOx controls may not be commercially available for all manufacturers and models of four stroke lean burn spark ignited reciprocating engines. It appears that the actual achievable NOx emission rate, in terms of g/bhp-hr, would tend to be engine design specific. Additionally, site specific installation issues may be greatly problematic or not cost effective. These engine and site specific issues are not altogether different than issues encountered with other types of emissions reduction technologies and projects. These types of issues can usually be addressed by providing appropriate flexibility in any rulemaking that includes consideration of site specific issues.

The available information suggests that retrofit combustion related modifications have the potential to achieve an approximate 90% reduction in NOx emissions from most four stroke lean burn spark ignited engines, given potential variability between engine designs. This suggests an approximate range of NOx emissions rate of 2.0 g/bhp-hr to 0.5 b/bhp-hr from otherwise uncontrolled lean burn spark ignited reciprocating engines, depending upon the make/model configuration of the engine.

The industry information also indicates that there is a wide range of estimated costs for installation of combustion related controls with a target NOx emissions rate of 0.5 g/bhp-hr. One source of information estimated a range of cost is from $245 per rated horsepower to $1475 per rated horsepower. The range in cost appears to be affected more by the make/model/configuration of the engine rather than strictly by the size of the engine. Some reasons for this include that some engines will require the installation of new turbocharger and auxiliaries, some engines will require relatively easy upgrades to existing turbochargers and auxiliaries, some engines will require head modifications to accept pre-combustion chamber ignitions while others can utilize screw in pre-combustion chamber ignition systems, etc.

4.2.4 Discussion of 4-Stroke Lean Burn NOx Reduction Capability – Post Combustion Controls

With regards to the NOx reduction capabilities of post combustion modifications for four stroke lean burn spark ignited reciprocating engines, the literature suggests that SCR is technically feasible to achieve significant NOx emission rate reductions from four stroke lean burn engines. However, some industry trade organizations indicate that there are problems that make the installation and successful operation of SCR questionable.

In a presentation titled “Challenges in Retrofitting Selective Catalytic Reduction (SCR) Systems to Existing Stationary Natural Gas Fired Engines” that was presented at the October 5, 2011 Gas Machinery Conference, it was stated that applying SCR to pipeline engines is not feasible because the exhaust temperatures are below the operating window for SCR or at a level where the SCR effectiveness is reduced, that the exhaust temperature is below the temperature range for reliable decomposition of urea into ammonia, and the effectiveness of SCR has not been demonstrated on the slow speed, large bore, low exhaust temperatures typical of gas pipeline reciprocating engines. For additional information see:
http://www.gmrc.org/ckfinder/userfiles/files/GMC%20Conf/Final%20Papers/Challenges%20in%20Retrofitting%20SCR%20Systems.pdf

However, there are a number of organizations that market SCR systems that indicate that their catalysts are capable of effectively operating over a wide range of exhaust gas temperature. Such catalysts would serve to offer considerable flexibility for application to varying makes/models of four stroke lean burn engines, as well as providing flexibility for effective NOx reduction over a range of operating conditions for those engines.

Another stated issue with the use of SCR for four stroke lean burn spark ignition reciprocating engines is that many compressor facilities are unmanned and that SCR installations have not been demonstrated in unmanned facilities. Other industry information indicates that while it may be true that there are currently few SCRs in unmanned facilities, with modern software based controls and supervisory control and data acquisition (SCADA) type communication technologies there does not appear to be any technical barrier to operating the SCR related controls and auxiliaries successfully from a remote location.

It has also been stated by the gas industry that SCRs have not been demonstrated on combustion devices with variable loads. SCR manufacturers offer catalysts that are effective over wide temperature ranges characteristic of a range in engine operating load. Modern controls also have the ability to closely regulate fuel and air flows to ensure combustion gas oxygen and temperature levels at expected levels and to regulate reagent flow, all serving to ensure proper SCR function over a broad range of load.

The industry trade organizations have also pointed out that many compressor locations are remote and do not include immediate access to an electric supply capable of handling the pumps, etc that are necessary for an SCR system. While this may be a true statement, not all compressor facilities are without access to electric supply resources. Further, any rules or regulations that support NOx emissions limits based on SCR NOx removal capabilities could be configured to offer alternatives for sites with acceptable justification for being unable to attain those limits.

The Manufacturers of Emission Controls Association (MECA) has stated that the commercial use of SCR systems for the control of NOx emissions from lean-burn stationary engines has been in place since the mid-1980s in Europe and since the early 1990s in the US. According to MECA, since 1995, one MECA member company has installed over 400 SCR systems worldwide for stationary engines with varying fuel combinations, including dozens of natural gas powered compressor engines at sites in the US. MECA indicated that these four stroke lean burn gas compressor engines equipped with urea-SCR achieved in excess of 90% reduction in NOx emissions.

Even though some industry sources indicate that SCR is not a practical or proven NOx reduction technology for four stroke lean burn spark ignition reciprocating engines, the information suggests that SCR is not technically infeasible from a generic standpoint. There are a number of manufacturers and suppliers that offer SCR systems that may be used on four stroke lean burn spark ignited reciprocating engines. Some of the manufacturer and supplier information is provided below:

- EF&EE (Engines, Fuel & Emissions Engineering Incorporated) announced on November 10, 2010, that it had received an order from Clean Air Power, Inc. for six SCR reductant metering and control systems. These systems were due to be delivered by the end of 2010, to be installed on large, lean-burn natural gas compressor engines at gas storage sites in Texas and Mississippi. For additional information see: http://www.efee.com/news.html

- EF&EE, on November 22, 2010, also announced Compact SCR(tm) system that enables conventional lean-burn natural gas and biogas engines to meet the California ARB Distributed Generation standard of 0.07 pounds of NOx per megawatt-hour. For additional information see: http://www.efee.com/news.html

- Caterpillar literature indicates that they offer SCR systems for many of their lean burn spark ignition reciprocating engine models, for both new engine installations and existing engine retrofits. Caterpillar indicates that NOx reductions of up to 95% are possible utilizing SCR.

- Johnson Matthey markets urea based SCR systems that reduce NOx emissions from lean burn natural gas fueled engines by 90% or more. Johnson Matthey offers catalysts with a broad effective operating temperature range to achieve NOx reductions earlier in an engine operating cycle and across a wide engine operating range. For additional information see: (http://ect.jmcatalysts.com/site.asp?siteid=836&pageid=888&furtherid=946)

- CleanAir Systems offers a SCR system that they advertise as being applicable to lean burn natural gas fired engines, including those utilized for gas compression. CleanAir indicates that their SCR catalyst allows NOx reduction operation in a wide range of temperatures, from approximately 300 degF to approximately 1000 degF. (CleanAir Systems was acquired by Caterpillar in 2010, and is now called CleanAir Systems, A Caterpillar Company.) Their lean burn engine SCR product is now being referred to as E-Pod SCR. CleanAir indicates that their lean burn engine capable SCR achieves up to 95% reduction in NOx emissions across a wide range of exhaust temperatures. For additional information see: http://www.cleanairsys.com/products/hybrids/index.htm

- Clean Air Power has a case study, dated 3/4/2009, indicating that they had supplied four SCR units (in 2006, with an additional 2 ordered for 2009 delivery) for emissions control of natural gas fueled spark ignition reciprocating engines at the Pine Prairie Energy Center, a salt cavern natural gas storage facility in Louisiana. FERC information indicates that the Pine Prairie Energy Center was incorporating six Caterpillar G16CM34 reciprocating engines, each rated 8,100 HP. For additional information see: http://www.cleanairpower.com/emissionCasestudies.php?mode=details&libraryId=2&start=0&caseId=TXpVPQ

- Clean Air Power has a case study, dated 3/4/2009, indicating that they had supplied an SCR unit for a Caterpillar G3616 natural gas engine located at the salt cavern natural gas storage/hub services facility EXTERRAN/TRESPALACIOS in Texas. For additional information see: http://www.cleanairpower.com/emissionCasestudies.php?mode=details&libraryId=2&start=0&caseId=TXpZPQ==

- Clean Air Power has a case study, dated 3/4/2009, indicating that they were involved in a project that would include supplying four SCR units for natural gas fueled Caterpillar G3616 engines at the EXTERRAN / LEAF RIVER facility in Mississippi. This facility is a salt cavern natural gas storage and delivery site. For additional information see: http://www.cleanairpower.com/emissionCasestudies.php?mode=details&libraryId=2&start=0&caseId=TXpnPQ==

- Miratech Corporation offers a SCR based NOx reduction system that is advertised to be applicable to lean burn engines used in natural gas compression applications. Miratech indicates that NOx reductions of up to 99% are achievable with their SCR system. For additional information see: http://www.miratechcorp.com/images/data/attachments/0000/0019/SCR_Systems.pdf

In 2007 the Illinois Environmental Protection Agency prepared its "Technical Support Document for Controlling Emissions from Stationary Reciprocating Internal Combustion Engines and Turbines". This document reviewed NOx emissions control capabilities and estimated cost effectiveness for a number of NOx controls for lean burn reciprocating engines. Included in this evaluation for lean burn engines is the application of SCR for NOx control. The document indicates that SCR has the capability of reducing NOx emissions from lean burn engines by approximately 90%. The following summarizes the lean burn engine SCR evaluation:

Type of Control	Nameplate Rating (HP)	Total Capital Cost (2004 $)
Lean Burn SCR	550 – 11,000	457,500 – 1,451,000

For additional information see: http://www.epa.state.il.us/air/rules/rice/tsd-rice.pdf

In support of its development of Rule 4702, Internal Combustion Engines Phase 2, in 2003 the San Joaquin Valley Air Pollution Control District prepared a cost effectiveness analysis for the retrofit installation of SCR on natural gas fueled lean burn spark ignited internal combustion engines. The analysis was performed for a range of engine output ratings. The analysis assumed the installation would achieve compliance with a proposed NOx emissions rate limit of 65 ppmvd @15% O2 (approximately 0.89 g/bhp-hr). The results of the analysis for lean burn spark ignition engines is summarized below:

Lean Burn Engine SCR NOx Reduction Control Installation Cost Estimation

Nameplate Rating (hp)	SCR Installed Cost ($)	Annual O&M Cost ($)	Annualized Cost ($)	25% Cap Fact Cost Effectiveness ($/ton)	75% Cap Fact Cost Effectiveness ($/ton)
50	45000	20102	27424	24593	8198
200	45000	26102	33424	7493	2498
500	60000	35102	44864	4023	1341
1000	149000	78102	102344	4589	1530
1500	185000	117102	147202	4400	1467

Note: Annualized cost based on 10 year life and 10% interest.
NOx reductions based on 9.55 g/bhp-hr pre-installation and 0.37 g/bhp-hr post-installation.
For a additional information see:
http://www.arb.ca.gov/pm/pmmeasures/ceffect/reports/sjvapcd_4702_report.pdf

4.2.5 Four Stroke Lean Burn Spark Ignition Reciprocating Engine NOx Control Summary

Industry information indicates that there are technically feasible, commercially available NOx reduction technologies applicable to natural gas fueled, spark ignited, lean burn reciprocating engines. The information suggests that most of these engines would be responsive to combustion and airflow modifications (potentially including installation/upgrade of turbochargers and inter-cooling, pre-chamber ignition or high energy ignition, improved fuel injection control, air/fuel ratio control, etc). The industry information also indicates that there are technically feasible, commercially available post-combustion (SCR) NOx reduction systems available for use on these same engines. However, some of the combustion related and post combustion NOx controls may not be commercially available for all manufacturers and models of four stroke lean burn spark ignited reciprocating engines.

From the industry information it appears that the actual achievable NOx emission rate, in terms of g/bhp-hr, would tend to be engine design specific. Additionally, site specific installation issues may impact controls installation such that the installations are operationally problematic or not cost effective. These engine design and site specific issues are not altogether different than issues encountered with other types of emissions reduction technologies and projects, and can usually be addressed by providing appropriate flexibility in any rulemaking that includes consideration of site specific issues.

The information therefore seems to support NOx emission rate limits of as low as 0.5 g/bhp-hr for many four-stroke lean burn spark ignition reciprocating engines with a nameplate rating of 250 hp or above, providing that there is consideration of individual engine design and site specific flexibility provisions. For four stoke lean burn spark ignited reciprocating engines with nameplate ratings below 250 hp, the available industry information indicates NOx emission rate limits of around 3 g/bhp-hr for some of the existing popular make/model combinations. Again, this could be addressed with appropriate rule or regulation consideration of individual engine design and site specific flexibility provisions.

Very little information was found regarding the cost of purchase and installation of combustion related and post-combustion NOx controls for four stroke lean burn engines. The following summarizes the limited information:

Type of NOx Control	Engine Size Range (hp)	Estimated Range of NOx Reduction (%)	Estimated Range of NOx Emissions Rate (g/bhp-hr)	NOx Control Estimated Costs ($)
Layered Combustion	100 - 250	60 - 90	3 - 0.5	182,000 - 456,000
Layered Combustion	500 - 11000	90	0.5	143,000 – 4,666,000
SCR	2000 - 2500	90	0.5	502,000 – 1,593,000

Note: Estimated control costs are initial capital cost estimates only. Costs are based on Illinois' "Technical Support Document for Controlling Emissions from Stationary Reciprocating Internal Combustion Engines and Turbines", adjusted for CPI.

It should be noted that the range of costs, especially for the combustion related NOx control modifications, is more representative of the diversity of the modifications that might be required to attain the NOx emission rate limits rather than a function of the nameplate rating of the engine. This is due to the fact that some engines may require complete new turbocharger systems with related auxiliaries, while some may require relatively modest modifications to existing systems, some may require new PCC combustion ignition systems while others may require only minor improvements, etc. These differences can exist across the range of four stroke lean burn spark ignited reciprocating engine nameplate ratings.

4.3 Reciprocating Engines - Four Stroke Rich Burn Spark Ignition Engines

In a reciprocating engine, combustion of a compressed fuel-air mixture is used to drive pistons in one or more cylinders, with the linear piston motion converted to rotary motion with a crankshaft. The rotary motion developed by the reciprocating engine may then be utilized to drive natural gas compressors, pumps, mechanical drives, or other rotary loads. Spark ignition engines use a spark (across a spark plug) to ignite the compressed fuel-air mixture to create the motive force.

Four-stroke spark ignition reciprocating engines use a separate engine revolution for the intake/compression stroke and the power/exhaust stroke. Four-stroke reciprocating engines complete the combustion cycle in two revolutions of the crankshaft. Each of the piston's four strokes has an important function in the engine cycle (intake, compression, power and exhaust). These engines have intake and exhaust valves to introduce combustion air into the cylinder and exhaust combustion gases from the cylinder. Most four-stroke spark ignition reciprocating engines use open-chamber spark plugs to ignite the air/fuel mixture. These engines may be either naturally aspirated, using the suction from the piston to entrain the air charge, or utilize a supercharger or turbocharger to pressurize the inlet air/fuel charge.

Rich-burn four-stroke spark ignited reciprocating engines are configured to operate at or near a stoichiometric air/fuel ratio with little or no excess air. The engines can be carbureted or fuel injected, and they use the intake stroke of the piston to draw air into the cylinder (naturally aspirated). Manufacturers have added superchargers and turbochargers to increase the delivery of combustion air, which increases horsepower output capability. Because the air-to-fuel ratio is rich with fuel, more fuel is used, which results in increased combustion temperatures, increased engine power, and decreased engine efficiency relative to a lean burn engine.

There are a number of four stroke rich burn (4SRB) spark ignition reciprocating engines in service in the oil and gas sector, representing several manufacturers and model numbers.

4.3.1 Four Stroke Rich Burn Spark Ignition Engine NOx Controls

Industry literature indicates that application of high energy ignition systems on rich burn spark ignited reciprocating engines has the potential of resulting in modest NOx emissions by providing a more stable combustion over an engine's entire operating range. The high energy ignition system is generally a conventional open-chamber system with the spark plug (or plugs) generally located with the spark plug protruding from the bottom of the combustion cylinder head into the combustion chamber. High energy ignition systems allow more energy to be delivered to the spark plug(s) with a larger gap, thereby increasing the spark energy delivered to the air/fuel mixture and ensuring proper ignition. High energy ignition systems may be digitally controlled systems that use crankshaft referenced angle encoders to deliver precise, high energy ignition sparks. These high energy ignition systems may have the capability to generate multiple, successive sparks during combustion to ensure proper air/fuel light- off. Modern high energy ignition systems tend to reduce misfires and engine detonation, and provide a more stable combustion over an engine's entire operating range. Industry information indicates that a slight NOx emissions reduction, approximately 10%, can be achieved through application of a high energy ignition system on an engine that does not have an existing high energy ignition system.

Non Selective Catalytic Reduction (NSCR) is an effective NOx reduction technology for rich burn spark ignited reciprocating engines that exhibit low levels of excess oxygen in the exhaust. A NSCR, or three way catalyst, is similar to the catalyst controls installed on most modern automobiles. Exhaust from the engine is passed through a metallic or ceramic honeycomb covered with a platinum group metal catalyst. The catalyst promotes the low temperature (approximately 850 degF) reduction of NOx into N_2, the oxidation of CO into CO_2, and the oxidation of VOCs into H_2O and CO_2. NSCR catalyst efficiency is directly related to the air /fuel mixture and temperature of the exhaust. Efficient operation of the catalyst requires the engine exhaust gasses contain no more than 0.5% O_2. In order to obtain the proper exhaust gas O_2 across the operating range, an air/fuel ratio controller is installed that measures the oxygen concentration in the exhaust and adjusts the inlet air fuel ratio to meet the proper 0.5% O_2 exhaust requirement for varying engine load and engine speed conditions and varying ambient conditions. Industry literature indicates that the proper use of NSCR on four-stroke rich burn spark ignition reciprocating engines has NOx reduction capabilities of up to 99%, with NOx emission rates well below 1 g/bhp-hr. Industry information indicates that, across the US, there are thousands of existing NSCR installations. [Retrofit installation of NSCR on five Caterpillar rich burn engines in Texas achieved a NOx reduction of 96% or greater on all of the engines. On two of those engines, testing conducted after more than 4000 hours of operation with the NSCR indicated the NSCR controls were still achieving 95% NOx reduction.]

Some industry literature suggests that some particular 4-stroke rich burn spark ignition reciprocating engines can be converted to lean burn configurations with the accompanying lean burn engine NOx reduction capabilities. One vendor indicates that conversion to a lean burn configuration and the use of exhaust gas recirculation delivers the advantages of a lean burn engine's efficiency and the rich burn engine's capability of utilizing NSCR for NOx control. The ability to convert a rich burn engine to a lean burn configuration is highly unit specific and does appear to have had widespread application in industry.

4-Stroke Rich Burn Spark Ignition Engine NOx Control Retrofit Technology	**Potential NOx Reduction**
High Energy Ignition System	10%
NSCR Catalyst (with air/fuel ratio controller)	90% - 99%

4.3.2 Example Existing Rules and Regulations – 4SRB

California - California's South Coast Air Quality Management District (SCAQMD) has established Rule 1110.2, Emissions from Gaseous and Liquid Fueled Engines, the latest revision of the rule dated July 2010. Rule 1110.2 regulates NOx emissions from new and existing stationary spark or compression ignition internal combustion engines with a nameplate rating of 50 hp or greater. (This rule, 1110.2, may be accessed from http://aqmd.gov/rules/download.html)

NOx emission limits noted in SCAQMD Rule 1110.2 applicable to existing stationary spark and compression ignition engines include:

Nameplate - Bhp≥500	36 ppmvd NOx (*approximately 0.5 g/bhp-hr*)
Nameplate - Bhp<500	45 ppmvd NOx (*approximately 0.6 g/bhp-hr*)
Effective July 1, 2010	
Nameplate - Bhp≥500	11 ppmvd NOx (*approximately 0.15 g/bhp-hr*)
Nameplate - Bhp<500	45 ppmvd NOx (*approximately 0.6 g/bhp-hr*)
Effective July 1, 2011	
Nameplate - All	11 ppmvd NOx (*approximately 0.15 g/bhp-hr*)

(Note that SCAQMD Rule 1110.2 contains exemptions for units that operate less than 500 hrs/yr or burn less than 100 MMBTU/yr.) (Note that the rule makes no distinction for rich burn, lean burn, etc stationary engines.)

Colorado - The state of Colorado's Air Quality Control Commission has established NOx emissions limitation for stationary spark ignited internal combustion reciprocating engines in its Regulation 7, Control of Ozone Via Ozone Precursors (Emissions of Volatile Organic Compounds and Nitrogen Oxides). (This rule may be viewed at http://www.cdphe.state.co.us/regulations/airregs/5CCR1001-9.pdf) NOx emissions limits noted in Colorado's Regulation 7 applicable to existing stationary natural gas fueled rich burn reciprocating internal combustion engines include:

Rich Burn Engine Nameplate – BHP>500 Install NSCR and AFR by July 1, 2010
(Note: The rule includes a $5000/ton cost effectiveness exemption for combined NOx and VOC reductions from rich burn engines.)

NOx emissions limits noted in Colorado's Regulation 7 applicable to new, modified, or relocated stationary natural gas fueled reciprocating internal combustion engines include:

Nameplate-100≤Bhp<500	
Effective January 1, 2008	2 g/bhp-hr
Effective January 1, 2011	1 g/bhp-hr
Nameplate Bhp≥500	
Effective July 1, 2007	2 g/bhp-hr
Effective July 1, 2010	1 g/bhp-hr

Texas - The Texas Commission on Environmental Quality revised its permit by rule (revision date February 17, 2012) for the oil and gas industry sources in Texas, §106.352 Oil and Gas Handling and Production Facilities. The Texas rule provides NOx emissions limitations for the various types of oil and gas sector sources, including NOx emissions limitations for 4-stroke lean burn spark ignition engines. The relevant emissions limitations in the rule include the following:

Rich Burn SI Engines – BHP ≥ 500	Mfg before 1/1/2011	2g/bhp-hr

Mfg on or after 1/1/2011	1g/bhp-hr
After 1/1/2020, regardless of mfg date	1g/bhp-hr

(This rule can be reviewed at:
http://www.tceq.texas.gov/assets/public/permitting/air/NewSourceReview/oilgas/og-easy-2012.pdf).

Additionally, Texas Administrative Code, Combustion Control at Major Industrial, Commercial, and Institutional Sources in Ozone Non-Attainment Areas, Beaumont-Port Arthur Ozone NonAttainment Area Major Sources, Rule §117.105, Emission Specifications for Reasonably Available Control Technology (RACT), provides NOx emissions limitations for rich burn spark ignited engines as follows:

Gas Fueled Rich Burn SI Engine ≥ 300 bhp	2.0 g/bhp-hr

Pennsylvania has recently proposed a revision to its General Permit for Natural Gas Production and Processing Facilities (GP-5). The proposed GP-5 will apply to all spark ignition internal combustion engines and other air contamination sources at natural gas production and processing facilities. In the proposed GP-5, existing rich and lean burn engines with a nameplate rating of less than or equal to 100 horsepower, but less than 1500 horsepower, will be required to continue to meet the existing GP-5 NOx emissions limit of 2 g/bhp-hr. When the currently proposed GP-5 becomes effective, new and reconstructed rich burn engines will be required to meet the following NOx emissions limits:

Configuration	NOx Limit
New and reconfigured Rich Burn Engine - All	0.2 g/bhp-hr

The USEPA established NOx emissions limitations for natural gas fueled rich burn spark ignition engines in 40 CFR Part 60, Subpart JJJJ (NSPS) (1/18/08 73 FR 3567). The applicable NOx emissions limits for rich burn natural gas-fueled, spark ignition engines are as follows:

Engine Type	Output Rating	Manufacture Date	NOx Emissions Limit
SI Nat. Gas	100≤HP<500	mfg after 7/1/2008	2.0 g/HP-hr
SI Nat. Gas	100≤HP<500	mfg after 1/1/2011	1.0 g/HP-hr
SI Nat. Gas	HP≥500	mfg after 7/1/2007	2.0 g/HP-hr
SI Nat. Gas	HP>500	mfg after 7/1/2010	1.0 g/HP-hr

4.3.3 Discussion of Four Stroke Spark Ignition Engine NOx Reduction Capability – Combustion Modifications

Industry literature indicates that there are relatively few highly effective combustion related NOx emission controls utilized for four stroke rich burn spark ignition engines, other than ignition related controls that would be expected to have only minor NOx reduction benefits. Industry literature suggests that some individual model four stroke rich burn spark ignition engines can be converted to a lean burn configuration with the potential of achieving NOx reductions similar to those of other lean burn engines. However, the literature suggests that such conversion capabilities appear to be very limited and expensive.

Some information that was found regarding combustion controls for NOx reduction from rich burn engines is summarized below:

- A 1999 paper by Enginuity (now part of Dresser-Rand) discusses a project to install NOx reduction combustion controls on five 1950's vintage Ingersoll Rand KVG-103 four stroke rich burn carbureted engines rated at 1000hp each. The project included the installation of a turbocharger and related auxiliaries, removal of the carburetor and installation of single point fuel injection and related controls, installation of a screw-in pre-combustion chamber to improve ignition, and improved engine controls. NOx emissions were reduced 80% to 90% to below 2 g/bhp-hr across the engines' load range, with improvements in fuel consumption. For additional information see: http://www.dresser-rand.com/techpapers/tp149.pdf

- Attainment Technologies company markets gas recirculation systems for NOx control for four stroke rich burn spark ignition engines. (Exhaust gas recirculation as a NOx control for these engines is also being offered by some original equipment manufacturers (OEMs).) Attainment Technologies' literature indicates that the use of their rich burn engine NOx reduction process can lower the engine out NOx emissions by up to 80%. The NOx reduction is accompanied by a higher power output and better fuel efficiency when a higher compression ratio can be used. Experience with a Caterpillar 3516 turbocharged engine showed an increase in power output by 10**%** and a decrease in fuel consumption of 7**%** when this principal is applied. Attainment Technologies' literature indicates that retrofitted rich burn spark ignition reciprocating engines have achieved NOx emission rates of 0.1 g/bhp-hr in testing using the Attainment Technologies NOx reduction systems. For additional information see: http://www.attainmenttech.com/solutions.html

- Caterpillar literature indicates that they offer emissions upgrade groups for retrofit for certain of its engine models, including many 3306 and 3406 models. These emissions upgrade groups may include an upgraded turbocharger, fuel pump/governor, nozzles, cylinder pack, after-coolers (if applicable), and installation parts.

4.3.4 Discussion of NOx Reduction Capability – Post Combustion Modifications

Industry literature suggests that the use of non-selective catalytic reduction NOx controls (both in new and retrofit application), in conjunction with a modern air/fuel controller, on four stroke rich burn engines is a highly effective NOx control for these engines and has been installed in relatively high numbers. NSCR controls are available from a number of suppliers including some engine OEMs. With modern air/fuel controllers, the NSCR is an effective NOx control over a broad range of engine operation. The data suggests that there are many NSCRs in successful service on four stroke rich burn spark ignition reciprocating engines, and the controls have been installed on four stroke rich burn reciprocating engines representative of a wide range of engine nameplate ratings. Industry literature suggests that NOx control in excess of 90% can be expected through utilization of NSCR and air/fuel ratio controller on an otherwise uncontrolled four stroke rich burn engine.

While NSCR is considered a post-combustion control, successful application of the NSCR usually also requires the installation of a modern air fuel ratio controller (AFRC). The AFRC is necessary to properly manipulate the engine combustion parameters across the rich burn engine's operating range in order to maintain the exhaust gas excess oxygen in the range required for proper, efficient operation of the NSCR. Because successful, efficient operation of the NSCR is dependent upon proper control of an AFRC, the further discussion of NSCR below implies the simultaneous installation of an appropriate AFRC.

There are a number of manufacturer's and suppliers that offer NSCR systems that may be used on four stroke rich burn spark ignition reciprocating engines. Some of the manufacturer and supplier information reviewed is summarized below:

- A presentation by Environ, Demonstration of NOx Emission Controls for Gas Compressor Engines, A Study for Northeast Texas Presented by ENVIRON, dated December 6, 2005, discussed a study where NSCR NOx controls were installed on existing Caterpillar rich burn engines with output rating from 145 hp to 265 hp. After installation of the NSCR controls, NOx emissions were reduced to a range of 0.3 g/bhp-hr to 0.5 g/bhp-hr. The document indicated that the average cost was $10,622 per engine, including the NSCR module, an AFR controller, a solar power unit, and installation labor. For additional information see: http://www.epa.gov/glo/SIPToolkit/documents/12-20-05_rich-burn_engine_control_briefing.pdf (The above project was more completely documented in "A Pilot Project to Assess the Effectiveness of an Emission Control System for Gas Compressor Engines in Northeast Texas", Final Report, November 4, 2005, http://www.scribd.com/doc/1597001/Environmental-Protection-Agency-NETAC-Compressor-Retrofit-Final-Report-110405)

- Dresser-Rand markets NSCR systems for NOx reduction from rich burn engines, as both new unit installations and for retrofit to existing engines. For additional information see: http://dresser-rand.com/literature/enginuity/2187_Enginuity-Compi_catsys.pdf

- Caterpillar literature indicates that they offer NSCR systems for many of their rich burn engine models, for both new engine installations and existing engine retrofits. Caterpillar indicates that NOx reductions of up to 95% are possible utilizing NSCR.

- CleanAir Systems offers a NSCR NOx reduction catalyst for rich burn engines, including those utilized for gas compression. (CleanAir Systems was acquired by Caterpillar in 2010, and is now called CleanAir Systems, A Caterpillar Company.) CleanAir Systems' NSCR is now referred to as ASURE TWC (three way converter). The use of an air fuel ratio controller is also recommended in these applications, and they are also offered by CleanAir Systems. CleanAir Systems indicates that their ASSURE TWC NSCR can achieve NOx emission reductions up to 99%. For additional information see: http://www.cleanairsys.com/products/converters/ASSURE-OC-TWC.htm

- Miratech Corporation offers a NSCR catalyst system for NOx reduction from rich burn engines used in natural gas compression applications. For additional information see: http://www.miratechcorp.com/site/miratech/section/17

- Johnson Matthey markets 3-way catalyst systems that reduce NOx emissions from rich burn natural gas fueled engines by 95% or more, and able to achieve NOx emission rates down to approximately

0.07 g/bhp-hr. For additional information see : (http://ect.jmcatalysts.com/site.asp?siteid=836&pageid=888&furtherid=946)

- A 2009 brochure from Dresser Waukesha indicates that new Waukesha rich burn engines are commercially available with horsepower ratings up to 1,980 hp and, equipped with NSCR, achieve NOx emissions levels below 0.15 g/bhp-hr. For additional information see: http://www.dresserwaukesha.com/documents/1256_0309.pdf

In an April 28, 2006 memo from Alpha-Gama Technologies to the USEPA, Control Costs for Reciprocating Internal Combustion Engines at Major and Area Sources, cost estimates were prepared for the installation of NSCR on four stroke rich burn engines. For capital cost estimates, the following equation was determined: NSCR Capital Cost = 19.7 * HP + 1799, where HP is the engine's horsepower output rating. For annual operating costs, the following equation was determined: NSCR Annual Cost = 2.65 * HP + 657, where HP is the engine's horsepower output rating. For additional information see: http://www.regulations.gov/#!documentDetail;D=EPA-HQ-OAR-2005-0030-0005

In 2007 the Illinois Environmental Protection Agency prepared its "Technical Support Document for Controlling Emissions from Stationary Reciprocating Internal Combustion Engines and Turbines". This document reviewed NOx emissions control capabilities and estimated cost effectiveness for a number of NOx controls for rich burn reciprocating engines. Included in this evaluation for rich burn engines is the application of NSCR for NOx control. The document indicates that NSCR has the capability of reducing NOx emissions from rich burn engines by approximately 90% to 98%. The following summarizes the rich burn engine NSCR evaluation:

Type of Control	Nameplate Rating (HP)	Total Capital Cost (2004 $)	Cost Effectiveness (2004 $/ton)
Rich Burn NSCR	500 – 8,000	35,400 – 330,700	319 – 1,647

For additional information see: http://www.epa.state.il.us/air/rules/rice/tsd-rice.pdf

In support of its development of Rule 4702, Internal Combustion Engines Phase 2, in 2003 the San Joaquin Valley Air Pollution Control District prepared a cost effectiveness analysis for the retrofit installation of NSCR on rich burn spark ignited internal combustion engines. The analysis was performed for a range of engine output ratings. The analysis assumed the installation would achieve compliance with a proposed NOx emissions rate limit of 25 ppmvd @15% O2 (approximately 0.37 g/bhp-hr). The results of the analysis for rich burn spark ignition engines is summarized below:

Rich Burn Engine NSCR NOx Reduction Control Installation Cost Estimation

Nameplate Rating (hp)	NSCR Installed Cost ($)	Annual O&M Cost ($)	Annualized Cost ($)	25% Cap Fact Cost Effectiveness ($/ton)	75% Cap Fact Cost Effectiveness ($/ton)
50	13500	7199	9395	8415	2829
200	18500	7819	10829	2446	815
500	20500	8819	12154	1098	366
1000	30500	11319	16281	735	245
1500	47000	18919	26566	800	267

Note: Annualized cost based on 10 year life and 10% interest.

NOx reductions based on 9.55 g/bhp-hr pre-installation and 0.37 g/bhp-hr post-installation.
For additional information see:
http://www.arb.ca.gov/pm/pmmeasures/ceffect/reports/sjvapcd_4702_report.pdf

4.3.5 Four Stroke Rich Burn Spark Ignition Engine NOx Control Summary

Industry information indicates that there are technically feasible, commercially available NOx reduction technologies applicable to natural gas fired, spark ignited, rich burn engines. The information suggests that there are a few combustion related NOx emissions control applicable to these rich burn engines, such as installation of EGR, improved induction and fuel delivery, modification for lean burn operation, etc. However, such modifications may not be feasible for retrofit for all subject rich burn engines due unavailability of the required components or extraordinarily high costs to make the conversions. The industry information also indicates that there are technically feasible, commercially available post-combustion (NSCR) NOx reduction systems available for use on virtually the entire range of nameplate ratings and make/model variability of the four stroke rich burn spark ignition reciprocating engines.

From the industry information it appears that the actual achievable NOx emission rate, in terms of g/bhp-hr, achievable from installation of NSCR tends to be engine design specific. However, it appears that commercially proven NSCR NOx reduction technologies are widely available from engine original equipment manufacturer (OEM) companies as well as aftermarket suppliers that can be expected to achieve NOx reductions of 90% or greater. While there may be a few engine specific or site specific installation or operational problems that could impact NSCR performance, there appears to be little industry information that documents such issues. Any potential engine design or site specific issues could generally be addressed by providing appropriate flexibility in any rulemaking that includes consideration of site specific issues.

The information therefore seems to support NOx emission rate limits of 0.5 g/bhp-hr for many four-stroke rich burn spark ignition reciprocating engines with a nameplate rating of 50 hp or above, providing that there is consideration of individual engine design and site specific flexibility provisions. Engine specific and site specific issues could be addressed with appropriate rule or regulation flexibility of consideration of individual engine design and site specific flexibility provisions.

The installation of NSCR on both a new and retrofit basis for rich burn engines has been a widespread practice for a considerable time, and should be considered a relatively mature process. While capital costs would be somewhat site specific, industry literature indicates that for the majority of installations the capital costs are primarily a function of the rich burn engine's nameplate rating.

Type of NOx Control	Engine Size Range (hp)	Estimated Range of NOx Reduction (%)	Estimated Range of NOx Emissions Rate (g/bhp-hr)	NOx Control Estimated Costs ($)
Retrofit NSCR	50 - 8000	90	0.5	16,700 - 363,000
New Unit w/NSCR	50 - 8000	N/A	0.15	N/A

(Note: Estimated control costs are initial capital cost estimates only. Costs are based on Illinois' "Technical Support Document for Controlling Emissions from Stationary Reciprocating Internal Combustion Engines and Turbines", adjusted for CPI.)

It should be noted that the range of costs for installation of NSCR on four stroke rich burn spark ignition reciprocating engines is primarily a function of the nameplate rating of the engine. However, variability may exist due to site specific conditions and complexity of installation of an air/fuel ratio controller.

4.4 Reciprocating Engines - Diesel Engines

In a reciprocating engine, combustion of a compressed fuel-air mixture is used to drive pistons in one or more cylinders, with the linear piston motion converted to rotary motion with a crankshaft. The rotary motion developed by the reciprocating engine may then be utilized to drive natural gas compressors, pumps, mechanical drives, or other rotary loads. Compression ignition engines utilize the heat generated during relatively high levels of compression of the combustion air in the combustion chamber to cause ignition of the fuel air mixture when the fuel is introduced into the combustion chamber. Diesel engines may be either two-stroke or four-stroke.

In a diesel engine, combustion air is drawn into the cylinder and compressed in the combustion chamber with a relatively high compression ratio compared to most spark ignition engines. As a result of the compression, the combustion air temperature is raised to a high level, often 1300 degF to 1650 degF. With the piston at or near the top of the compression stroke, diesel fuel is injected into the combustion chamber through an atomizing fuel nozzle, mixing the fuel with the hot combustion air. The fuel air mixture ignites as a result of the high temperature in the combustion chamber. The expanding combustion products push down on the piston and connecting rod, which transfers this motion to the crankshaft, resulting in rotary motion and engine output power. The inlet of combustion air and exhaust of spent combustion products occurs through ports or valves in the cylinder heads. To further improve the output and efficiency of a diesel engine, turbochargers are often utilized to compress the combustion air prior to entry into the cylinder and attaining a high level of cylinder filling and pressure. The use of air coolers between the air outlet of the turbocharger and the cylinder inlet cools the combustion air and helps further improve the engine efficiency.

Diesel engines may be either 2 stroke or 4 stroke configurations, with the majority being 4 stroke and some large units being 2 stroke. Diesel engines are lean burn engines.

There are various diesel engine manufacturers, with most manufacturing multiple models with a range of rated outputs.

4.4.1 Diesel Engine NOx Controls

One potential method to achieve modest NOx emissions reductions from diesel engines is the appropriate setting of the fuel injection timing. Control of the start of fuel injection timing, relative to the crankshaft angle of top-dead-center for the specific cylinder, can affect the diesel engine's efficiency and NOx emissions, depending upon engine design and load. Advancing the fuel injection timing, relative to the cylinder's compression top dead center, will tend to improve the engines efficiency and result in higher NOx emissions. Retarding the injection timing, relative to the cylinder's compression top dead center, will tend to reduce NOx emissions but also reduced the engine's efficiency, possibly increasing the engine's particulate emissions. The amount of effective control is highly dependent upon the engine design and operating characteristics. While this NOx reduction technology is applicable to nearly any diesel engine, its effectiveness is likely greatest on older, otherwise uncontrolled, diesel engines. Industry literature suggests that NOx reductions of up to 20% to 25% may be possible utilizing diesel injection timing retard, with a 10% reduction being more common.

Another potential method to achieve modest diesel engine NOx emissions reductions is the use of emulsified fuels. Emulsified diesel fuel is a blended mixture of diesel fuel, water and other additives.

The water is suspended in droplets within the fuel, creating a cooling effect in the combustion chamber that decreases NOx emissions. A fuel-water emulsion creates a leaner fuel environment in the engine, lowering NOx and PM emissions. Emulsified diesel can be used in any diesel engine, but there is a decrease in power and fuel economy due to the fact that the addition of water reduces fuel energy content. Emulsified fuel can achieve emission reduction of NOx by about 10 to 20 percent and PM by about 50 to 60 percent.

The use of exhaust gas recirculation (EGR) is an effective NOx control for diesel engines in new and retrofit applications. Both low-pressure and high-pressure EGR systems exist but low-pressure EGR is used for retrofit applications because it does not require engine modifications. EGR involves recirculating a portion of the engine's exhaust gas back to the turbocharger inlet or intake manifold, in the case of a naturally aspirated engines. In most systems, an intercooler lowers the temperature of the recirculated exhaust gas. The cooled recirculated exhaust gas mixed in with the combustion air tends to result in an overall lower combustion temperature in the engine, thus inhibiting NOx formation. Diesel particulate filters are always used with a low-pressure EGR system to ensure that large amounts of particulate matter are not recirculated to the engine. EGR systems are capable of achieving NOx reductions of more than 40 percent in both new and retrofit applications.

Selective catalytic reduction (SCR) is a post-combustion NOx control applicable to diesel engines that utilizes a catalyst and a reducing agent to reduce the concentration of NOx in the exiting combustion gasses. The reagent, typically ammonia or urea, is injected into the exhaust stream of the engine. Once in the exhaust, the ammonia (or urea that decomposes to produce ammonia in the exhaust stream) passes over a catalyst to turn NOx into water, nitrogen and CO_2. Catalyst selection is somewhat based on the expected temperature range of the engine exhaust, and is sized to achieve the desired amount of NOx reduction. The reagent injection system is comprised of a storage tank, reagent injector(s), reagent pump, pressure regulator and electronic controls to accurately meter the quantity of reagent injected as a function of engine load, speed, temperature and NOx emissions. Industry information indicates that the use of SCR for NOx control may facilitate NOx reductions of up to 95%, although 75% to 90% reduction is more typical. Industry information indicates that there are a number of suppliers of SCR systems for diesel engines, and many systems have been installed and are successfully in commercial operation. SCR may be utilized in either a new or retrofit application.

Industry information indicates that there are additional NOx reduction technologies applicable to diesel engines. One technology, lean NOx catalyst systems, utilize injection of a small amount of fuel into the exhaust to act as a reductant in conjunction with a zeolite catalyst to attain NOx reductions of 10% to 30%. Another, lean NOx traps, traps NOx in a barium hydroxide or barium carbonate material during normal engine lean operation, and engine controls periodically cause the engine to operate fuel rich mode to regenerate the trap material and release the NOx as N2 or NH3. Industry information indicates that lean NOx traps may be able to reduce NOx emissions by as much as 90%. No information was found regarding commercial operation of either of these technologies in the field, so they are not considered to be commercially available diesel engine NOx reduction technologies for the purposes of this review.

Compression Ignition Engine NOx Control Retrofit Technology	**Potential NOx Reduction**
Fuel Injection Timing	10%
Emulsified Fuel	10% - 20%
Exhaust Gas Recirculation	40% - 50%

Selective Catalytic Reduction	75% - 90%

4.4.2 Example Existing Rules and Regulations – Diesel Engines

California - California's South Coast Air Quality Management District (SCAQMD) has established Rule 1110.2, Emissions from Gaseous and Liquid Fueled Engines, the latest revision of the rule dated July 2010. Rule 1110.2 regulates NOx emissions from new and existing stationary spark or compression ignition internal combustion engines with a nameplate rating of 50 hp or greater. (This rule, 1110.2, may be accessed from http://aqmd.gov/rules/download.html)

NOx emission limits noted in SCAQMD Rule 1110.2 applicable to existing stationary spark and compression ignition engines include:

Nameplate - Bhp≥500 36 ppmvd NOx (*approximately 0.5 g/bhp-hr*)
Nameplate - Bhp<500 45 ppmvd NOx (*approximately 0.6 g/bhp-hr*)

Effective July 1, 2010
Nameplate - Bhp≥500 11 ppmvd NOx (*approximately 0.15 g/bhp-hr*)
Nameplate - Bhp<500 45 ppmvd NOx (*approximately 0.6 g/bhp-hr*)

Effective July 1, 2011
Nameplate - All 11 ppmvd NOx (*approximately 0.15 g/bhp-hr*)

(Note that SCAQMD Rule 1110.2 contains exemptions for units that operate less than 500 hrs/yr or burn less than 100 MMBTU/yr.) (Note that the rule makes no distinction for rich burn, lean burn, etc stationary engines.)

The USEPA has established NOx emissions limitations for new compression ignition engines, and those limitations vary with the manufacture date of the subject engines. For example 40 CFR Part 60, Subpart IIII—Standards of Performance for Stationary Compression Ignition Internal Combustion Engines, requires that the owners and operators of pre-2007 model year non-emergency stationary compression ignition engines with a displacement of less than 10 liters per cylinder comply with the following NOx emission standards:

Maximum Engine Power	Emission standards or stationary pre-2007 model year engines with a displacement of <10 liters per cylinder and 2007 -2010 model year engines > 3000 HP and with a displacement of <10 liters per cylinder (g/HP-hr)
HP<11	
11≤HP<25	

25≤HP<50	
50≤HP<75	6.9
75≤HP<100	6.9
100≤HP<175	6.9
175≤HP<300	6.9
300≤HP<600	6.9
600≤HP≤750	6.9
HP>750	6.9

NOx emissions standards for 2011 and beyond compression ignition engines are identified in 40 CFR Part 1039—Control Of Emissions From New And In-Use Nonroad Compression-Ignition Engines, as shown in the following table:

Maximum engine power	NO_X
kW < 19	
19 ≤ kW < 56	
56 ≤ kW < 130	0.4
130 ≤ kW ≤ 560	0.4
kW > 560	3.5

(Note: Nox emissions limits in above table are in g/kw-hr)

4.4.3 Discussion of Diesel Engine NOx Reduction Capability – Combustion Modifications

The use of emulsified fuels is accomplished by using surfactant additives to encapsulate water droplets in diesel fuel to form a stable mixture while ensuring that the water does not contact metal engine parts. Firing emulsified fuels in diesel engines tends to reduce peak engine combustion temperatures and increase fuel atomization and combustion efficiency. However, the use of the emulsified fuels also tends to result in an approximate 20% reduction in peak engine output. Emulsified fuels are expected to have an approximate 15% cost penalty compared to traditional diesel fuel costs. The low NOx reduction capability of this technology, along with the relatively large impact on engine output, make the use of emulsified fuels an unlikely standalone technology for use in diesel engine NOx reduction.

Exhaust gas recirculation (EGR) is an available NOx reduction technology applicable to diesel engines. Some original equipment manufacturer (OEM) diesel engines are currently being marketed with EGR as original equipment. There are also some suppliers of retrofit EGR systems for existing diesel engines. There is little information concerning the availability of such retrofits for the wide range of diesel engine makes and models. Any EGR system would likely require a custom design for each make and model, with potential further customization required for site specific conditions. Some of the industry information indicates that low sulfur fuels and particulate traps are required with the retrofit of EGR systems to help maintain system performance and to limit additional wear on engine components and contamination of lube oil. The industry information indicates that the use of EGR can achieve NOx reductions of from 40% to 50%. The information also indicates that the use of EGR can result in an approximate 2% loss in fuel efficiency and a loss of approximately 2% in engine output capability, dependent upon the amount of exhaust gas recirculated. No specific cost estimates were found regarding the retrofit of EGR on existing diesel engines. However, one source suggested a potential retrofit capital cost of $500 to $700 per engine rated horsepower.

4.4.4 Discussion of Diesel Engine NOx Reduction Capability – Post Combustion Modifications

The post-combustion control selective catalytic reduction (SCR) is the process where a reductant (typically ammonia or urea) is added to the flue gas stream and is absorbed onto the catalyst (typically vanadium or zeolite) enabling the chemical reduction of NOx to molecular nitrogen and water. Diesel engines typically have unconsumed oxygen in the exhaust, which inhibits removal of oxygen from the NOx molecules. To remove the unconsumed oxygen, the catalyst decomposes the reductant causing the release of hydrogen, which reacts with the oxygen. This creates local oxygen depletion near the catalyst allowing the hydrogen to also react with the NOx molecules to form nitrogen and water.

A number of information sources discuss diesel engine applicable SCR systems and the performance of some installation examples, including the following:

- A presentation by Shell indicated that Shell has been installing SCR NOx reduction systems on diesel engines used to support drilling rig operations. Shell's information indicated that Shell has observed NOx reductions of greater than 90% in this application with minimal impact on operations. This project is further documented in an application fact sheet from Johnson Matthey Catalysts, "Case No. 801: Controlling NOx From Gas Drilling Rig Engines With Johnson Matthey's Urea SCR System" . For the project, Johnson Matthey provided urea SCR systems for three 1476 hp Caterpillar 3512 BDITA diesel engines. Johnson Matthey indicated that the supplied SCR systems were designed to operate in harsh environmental conditions and with the dramatic engine load swings associated with drilling operations. Johnson Matthey indicated that they met the 90% NOx emissions reduction requirements, actually achieving NOx reductions between 91% and 99%. For additional information see: http://ect.jmcatalysts.com/pdfs-library/Application%20Fact%20Sheet%20801%20-%20Shell%20Gas%20Drill%20Rig.pdf

- Johnson Matthey markets urea based SCR systems that reduce NOx emissions from diesel engines by 90% or more. Johnson Matthey offers catalysts with a broad effective operating temperature range to achieve NOx reductions earlier in an engine operating cycle and across a wide engine operating range. For additional information see: http://ect.jmcatalysts.com/site.asp?siteid=836&pageid=888&furtherid=946

- CleanAir Systems offers a SCR system that they advertise as being applicable to dieselengines. CleanAir indicates that their SCR catalyst allows NOx reduction operation in a wide range of temperatures, from approximately 300 degF to approximately 1000 degF. (CleanAir Systems was acquired by Caterpillar in 2010, and is now called CleanAir Systems, A Caterpillar Company.) Their diesel engine SCR product is now being referred to as E-Pod SCR. CleanAir indicates that their diesel engine capable SCR achieves up to 95% reduction in NOx emissions across a wide range of exhaust temperatures. For additional information see: http://www.cleanairsys.com/products/hybrids/index.htm

- Miratech Corporation offers a SCR based NOx reduction system that is advertised to be applicable to diesel engines. Miratech indicates that NOx reductions of up to 99% are achievable with their SCR system. For additional information see: http://www.miratechcorp.com/images/data/attachments/0000/0019/SCR_Systems.pdf

- Wartsila offers a retrofit SCR NOx reduction system for diesel engines. Wartsila indicates that their product is scalable to meet the needs of various engine size/needs and may be provided as a skid-based system. Wartsila specifically targets the oil/gas industry for this system, most specifically for drilling rig operations. Wartsila indicates that their SCR system can attain 85% to 95% reduction in NOx emissions. For additional information see: http://wartsila.com/en/environmental-technologies/air-emissions-control/NOR

- A Combustion Components Associates Inc. technical bulletin describes a project involving the installation of SCR systems on four new Caterpillar 3516 2.5MW diesel engines. The SCR systems were designed to eliminate the need for compressed air in atomizing the urea, and achieved NOx reductions of over 90%. The bulletin indicates that the SCR systems allowed the engines to achieve NOx emissions rates below the 0.6 g/bhp-hr across an operating load range of 25% to 100% load. For additional information see: (http://combustioncomponents.com/downloads/Technical_Bulletin_2009-001.pdf)

- A Combustion Components Associates Inc. technical bulletin describes a project involving the installation of SCR systems on four existing General Motors EMD two-stroke V-16 2100kw diesel engines. The SCR systems were designed to achieve a NOx emissions rate limit of 2.3 g/bhp-hr which represented an approximate 73% reduction from the uncontrolled emissions rate. For additional information see: (http://combustioncomponents.com/downloads/BL_England_Case_Study.pdf)

In 2007 the Illinois Environmental Protection Agency prepared its "Technical Support Document for Controlling Emissions from Stationary Reciprocating Internal Combustion Engines and Turbines". This document reviewed NOx emissions control capabilities and estimated cost effectiveness for a number of NOx controls for diesel reciprocating engines. Included in this evaluation for diesel engines is the application of SCR for NOx control. The document indicates that SCR has the capability of reducing NOx emissions from diesel engines by approximately 80% to 90%. The following summarizes the diesel engine SCR evaluation:

Type of Control	Nameplate Rating (HP)	Total Capital Cost (2004 $)	Cost Effectiveness (2004 $/ton)
Diesel SCR	500 - 8000	308,500 – 1,264,100	899 – 4,536

For additional information see: http://www.epa.state.il.us/air/rules/rice/tsd-rice.pdf

In its "Alternative Controls Techniques Document: Stationary Diesel Engines", the EPA provided estimated costs for the installation of SCR on diesel engines. In the document, the EPA states that the capital costs for diesel EGR are approximately $98 per rated horsepower, including the catalyst, reactor housing and ductwork, ammonia injection system, controls, engineering, and installation. The following table summarizes the EPA's estimates presented in the document:

Diesel Engine Nameplate Rating (hp)	Estimated Capital Cost (2009$)
75 – 100	7,350
175 – 300	23,324
600 – 750	66,150
>750	98,000

For additional information see:
http://www.epa.gov/ttn/atw/rice/diesel_eng_act.pdf

4.4.5 Diesel Engine NOx Control Summary

Industry information indicates that there are several available NOx reduction technologies applicable to diesel engines. Some combustion related NOx reduction technologies offer only low levels of NOx reduction, e.g. injection timing (~ 10% reduction), emulsified fuel (10% to 20% reduction). Another combustion related diesel engine NOx reduction technology, exhaust gas recirculation (EGR), is reported to be capable of moderate levels of NOx reduction (40% to 50%), but has had limited retrofit application to date. Because of the limited NOx reduction capabilities of these technologies and apparent limited commercial availability of the technologies, at this time these combustion related technologies are not considered primary NOx reduction technologies for use in diesel engine retrofit. This could change in the future as the technologies become more developed and more widely commercially available.

The industry information indicates that post-combustion controls are also applicable to diesel engines for NOx reduction. The available information describes NOx traps and NOx absorbers for diesel engine applications, but no examples of commercial application of these technologies on diesel engines could be found. In contrast, SCR is a post combustion NOx reduction technology applicable to diesel engines, it is commercially available from several suppliers, and has been in commercial operation on diesel engines for some time. Some examples of existing installation of SCR on diesel engines include the use of diesel to drive electric generators in base, intermediate, and peak operating modes and for use on diesel generators utilized to power drilling rigs (variable operation). Industry information indicates the SCR can achieve NOx reductions from diesel engines in the range of 75% to 90%.

Based on the available information, it appears that a properly sized and engineered SCR system is the only currently commercially available NOx emission control for diesel engines with the capability of achieving up to 90% control of NOx emissions.

NOx Reduction Technology	Nameplate Rating (hp)	Estimate Range of Controlled NOx (%)	Estimated Cost ($)
SCR	500 - 8000	75 – 90	371,700 – 1,523,200

(Note: Estimated control costs are initial capital cost estimates only. Costs are based on Illinois' "Technical Support Document for Controlling Emissions from Stationary Reciprocating Internal Combustion Engines and Turbines", adjusted for CPI.)

4.5 Combustion Turbines

Combustion turbines have three main sections; the compressor, the combustor, and the power turbine. The compressor draws in and pressurizes ambient air. In the combustor, fuel is mixed and combusted with a portion of the compressed air. The resulting combustion gases are diluted with the remainder of the air from the compressor to create a large volume of a hot, compressed combustion gas mixture. The hot, compressed gases then expand in the turbine section, driving the power turbine and creating the turbine's output rotary motion. The rotating turbine shaft is connected to the driven load, sometimes through a gear box.

There are several different manufacturers of combustion turbines, and each manufacturer generally has multiple combustion turbine models that represent a wide range of combustion turbine output ratings.

4.5.1 Combustion Turbine NOx Controls

There are a number of commercially available NOx reduction technologies for combustion turbines, but not all may be applicable or available for any given make/model of combustion turbine.

Water injection is a NOx reduction technology applicable to most combustion turbines. Injecting water into the combustion zone tends to lower peak flame temperatures, thereby lowering the amount of thermal NOx formation during combustion. Water may be injected directly into the turbine combustor, or may be converted to steam using turbine exhaust waste heat with a heat recovery steam generator (HRSG), and then injected into the combustor as steam. More steam than water must be used to achieve a comparable NOx reduction, but the use of steam may result in a lower energy penalty than use of water if the turbine's waste heat would not otherwise be recovered and used. Depending upon the make/model of the applicable combustion turbine, turbine modifications may be as simple as replacement of fuel nozzles with nozzles capable of supplying fuel and water/steam (and associated plumbing), or may be as complex as requiring replacement of the combustors designed to operate with water/steam injection (and associated plumbing). Other required equipment would include appropriate combustion turbine control systems, a source of demineralized water (onsite water plant with storage, or storage tank for demineralized water prepared offsite), a water injection pump, and a water/steam flow metering station. Industry literature indicates that water/steam injection can result in combustion turbine NOx emissions reductions of 40% or more.

The use of dry low NOx burners (DLNB) is a NOx emissions reduction technology available for many makes and models of combustion turbines. DLNB technology utilizes a lean, premixed flame in the combustor as opposed to a turbulent diffusion flame. In a lean, premixed combustor, the fuel and air are premixed prior to entering the combustion zone. With a lean, premixed flame, the contribution of prompt and thermal NOx can be much lower than for a turbulent diffusion flame that is typical for non-DLNB combustion turbine combustors. Many DLNB combustors are capable of achieving NOx emissions reductions across the full load range, but some require more sophistication to allow variable operating modes in order to maintain flame stability across the full load range. Not all turbine designs can accommodate a DLNB, and DNLB combustors may not be available for all makes and models of combustion turbines. In addition to the replacement of the turbine's combustors, installation of DLNB technology may require modifications or replacement of associated piping and turbine combustion control modification or replacement. Industry literature indicates that the retrofit utilization of DLNB technology can achieve NOx reductions of 60% or more for those units where the technology is available.

Selective catalytic reduction (SCR) is a NOx reduction technology applicable to combustion turbines. SCR is a post-combustion NOx control that utilizes a catalyst and a reducing agent to reduce the concentration of NOx in the exiting combustion gasses. The reagent, typically ammonia or urea, is injected into the exhaust stream of the combustion turbine. Once in the exhaust, the ammonia (or urea that decomposes to produce ammonia in the exhaust stream) passes over a catalyst to turn NOx into water, nitrogen and CO_2. Catalyst selection is somewhat based on the expected temperature range of the combustion turbine exhaust, and is sized to achieve the desired amount of NOx reduction. The reagent injection system is comprised of a storage tank, reagent injector(s), a reagent pump, pressure regulator and electronic controls to accurately meter the quantity of reagent injected as a function of combustion turbine load, temperature and NOx emissions. Industry information indicates that the use of SCR for NOx control on combustion turbines may facilitate NOx reductions of 95% or more.

Combustion Turbine NOx Control Technology	Potential NOx Reduction
Water Injection	40%
Dry Low NOx Burners (DLNB)	60%
SCR	95%

4.5.2 Example Existing Rules and Regulations - Combustion Turbines

California - California's South Coast Air Quality Management District (SCAQMD) has established Rule 1134, EMISSIONS OF OXIDES OF NITROGEN FROM STATIONARY GAS TURBINES, that provides NOx emissions limitations for combustion turbines. (This rule may be viewed at http://aqmd.gov/rules/reg/reg11/r1134.pdf)

Rule 1134 provides an equation that is used to determine the NOx emissions limitations for various sizes of combustion turbines. The equation is:

Compliance Limit = Reference Limit x (EFF/25%)

Where Compliance Limit = NOx emissions limit (ppmvd@15% O_2)

EFF = Thermal efficiency (%)

Reference Limit = NOx rate (ppmvd) from following table

Nameplate Rating	Ref. NOx Limit
0.3 to Less Than 2.9 MW	25
2.9 to Less Than 10.0 MW	9
2.9 to Less Than 10.0 MW No SCR	15
10.0 MW and Over	9
10.0 MW and Over No SCR	12

Texas - The Texas Commission on Environmental Quality revised its permit by rule (revision date February 17, 2012) for the oil and gas industry sources in Texas, §106.352 Oil and Gas Handling and Production Facilities. The Texas rule provides NOx emissions limitations for the various types of oil and gas sector sources, including NOx emissions limitations for combustion turbines. The relevant emissions limitation in the rule includes the following:

Combustion Turbine	25 ppmvd@15% O2

Additionally, Texas Administrative Code, Combustion Control at Major Industrial, Commercial, and Institutional Sources in Ozone Non-Attainment Areas, Beaumont-Port Arthur Ozone NonAttainment Area Major Sources, Rule §117.105, Emission Specifications for Reasonably Available Control Technology (RACT), provides NOx emissions limitations for combustion turbines as follows:

Combustion Turbine > 10.0 MW	42 ppmv @ 15% O2

Pennsylvania has recently proposed a revision to its General Permit for Natural Gas Production and Processing Facilities (GP-5). The proposed GP-5 will apply to simple cycle combustion turbines and other air contamination sources at natural gas production and processing facilities. When the currently proposed GP-5 becomes effective, new and reconstructed simple cycle combustion turbines with a nameplate rating greater than or equal to 1000 hp will be required to comply with a NOx emissions rate limit of 15 ppm @ 15% O2.

USEPA - The USEPA established NOx emissions limitations for combustion turbines in 40 CFR Part 60, Subpart KKKK (NSPS) (7/6/06 71 FR 38482) applicable to natural gas-fueled combustion turbines are summarized in the following table:

Combustion Turbine Type	Peak Load Heat Input	NOx Limit
New turbine firing natural gas, electric generating	≤ 50 MMBtu/h	42 ppm at 15 percent O_2or 290 ng/J of useful output (2.3 Ib/MWh).
New turbine firing natural gas, mechanical drive	≤ 50 MMBtu/h	100 ppm at 15 percent O_2or 690 ng/J of useful output (5.5 Ib/MWh).

New turbine firing natural gas	> 50 MMBtu/h and ≤ 850 MMBtu/h	25 ppm at 15 percent O_2or 150 ng/J of useful output (1.2 lb/MWh).
New, modified, or reconstructed turbine firing natural gas	> 850 MMBtu/h	15 ppm at 15 percent O_2or 54 ng/J of useful output (0.43 lb/MWh)
New turbine firing fuels other than natural gas, electric generating	≤ 50 MMBtu/h	96 ppm at 15 percent O_2or 700 ng/J of useful output (5.5 lb/MWh).
New turbine firing fuels other than natural gas, mechanical drive	≤ 50 MMBtu/h	150 ppm at 15 percent O_2or 1,100 ng/J of useful output (8.7 lb/MWh).
New turbine firing fuels other than natural gas	> 50 MMBtu/h and ≤ 850 MMBtu/h	74 ppm at 15 percent O_2or 460 ng/J of useful output (3.6 lb/MWh).
New, modified, or reconstructed turbine firing fuels other than natural gas	> 850 MMBtu/h	42 ppm at 15 percent O_2or 160 ng/J of useful output (1.3 lb/MWh).
Modified or reconstructed turbine	≤ 50 MMBtu/h	150 ppm at 15 percent O_2or 1,100 ng/J of useful output (8.7 lb/MWh).
Modified or reconstructed turbine firing natural gas	> 50 MMBtu/h and ≤ 850 MMBtu/h	42 ppm at 15 percent O_2or 250 ng/J of useful output (2.0 lb/MWh).
Modified or reconstructed turbine firing fuels other than natural gas	> 50 MMBtu/h and ≤ 850 MMBtu/h	96 ppm at 15 percent O_2or 590 ng/J of useful output (4.7 lb/MWh).

4.5.3 Combustion Turbine NOx Reduction Combustion Controls

The literature suggests that the combustion related NOx reduction technologies of water injection and dry low NOx burners (DLNB) are commercially available NOx reduction technologies for combustion turbines that are capable of achieving NOx reductions of 40% and 60%, or greater, respectively. Although there appears to be both OEM and aftermarket suppliers of these NOx reduction technologies for combustion turbines, the literature indicates that these NOx reduction technologies may not be commercially available for all makes and models of combustion turbines, more so for the relatively small size of combustion turbine representative of industrial utilization.

Some of the combustion turbine manufacturers offer a version of low NOx burners for many of their particular models of combustion turbine, some as original equipment and some as retrofit, as follows:

- Capstone markets a new natural gas fueled combustion microturbine, turbine generator with a 1 MW electrical rating. Capstone indicates that the NOx emissions from this turbine generator are less than 9 ppmvd in standard version and less than 4 ppmvd in CARB version. For additional information see: http://www.microturbine.de/uploads/File/C1000%20HPNG.pdf

- GE offers retrofit dry low NOx emissions systems for many of their combustion turbines. Dependent upon the model of the combustion turbine (technology/product may not be available for all models), GE offers low NOx burner systems that may result in NOx emissions levels in the single digit ppmvd range. For certain models, GE offers dry low NOx emissions systems along with water injection for further NOx emissions reductions. For additional information see: http://www.ge-energy.com/products_and_services/industries/oil_and_gas_upstream.jsp

- Solar Turbines information indicates that Solar offers an extensive line of standard NOx reduction retrofit kits for most of the Solar gas turbine product line, including their low-NOx SoLoNOx gas fuel system upgrade to achieve NOx emissions reductions. Solar also offers its SoLoNOx emissions reduction technology for many of its currently offered gas turbine models. For additional information see: http://mysolar.cat.com/cda/layout?m=35881&x=7

- A paper presented by Alstom described a project to achieve low NOx emissions from an Alstom GT10 combustion turbine, with an approximate 23 MW nameplate rating. The paper indicates that this series of combustion turbine was originally intended to drive compressors, but was being used for cogeneration in this particular application. The NOx control system used a combination of low-NOx combustor design and water injection to meet a 15 ppmvd NOx emissions limit over a wide range of operating and ambient conditions. The paper indicated that the combustion turbine outlet NOx emissions were generally held to 10 ppmvd. For additional information see: http://cogen.mit.edu/files/powergen.pdf

Similarly, the literature suggests that the cost for combustion related and post combustion NOx emissions controls vary greatly with the make and model of the combustion turbine. For example, in a 1999 document, Cost Analysis of NOx Control Alternatives for Stationary Gas Turbines, the following capital cost estimates were prepared for presentation to the US Department of Energy:

Make/Model	Rating (approximate) (MW)	Water Injection Capital Cost ($)	DLN Capital Cost ($)	Hi-Temp SCR Capital Cost ($)
GE LM2500	23	1,083,175	800,000	1,269,324
GE 7FA	170		4,500,000	5,216,400
Solar Centaur 50	4.2	405,500	190,000	
Allison 501-KB5	4	291,000	20,000	
Solar Taurus 60	5		190,000	652,050

Note: The above costs are in 1999 $.
The DLN capital costs are incremental costs compared to conventional burners.

For additional information see:
http://www1.eere.energy.gov/industry/distributedenergy/pdfs/gas_turbines_nox_cost_analysis.pdf

4.5.4 Combustion Turbine NOx Reduction Post Combustion Controls

The post combustion NOx reduction technology SCR appears to be a technically feasible NOx reduction technology for many combustion turbines, and systems appear to be commercially available for simple cycle combustion turbines. However, industry representatives have raised several issues questioning the applicability of SCR to combustion turbines driving natural gas compressors.

One industry stated issue concerned with the use of SCR for combustion turbines is that many related facilities are unmanned and that SCR installations have not been demonstrated in un-manned facilities. Other industry information indicates that while it may be true that are currently few SCRs in unmanned facilities, with modern software based controls and supervisory control and data acquisition (SCADA) type communication technologies there does not appear to be any technical barrier to operating the SCR related controls and auxiliaries successfully from a remote location.

Industry sources have also stated that SCRs have not been demonstrated on combustion devices with variable loads. SCR manufactures offer catalysts that are effective over wide temperature ranges characteristic of a range in combustion turbine operating load. Modern controls also have the ability to closely regulate fuel and air flows to ensure combustion gas oxygen and temperature levels at expected levels and to regulate reagent flow, all serving to ensure proper SCR function over a broad range of load.

Several organizations market SCR systems applicable to combustion turbines. A summary of some of the marketed systems are summarized below:

- Johnson Matthey markets SCR systems for combustion turbines, and indicates that they have supplied SCR systems for combustion turbines with output ratings ranging from 3MW to greater than 200MW. Johnson Matthey indicates that they can engineer the systems to work with natural gas fuel, diesel fuel, or co-fired natural gas and diesel. Johnson Matthey states that their SCR systems are designed to have a rapid startup capability, permitting the combustion turbine to come in compliance with NOx emission limits within minutes of startup. The Johnson Matthey SCR systems for combustion turbines are capable of achieving NOx reductions in excess of 95%, and attaining NOx emission rates below 2 ppm. For additional information see: http://ect.jmcatalysts.com/emission-control-technologies-gas-turbines

- Nationwide Environmental Solutions offers their CataStak SCR NOx reduction systems for combustion turbines, delivering reliable NOx emissions as low as 2.5 ppm @ 15% O2. Nationwide Environmental Solution's literature indicates that they offer SCR systems for combustion turbines sized down to an output rating of 0.5 MW, and with a combustion gas exhaust temperature of up to 1000 degF. The Nationwide Environmental Solution's information also indicates that their design includes simple controls, requires minimal operator intervention (Auto Start/Stop) and is easy to retrofit on existing equipment (vertical or horizontal arrangements). For additional information see: For additional information see: http://www.catastak.com/catastak_gt/index.html

- Turner EnviroLogic offers SCR systems for simple cycle combustion turbines that are designed to integrate with the combustion turbine controls to provide operation with little to no operator attention. The design is intended to facilitate efficient, reliable operation with the frequent start/stop cycling typical of the operation of many simple cycle combustion turbines. The document also indicates that the SCR systems and components can be custom designed to accommodate site specific installation requirements. For additional information see: http://equipmentsourceco.com/pdf/scr_systems.pdf

In 2007 the Illinois Environmental Protection Agency prepared its "Technical Support Document for Controlling Emissions from Stationary Reciprocating Internal Combustion Engines and Turbines". This document reviewed NOx emissions control capabilities and estimated cost effectiveness for a number of NOx controls for reciprocating engines and combustion turbines. Included in this evaluation for combustion turbines is the application of SCR for NOx control. The document indicates that SCR has the capability of reducing NOx emissions from combustion turbines by approximately 90%. The following summarizes the combustion turbine SCR evaluation:

Type of Control	Nameplate Rating (MW)	Total Capital Cost (2004 $)	Cost Effectiveness (2004 $/ton)
SCR (gas fuel)	5 – 25	748,000 – 2,018,000	1,606 – 3,203
SCR (oil fuel)	5 – 25	748,000 – 2,018,000	1,072 – 2,039

For additional information see: http://www.epa.state.il.us/air/rules/rice/tsd-rice.pdf

4.5.5 Combustion Turbine NOx Control Summary

Industry information indicates that there are technically feasible, commercially available combustion and post combustion NOx controls available for combustion turbine. The most common combustion controls are water injection and the installation of low-NOx combustors. These controls are generally able to attain moderate levels of NOx reduction in retrofit application; approximately 40% for water injection and up to approximately 60% for low-NOx combustors. Due to the design differences between makes and models of combustion turbines, not all combustion turbines are able to achieve those levels of NOx reduction. Also because of the design differences between makes and models of combustion turbines, water injection systems and/or low-NOx combustors must be designed for the specific make and model of combustion turbine. Water injection systems and/or low-NOx combustors are not available for all makes and models of existing combustion turbines. Some organizations market a NOx reduction system that incorporates both low-NOx combustors and water injection to optimize unit efficiency, operability, and emissions control over a wide range of unit load and ambient conditions.

Combustion turbine manufacturers offer multiple models of new combustion turbines with low NOx combustion technology that are capable of operating with NOx emission rates in the single digit ppmvd range.

Industry information also indicates that retrofit SCR is a technically feasible, commercially available post-combustion NOx control for combustion turbines. SCR is applicable and available for both retrofit and new unit installations. SCR is capable of achieving combustion turbine NOx reductions of 90% or more. Based on the available information, SCR appears to be the only commercially available combustion turbine NOx reduction technology capable of attaining those high levels of NOx reduction. While the SCR process is generally applicable to any combustion turbine, site specific conditions or economic considerations may affect the feasibility of a given SCR retrofit project. SCR systems are generally able to attain outlet NOx emission rates in the low single digit ppmvd range.

NOx Control	Nameplate Rating (MW)	Estimated NOx Reduction (%)	Estimated Cost ($)
Water Injection	4 – 23	40	398,000 – 1,481,000
Low NOx Combustors	4 – 23	60	260,000 – 1,094,000
SCR	5 – 25	90	901,000 – 2,432,000

(Note: Estimated control costs are initial capital cost estimates only. Costs are based on “Cost Analysis of NOx Control Alternatives for Stationary Gas Turbines”, adjusted for CPI.)

It should be noted that the range of costs for installation of the combustion related NOx reduction controls on combustion turbines is highly dependent upon the make and model of the combustion turbine, and less dependent upon the combustion turbine’s nameplate rating for this size range.

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Attachment 1
Upstream Oil and Gas Sector NOx Emissions
OTR Region

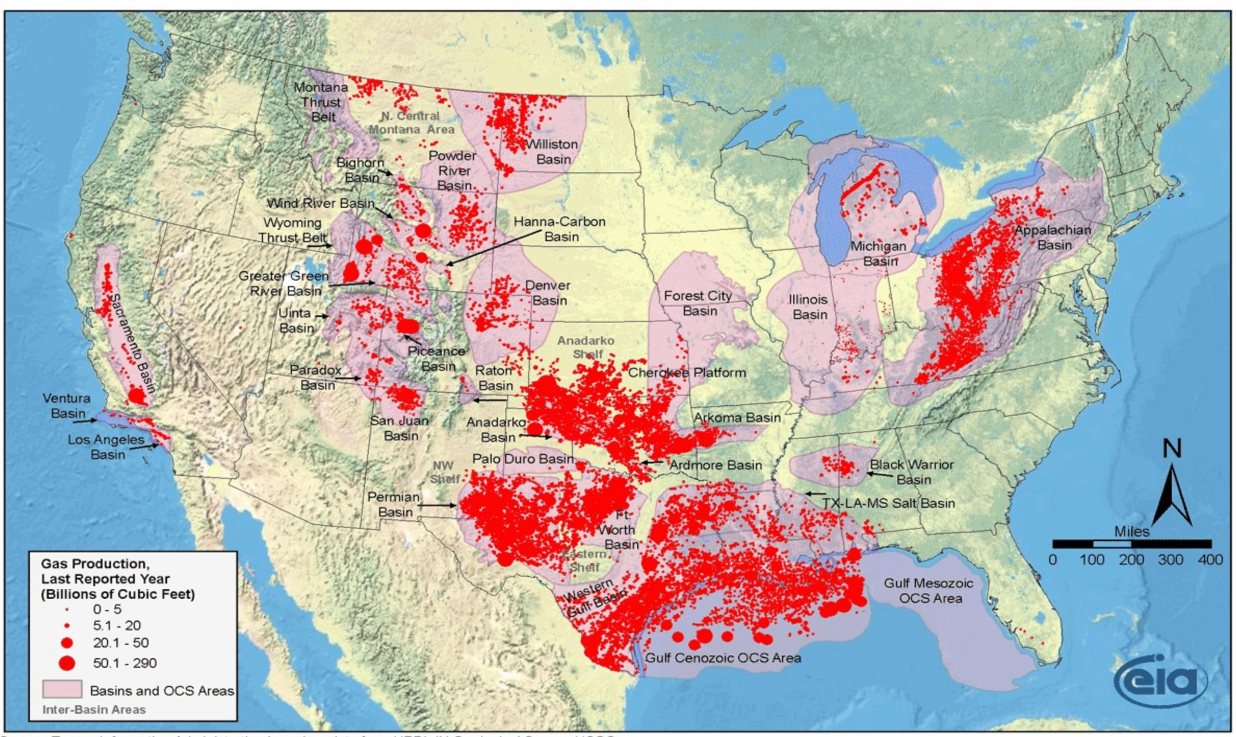
Oil and gas sector activities in the ozone transport region (OTR) that emit NOx closely mimic those of the overall lower 48 states, as discussed in the body of this document. Within the OTR these activities include crude oil and gas well drilling operations, oil well pumps and wellhead heaters, gas well compressors and wellhead gas heating, field gathering activities, mainline pumps and compressors, and underground storage activities.

OTR Oil and Gas Well Drilling

While both crude oil and natural gas are produced in the OTR, from an upstream activities standpoint the gas sector is larger and better documented than the oil sector.

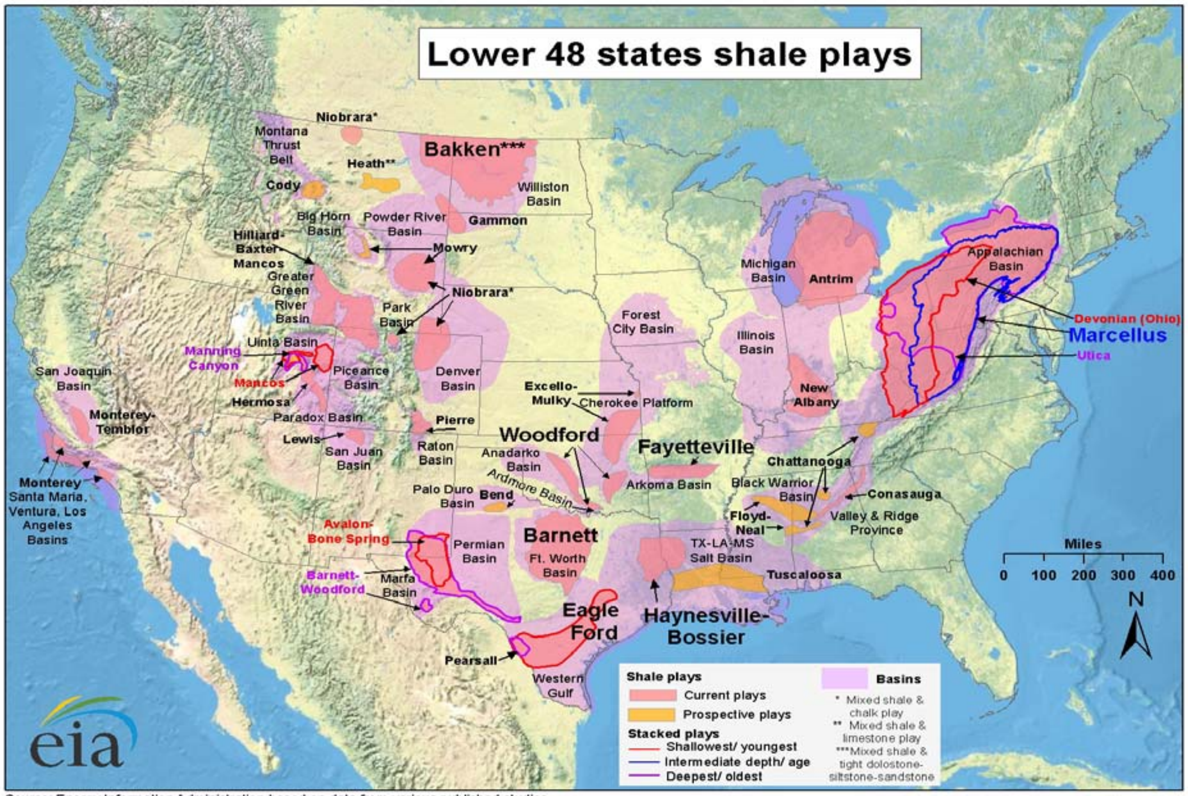
Gas drilling in the OTR includes drilling for conventional gas, shale gas, and coal bed methane. The following illustration from the EIA shows the conventional gas fields in the lower 48 states, including those in the OTR:

Gas Production in Conventional Fields, Lower 48 States



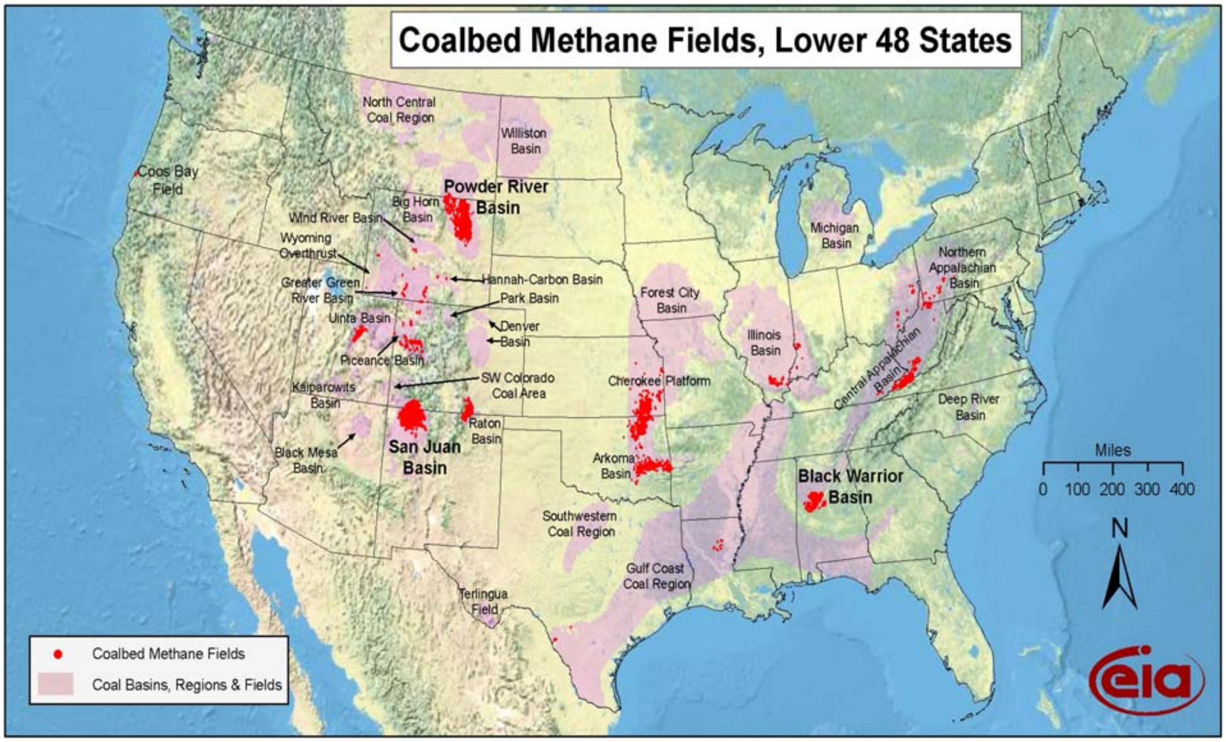
Source: Energy Information Administration based on data from HPDI, IN Geological Survey, USGS
Updated: April 8, 2009

The following illustration, also taken from the EIA website, shows the shale gas fields in the lower 48 states, including those in the OTR:



Source: Energy Information Administration based on data from various published studies.
Updated: May 9, 2011

The following illustration is also from the EIA website, and shows the coal bed methane fields in the lower 48 states, including those in the OTR:



Source: Energy Information Administration based on data from USGS and various published studies
Updated: April 8, 2009

Rotary drill rigs are utilized for the drilling of oil wells and gas wells. These drill rigs are moved from site to site to support the drilling of exploratory and production wells. Within the last decade, drill rigs have been employed to drill oil and/or gas wells in the OTR states of Maryland, New York, and Pennsylvania. The following table presents data from the EIA website, and shows the annual average number of rotary drill rigs in operation in these OTR states:

Annual Average Count of Rotary Rigs in Operation
(Average of Monthly Averages)

Year	Maryland	New York	Pennsylvania
2002	0	4	11
2003	0	3	10
2004	0	5	9
2005	0	4	13
2006	0	6	16
2007	1	6	16
2008	0	6	23
2009	0	2	42
2010	0	1	85
2011	0	0	110

Data from the RigData website indicates that as of the date the website was accessed, in the OTR only the states of New York and Pennsylvania have had rotary drill rigs in operation so far in 2012. The following table shows the number of drill rigs in operation by month for the OTR states:

Drilling Rigs In Operation 2012
Weekly Average for the Month

	January	February	March	April
New York	2	0	0	2
Pennsylvania	139	124	120	116

The RigData website also provided information concerning the number of wells started for each state by month. As of the date the website was accessed, the following table shows the number of wells started for the OTR states:

Well Starts 2012

	January	February	March
New York	3	0	0
Pennsylvania	196	184	208

For the wells started in 2012, the RigData website provided data regarding the depth range of the wells and the approximate total number of feet drilled for those wells. As of the date the website the accessed, the following table shows the number of wells started for each depth range and the approximate total number of feet drilled for those wells:

Well Starts by Depth Range
January – March 2012

	1 – 2,499 ft depth	2,500 – 4,999 ft depth	5,000 – 9,999 ft depth
New York	1 well, 2000 ft	2 wells, 5,000 ft total	0
Pennsylvania	20 wells, 37,000 ft total	27 wells, 102,000 ft total	535 wells, 3,891,000 ft total

OTR Oil and Natural Gas Production

Within the OTR, New York and Pennsylvania are the two states that produce crude oil. Only a limited amount of data could be located documenting the number of oil wells in the New York and Pennsylvania. The following data is the latest data available from the EIA website, and represents the annual number of oil wells operating in the respective states:

Year	No. of Oil Wells New York	No. of Oil Wells Pennsylvania
2000	NA	6011
2001	NA	6589
2002	916	5243
2003	2884	5480
2004	2968	5167
2005	2789	NA
2006	3121	NA
2007	2979	NA
2008	3271	NA
2009	3011	NA

Collectively, the production of crude oil in Pennsylvania and New York represent less than 0.5% of the crude oil produced in the US. The following table shows the annual crude oil production in Pennsylvania and New York for the last several years:

Year	New York Field Production of Crude Oil (Thousand Barrels)	Pennsylvania Field Production of Crude Oil (Thousand Barrels)
2001	166	1620
2002	165	2233
2003	144	2425
2004	170	2538
2005	197	3947
2006	319	3626
2007	380	3653
2008	386	3611
2009	339	3541
2010	378	3474
2011	390	3656

The above data was extracted from EIA sources, and includes the latest annual data available at the time the data was accessed. It can be seen in the above data that after a step increase in crude oil production around 2005, the crude oil production from New York and Pennsylvania was relatively flat through 2011.

Within the OTR, the states of Pennsylvania and New York are also two of the three natural gas producing states, the third state being Maryland. The following table shows the latest data available from the EIA website, and represents the annual number of gas wells in the respective states:

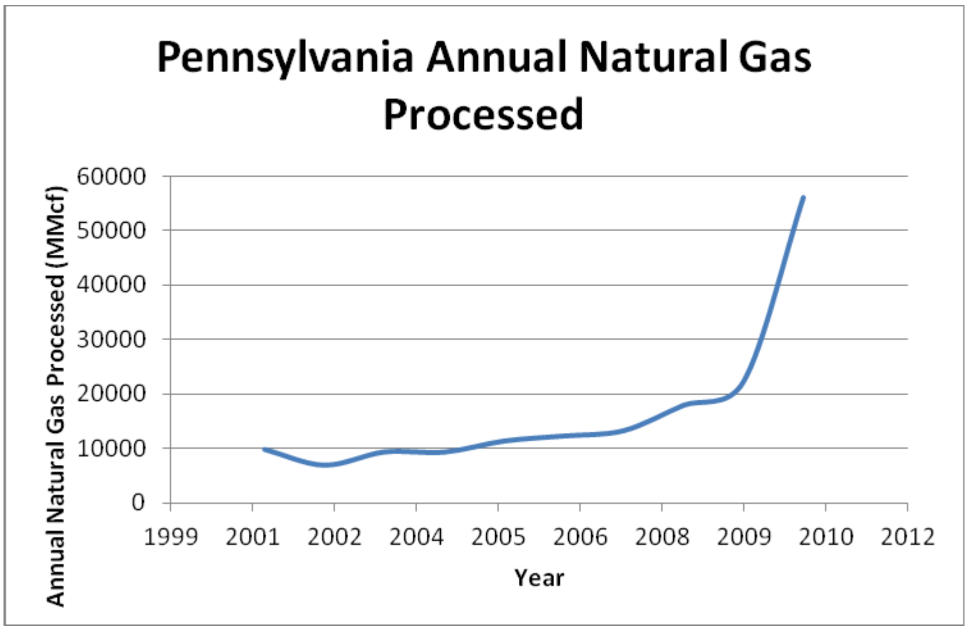
Year	Maryland Natural Gas Number of Gas and Gas Condensate Wells	New York Natural Gas Number of Gas and Gas Condensate Wells	Pennsylvania Natural Gas Number of Gas and Gas Condensate Wells
2001	7	5913	40100
2002	5	6496	40830
2003	7	5878	42437
2004	7	5781	44227
2005	7	5449	46654
2006	7	5985	49750
2007	7	6680	52700
2008	7	6675	55631
2009	7	6628	57356
2010	7	6736	44500

The following table shows the natural gas production in Maryland, New York, and Pennsylvania for the last several years:

Year	Maryland Natural Gas Gross Withdrawals (MMcf)	New York Natural Gas Gross Withdrawals (MMcf)	Pennsylvania Natural Gas Gross Withdrawals (MMcf)	Total OTR Natural Gas Gross Withdrawals (MMcf)
2001	32	27787	130853	158672
2002	22	36816	157800	194638
2003	48	36137	159827	196012
2004	34	46050	197217	243301
2005	46	55180	168501	223727
2006	48	55980	175950	231978
2007	35	54942	182277	237254
2008	28	50320	198295	248643
2009	43	44849	273869	318761
2010	43	35813	572902	608758

The above data was extracted from EIA sources, and includes the latest annual data available at the time the data was accessed. It can be seen in the above data that between 2001 and 2008 there was a slow, steady increase in the collective annual natural gas production from the three states. However, the data also indicates that beginning in 2009 that here was a sharp increase in natural gas production collectively from the states. In can be seen that this increase is predominately from Pennsylvania, and that increase roughly corresponds to the expansion of shale gas development in Pennsylvania.

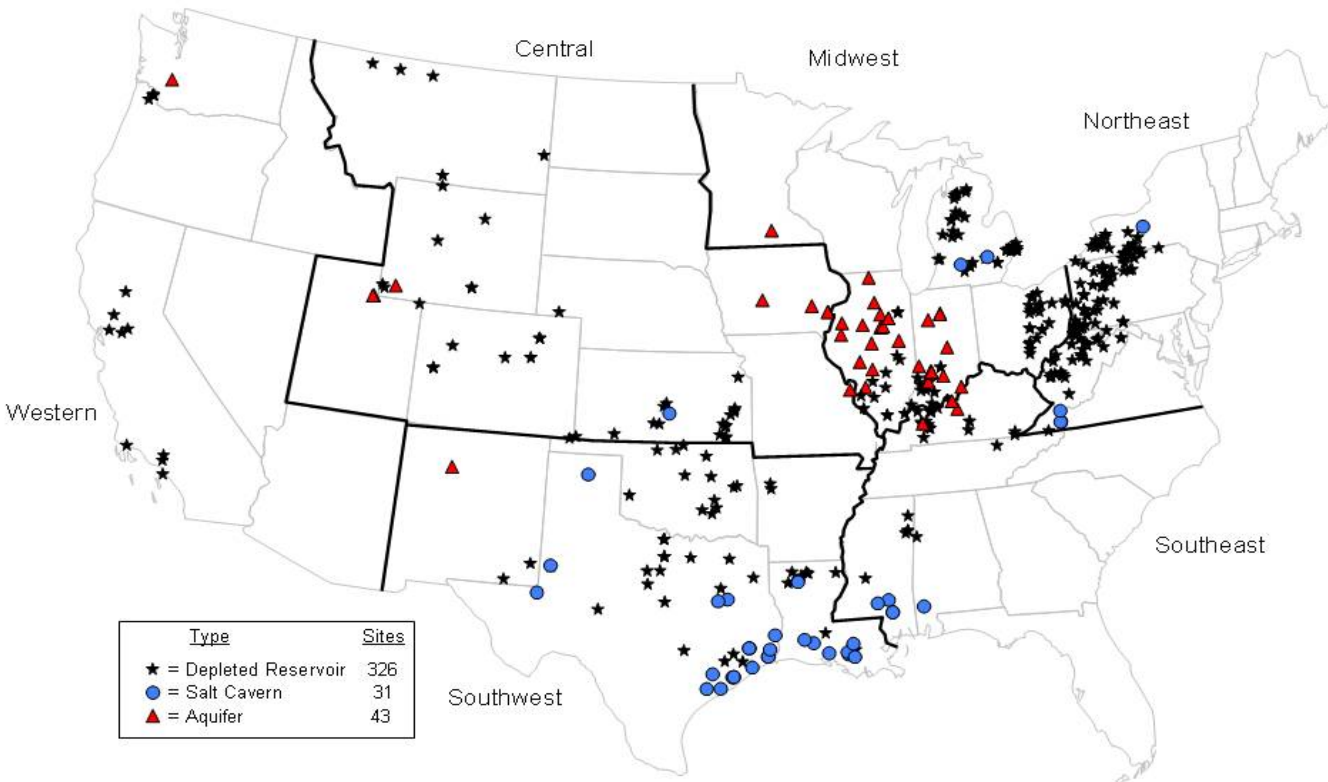
The sharp increase in natural gas production in recent years in Pennsylvania is also evidenced in the output from natural gas processing plants in Pennsylvania. (Pennsylvania is the only state in the OTR with large central natural gas processing plants according to EIA data.) Some natural gas requires processing before it is pipeline quality, and therefore must be appropriately processed before it can be injected into mainline or distribution pipelines. The following chart of EIA data shows the amount of natural gas processed in Pennsylvania's natural gas processing plants over the last several years:



OTR Underground Natural Gas Storage

The following map shows the natural gas storage facilities in the lower 48 states.

U.S. Underground Natural Gas Storage Facilities, 2007



Source: Energy Information Administration, Office of Oil & Gas, Natural Gas Division Gas, Gas Transportation Information System, December 2008.

It can be seen in the map that within the OTR, New York and Pennsylvania are the primary locations of underground natural gas storage facilities. The natural gas storage facilities in the OTR are important for balancing natural gas demand with supplies during peak demand periods. In New York and Pennsylvania, the majority of the underground storage is depleted natural gas production fields, thereby potentially taking advantage of existing wells, gathering stems, pipeline connections, etc that were installed originally to facilitate natural gas extraction. New York also has a salt cavern natural gas storage facility. Pennsylvania has more underground natural gas storage facilities than any other state.

The compressors at underground storage facilities may be used to inject pipeline natural gas into storage and then re-inject the natural gas back into the pipelines for transportation to the users. EIA data from 2006 indicated that Pennsylvania and New York ranked 5^{th} and 8^{th} highest among states with the largest increase in natural gas underground storage deliverability for the period of 1998 through 2005. (Pennsylvania exhibited a 13% increase (969 MMcuft/day added) and New York exhibited a 44% increase (510 MMcuft/day added)).

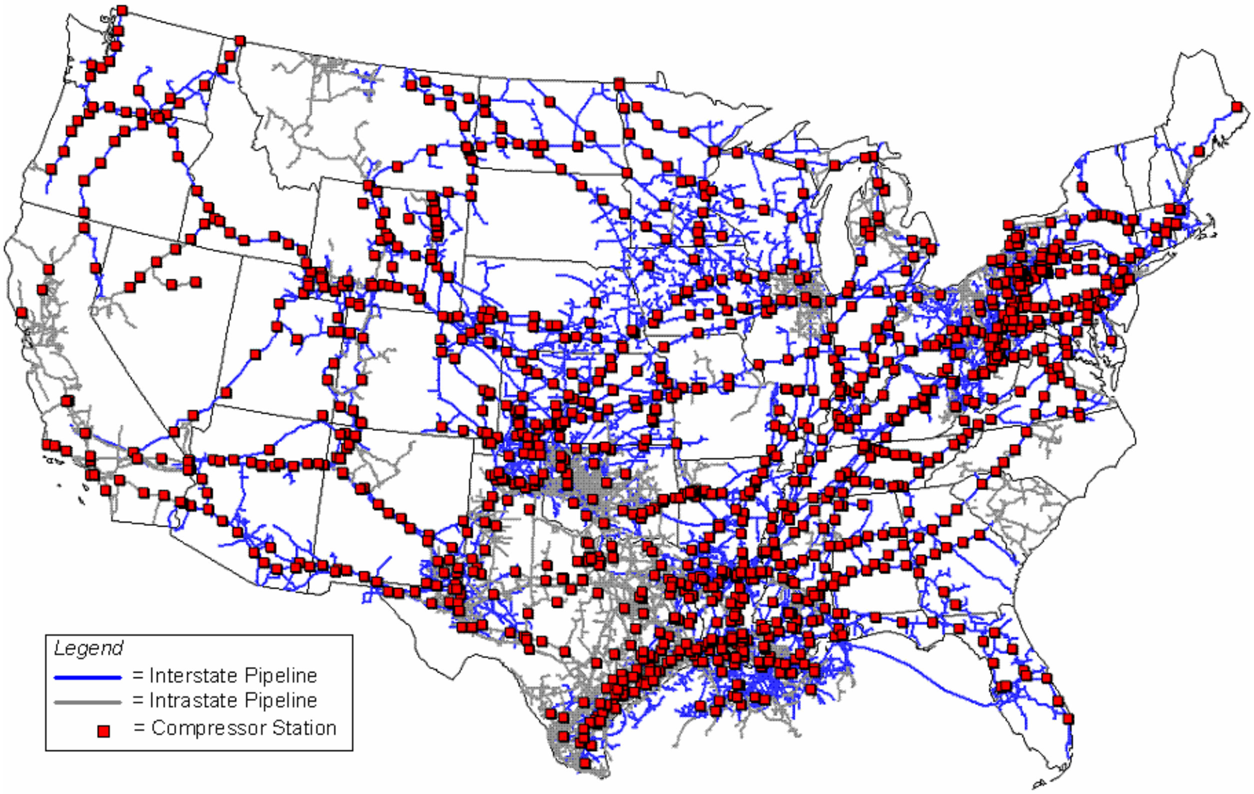
OTR State Natural Gas Underground Storage Capacity

State	Number of Storage Sites	Working Storage Capacity (bcf)
MD	1	17
NY	24	117
PA	50	406

OTR Natural Gas Pipeline Compressors

Mainline natural gas transmissions pipeline systems utilize compressors at gas compressor stations to maintain system flow and overcome pressure losses due to the movement of the natural gas through the natural gas pipeline system. These compressor stations are typically located at 40 mile to 100 mile intervals along the transmission pipeline, as required by the particular pipeline section duty, to maintain the required flow and pressure. These mainline natural gas compressor facilities will often include multiple gas compressors to add flexibility and reliability in meeting the variable natural gas flow demand. Below is a map from the EIA of the US interstate mainline gas system noting the location of the mainline compressor stations as of 2006. EIA and Federal Energy Regulatory Commission (FERC) data indicates that there have been a number of compressors stations (and compression additions to existing compressor stations) that have been put in service subsequent to 2006 to help meet the growing demand for natural gas as a fuel. Some of the new compression stations (and compression additions to existing compressor stations) have been added in the OTR.

U.S. Natural Gas Pipeline Compressor Stations, EIA, 2008



The map shows that there are many mainline compressor stations in the OTR, with a relatively high concentration in New York and Pennsylvania. Prime movers for these mainline compressors are typically natural gas fired reciprocating engines and combustion turbines, although there are also a number of electric motor gas compressor prime movers in the OTR. In some instances, combustion compressor prime movers and electric motor compressor prime movers are located in the same compressor facilities. The horsepower ratings of the individual combustion compressor prime movers range from less than 300 hp to 15,000 hp and more.

Many mainline natural gas compressor stations have multiple compressors operating in parallel to help meet large variations in the natural gas flow, and may also have some redundancy to minimize the impact of maintenance or problems with any given compressor unit. Industry data indicated that many of the mainline natural gas compressor stations have compressors in operation 24 hrs/day and 365 days/year, although not all compressors may be operating or may not be operating at high capacity. Within the OTR, FERC compressor facility specific (not unit specific) data indicated that for 2007 the range of facility operating capacity (in terms of compressor operating hours) ranged from 0% to approximately 95%, with an average of approximately 35%. For many mainline natural gas compressor facilities, reciprocating engines are preferred for their ability to adjust their output to meet the pipeline demand. Compressor loading will tend to increase during periods of high natural gas demand, such as cold periods with high heating fuel demand or high electric demand days in the northeast when natural gas fired electric generation is a significant consumer of natural gas. Within the OTR, FERC compressor facility specific data for 2007 indicated that 24 of 141 compressor facilities saw their peak 2007 day during the ozone season.

A review of 2010 FERC Form 2 and Form 2A data indicated that in 2010 there were 149 compressor stations in the OTR used for natural gas transmission service. The FERC data indicated that these compressor stations collectively had 518 natural gas compressors with a collective total horsepower rating of 2,053,510 hp (an unknown portion of which is likely powered by electric motors). The FERC data indicates that in 2010 these facilities collectively combusted 47,426,022 dth (approximately 47,426,022,000 cf) of natural gas for compression services.

Data from MARAMA's 2007 Point Source Inventory was reviewed to obtain a better understanding of the makeup of the OTR's population of fuel-combustion natural gas compressor prime movers. The review of the data indicated that a number of the units in the database did not give sufficient information to categorize each unit, sometimes not identifying the prime mover configuration (engine, turbine, 2SLB, etc), manufacturer, model number, output capacity, etc. It was possible to supplement some of the MARAMA data with information obtained from internet searches of compressor station operating permits, but there remains a significant number of units in the database with only partial information. Also, it is likely that the 2007 MARAMA data includes compressor units utilized for field gathering and underground storage in addition to the mainline compressors.

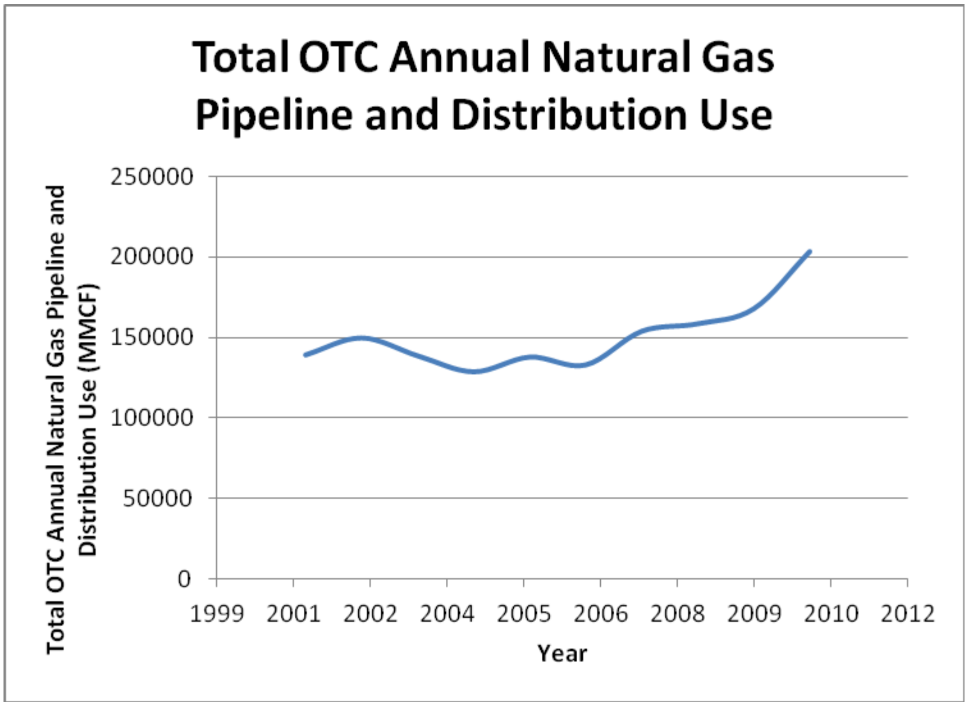
From the available information, it appears that the population of OTR natural gas compressor prime movers is diverse with regards to make, model, and capacity. For the reciprocating engines (2SLB, 4SLB, and 4SRB), the available data indicates that there are at least 60 different engine models spread among 13 different manufacturers. For the turbines, the available data indicates that there are at least 20 different models spread among 6 different manufacturers. [It should be noted that the number of manufacturers represented in the data are sometimes the result of mergers and buyouts. For example, the reciprocating engine manufacturer Superior (existing since the early 1900's) became White-Superior in the mid-1960s, then became Cooper-Superior in the early 1970s, and became Superior (within Cameron) in the mid-1970s. In fact, Cameron is also the current OEM for the Cooper-Bessemer line of engines.]

Within the available OTR compressor inventory data for reciprocating engines, the range of output for 2SLB reciprocating engines is approximately 400 HP to 5500 HP, the range of output rating for 4SLB reciprocating engines is approximately 650 HP to 4,300 HP, and the range of output rating for 4SRB reciprocating engines is approximately 200 HP to approximately 1,300 HP. Also within the available OTR compressor inventory data for combustion turbines, the range of output is approximately 1,000 HP to approximately 20,000 HP.

The data inventory also does not provide an indication of the vintage or age of the prime movers. Of most concern is the vintage of the reciprocating engines, as they have been available as compressor prime movers longer than combustion turbines and have been shown to have long service life. Industry information indicates that nationally there are many natural gas compression reciprocating engines that are in excess of 40 years old. While the data available at this time for the OTR natural gas pipeline compression reciprocating engines does not include an indication of the age of these engines, some inference can be made that many “vintage” reciprocating engine compressor prime movers continue in operation in the OTR by reviewing the manufacturer and model number of the subject engines. For example, industry information indicates that the Cooper-Bessemer family of GMW 2-stroke integral engines was manufactured between 1946 and 1965. The 2007 MARAMA database indicates that there are a number of such engines in the OTR that were still operating in 2007. The database does not contain sufficiently detailed information to determine if any of these vintage engines have undergone NOx RACT or been subject to any other NOx reduction activities.

The 2007 MARAMA point source data indicted that, collectively, the compressor prime movers in the OTR compressor facilities emitted approximately 11,000 tons of NOx in 2007, with the average facility emitting approximately 112 tons of NOx in 2007. The highest NOx emitting facility emitted in excess of 1100 tons of NOx in 2007, those emissions collectively from 12 reciprocating engines. Because portions of the 2007 MARAMA point source data is presented as “per facility” rather than all on a “per unit” basis, it is difficult to get a thorough understanding of the unit-by-unit annual NOx emissions of the OTR gas compressor prime movers. It appears that the range of unit specific 2007 annual NOx emissions ranged from approximately 177 tons of NOx to less than 0.1 ton of NOx. The gas compressor prime movers at the upper end of the range appear to be predominately gas turbines and 2-stroke lean burn reciprocating engines.

The following graph reflects EIA data and shows the annual amount of natural gas consumed in the OTR for use in natural gas pipeline and distribution operations. This natural gas consumption is primarily for compression. The graph shows that there has been a significant increase in the amount of natural gas utilized for gas pipeline and distribution purposes over the last few years. This increase in use follows the increased demand for natural gas from OTR users, and the increased production of natural gas from OTR sources.

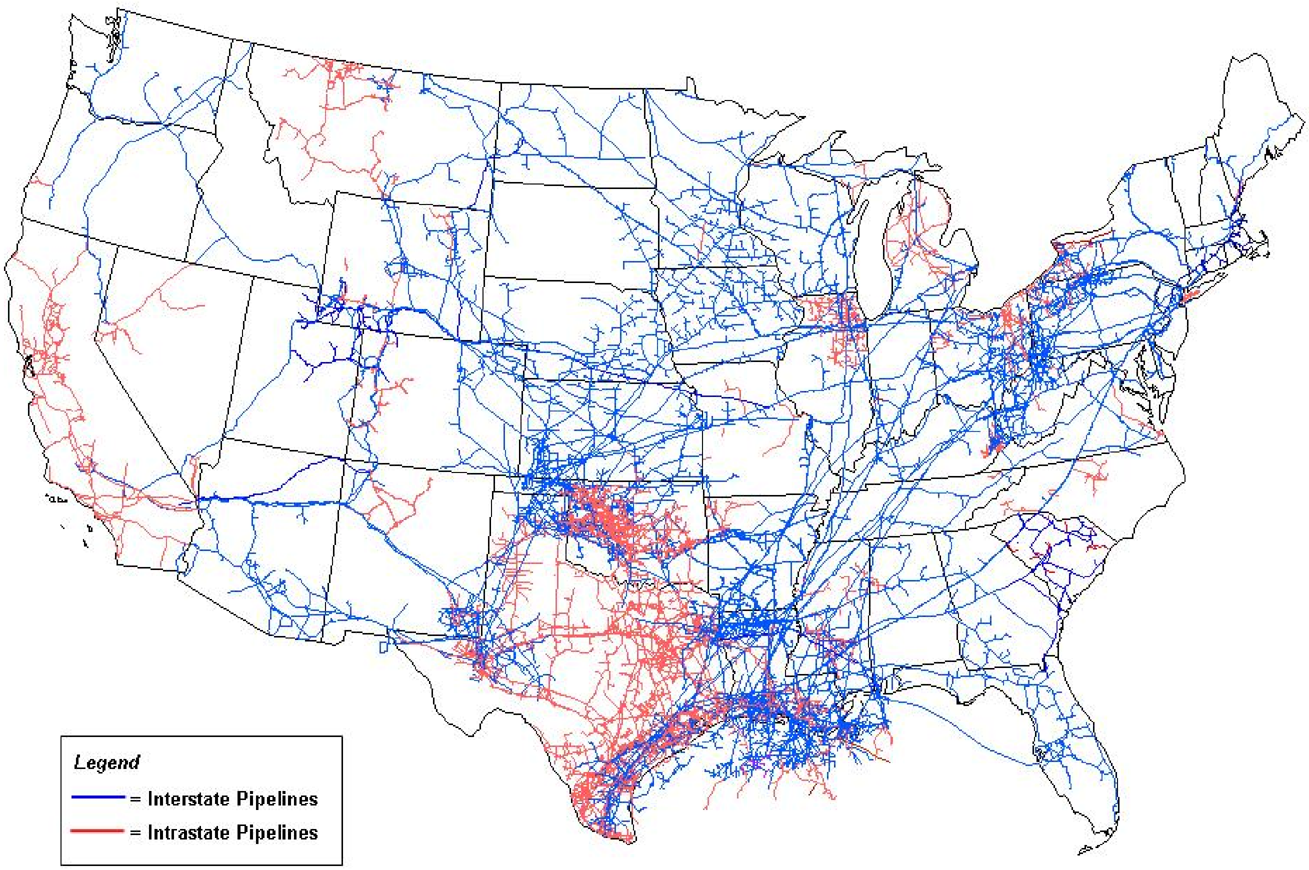


OTR Mainline Natural Gas Pipelines

While natural gas pipelines do not emit NOx themselves, the existence of the complex pipeline system is critical to the function of the natural gas industry in the OTR, and therefore the NOx emitting processes associated with the natural gas industry in the OTR. Interstate pipelines deliver natural gas to the OTR through several intrastate natural gas pipelines and to many local distribution companies in the OTR. In addition, the interstate pipelines also serve many large industrial concerns and natural gas fired electric power generation facilities.

The natural gas pipeline and local distribution companies serving the OTR have access to supplies from several major domestic natural gas producing areas, including those in the OTR, and from Canada. Natural gas from outside the OTR flows into the region from the Southeast through Virginia and West Virginia, and from the Midwest through West Virginia and Pennsylvania. Canadian natural gas imports come into the OTR principally through New York, Maine, and New Hampshire.

Liquefied natural gas (LNG) supplies also enter the region through import terminals located in Massachusetts, Maryland, and New Brunswick, Canada.



Source: Energy Information Administration, Office of Oil & Gas, Natural Gas Division, Gas Transportation Information System

The interstate natural gas pipeline systems that serve the OTR include the following:

- One of the largest natural gas pipelines transporting natural gas into the OTR is the Transcontinental Gas Pipeline Company system, which extends from South Texas to the New York City area.

- The Tennessee Gas Pipeline Company and the Texas Eastern Transmission Company natural gas pipeline systems bring supplies to the OTR from Texas, Louisiana, and the Gulf of Mexico. The Tennessee Gas Pipeline Company system, unlike the Transcontinental Gas Pipeline Company and Texas Eastern Transmission Company systems, extends its service northward as far as New Hampshire and is a major transporter of natural gas to Connecticut, Massachusetts, and Rhode Island.

- The Tennessee Gas Pipeline Company system is also a significant source of supply for the regional Algonquin Gas Transmission Company system, which is the principal interstate natural gas pipeline serving the Boston, Massachusetts area. The Texas Eastern Transmission Company, an affiliate of the Algonquin Gas Transmission Company, is the primary source of supply for that pipeline, delivering approximately 65 percent of Algonquin's requirements at interconnections in New Jersey. The Algonquin Gas Transmission Company system has the capability to move a significant portion of its system capacity from New Jersey into the New York metropolitan area.

- The Algonquin Gas Transmission Company is also receives natural gas processed at the Northeast Gateway liquefied natural gas (LNG) import terminal located 10 miles offshore of Massachusetts. The Northeast Gateway port's infrastructure features two submerged turret loading buoys for off loading, and is linked to the Algonquin Gas Transmission Company system by a 16-mile submerged pipeline.

- The Columbia Gas Transmission Company has an extensive network of natural gas pipelines that provide service to Maryland, New Jersey, New York, and Pennsylvania. The Columbia pipeline transports natural gas from the Gulf of Mexico as well as natural gas produced in the Appalachian region. The Columbia Gas Transmission Company supplies some of the largest natural gas distribution companies in the OTR.

- The Millennium Pipeline natural gas system begins at an interconnection with the Empire Pipeline system in southwest central New York State and terminates in the New York City metropolitan area. It is part of an overall regional effort involving expansion of the existing Empire, Algonquin and Iroquois Pipelines, which are among its major supply sources.

- The Dominion Transmission Company system serves Maryland, New York, and Pennsylvania. The Dominion Transmission Company also serves some of the largest natural gas distribution companies in the OTR.

In addition to the interstate natural gas pipeline companies that bring natural gas into the OTR, several smaller interstate natural gas pipeline companies operate primarily within the OTR (and OTR-neighboring states). Among these systems are:

- Equitrans Inc. serves western Pennsylvania, and its pipeline system was developed to move local production to regional markets through connections with local natural gas field gathering, distribution, and storage interconnections.

- The Eastern Shore Natural Gas Company is the only natural gas pipeline serving southern Delaware and the lower Delmarva Peninsula. It receives its supplies from Transcontinental Gas Pipeline Company and Columbia Gas Transmission Company at points in southeastern Pennsylvania, with a route that takes it southward through Delaware to Maryland's eastern shore.

- The Granite State Transmission Company receives natural gas from the Tennessee Gas Pipeline Company and/or the PNGTS/Maritimes and Northeast Pipeline system at the southern New Hampshire/Massachusetts border. From there it transports to customers in New Hampshire and to the Northern Utilities Company system.

- The KeySpan Energy Delivery Company is the principal provider of natural gas service to New York City and Long Island, New York, its intrastate operations also include service in Massachusetts and New Hampshire as well.

Canada is also a significant source of natural gas to the OTR through the pipeline system. Some of the more significant sources include the following:

- The Iroquois Gas Transmission Company system is supplied with natural gas from the TransCanada Pipeline Ltd system in Ontario, Canada.

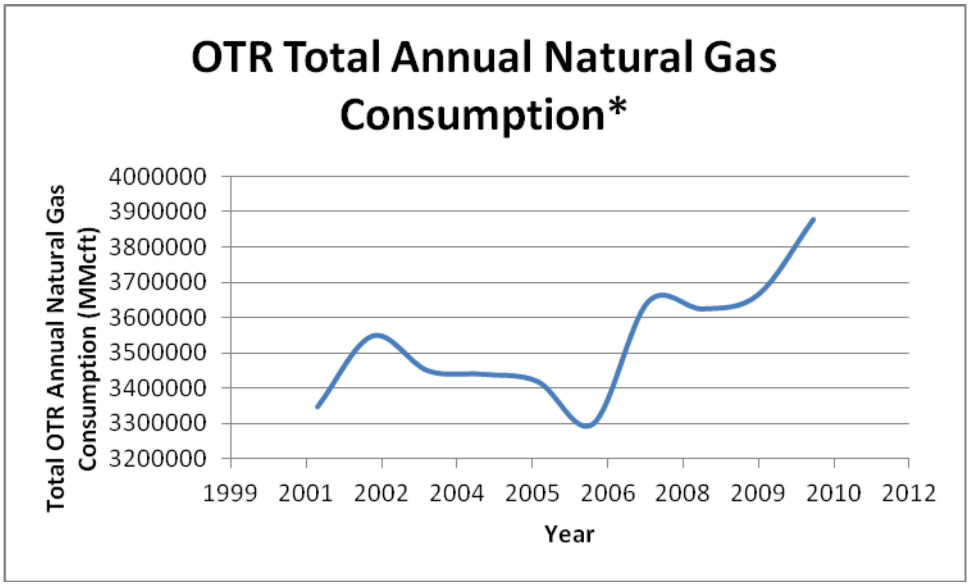
- The Empire Pipeline Company system, an intrastate affiliate of National Fuel Gas Supply Corporation, brings in Canadian natural gas at Grand Island, New York to north central New York State with interconnections to the Dominion Transmission Company and National Fuel Gas Supply Corporation systems. These latter two companies also access Canadian natural gas supplies from the Tennessee Gas Pipeline, which imports Canadian natural gas through Niagara Falls, New York.

- The Portland Natural Gas Transmission System (PNGTS) merges with the Maritimes and Northwest Pipeline system at Wells, Maine, where they form a joint natural gas pipeline that extends south through southern New Hampshire and terminates in northern Massachusetts (with an interconnection to the Tennessee Gas Pipeline Company system). PNGTS also provides bidirectional service to its customers allowing shippers of Canadian Sable Island natural gas (which use the Maritimes & Northeast Pipeline Company system) the opportunity to redirect some of their natural gas to markets located in Quebec (which previously had access only to western Canadian natural gas supplies).

- The U.S. portion of the Maritimes and Northeast Pipeline Company system begins at Calais, Maine, at the Canadian border and extends to Wells, Maine. The Maritimes and Northeast Pipeline system was built to access natural gas production off the eastern coast of Canada (Sable Island) and to transport it to New England. The Maritimes and Northeast Pipeline Company system was extended from Boston, Massachusetts to provide natural gas that area. The system also can transport natural gas processed at the Canaport liquefied natural gas (LNG) import terminal located in New Brunswick, Canada, to New England markets.

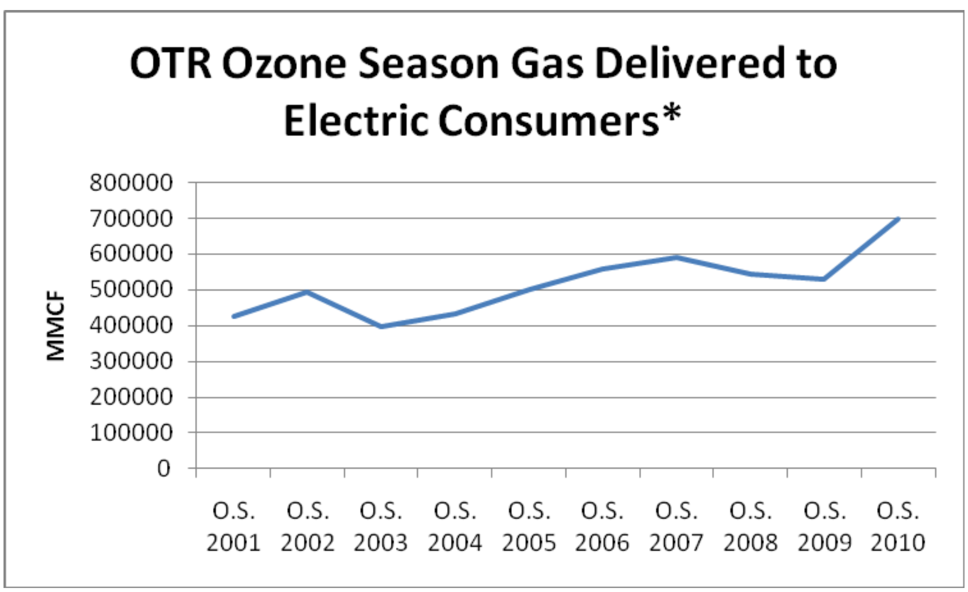
- Several smaller regional natural gas importing pipelines, such as North County Pipeline Company and the St. Lawrence Gas Company, both located in upper New York State, and the Vermont Gas Systems Company, the only natural gas pipeline in the State of Vermont, depend upon Canadian natural gas imports completely for their natural gas supplies since they do not interconnect with any other U.S. natural gas pipeline.

The robust natural gas pipeline system supplying and distributing natural gas in the OTR has been instrumental in supporting the widespread use of natural gas for residential, commercial, and industrial purposes. As shown in the following graph, the use of natural gas has been on a general incline in the OTR as a whole over the last decade:

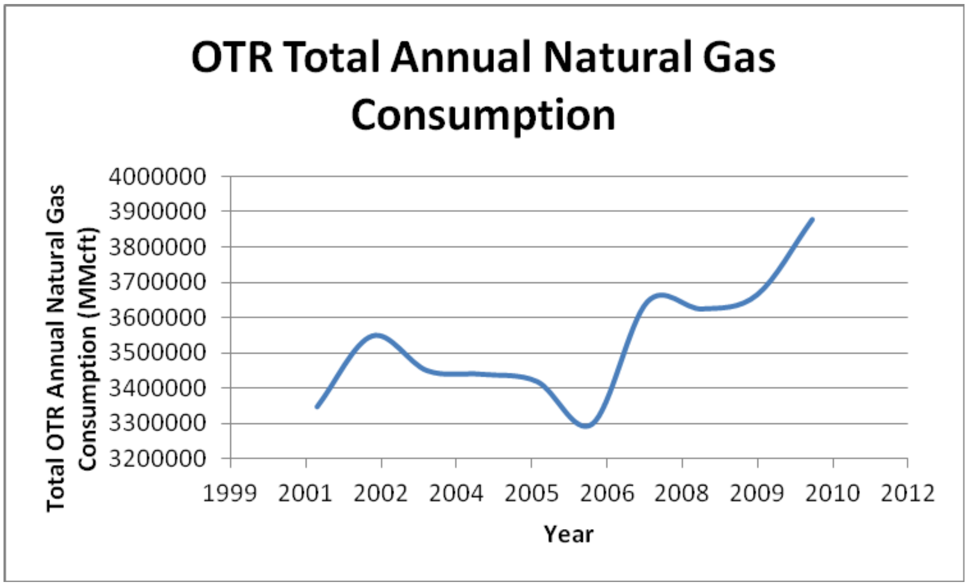


*Excluding Virginia

Some of the growth in the OTR's natural gas consumption has been due to increased use by electric generating units in the OTR. This increase is evdent in both the OTR annual total electric genrating unit natural gas consumption and the OTR ozone season total electric generating unit natural gas consumption, as shown in the following two graphs:



*Excluding VA

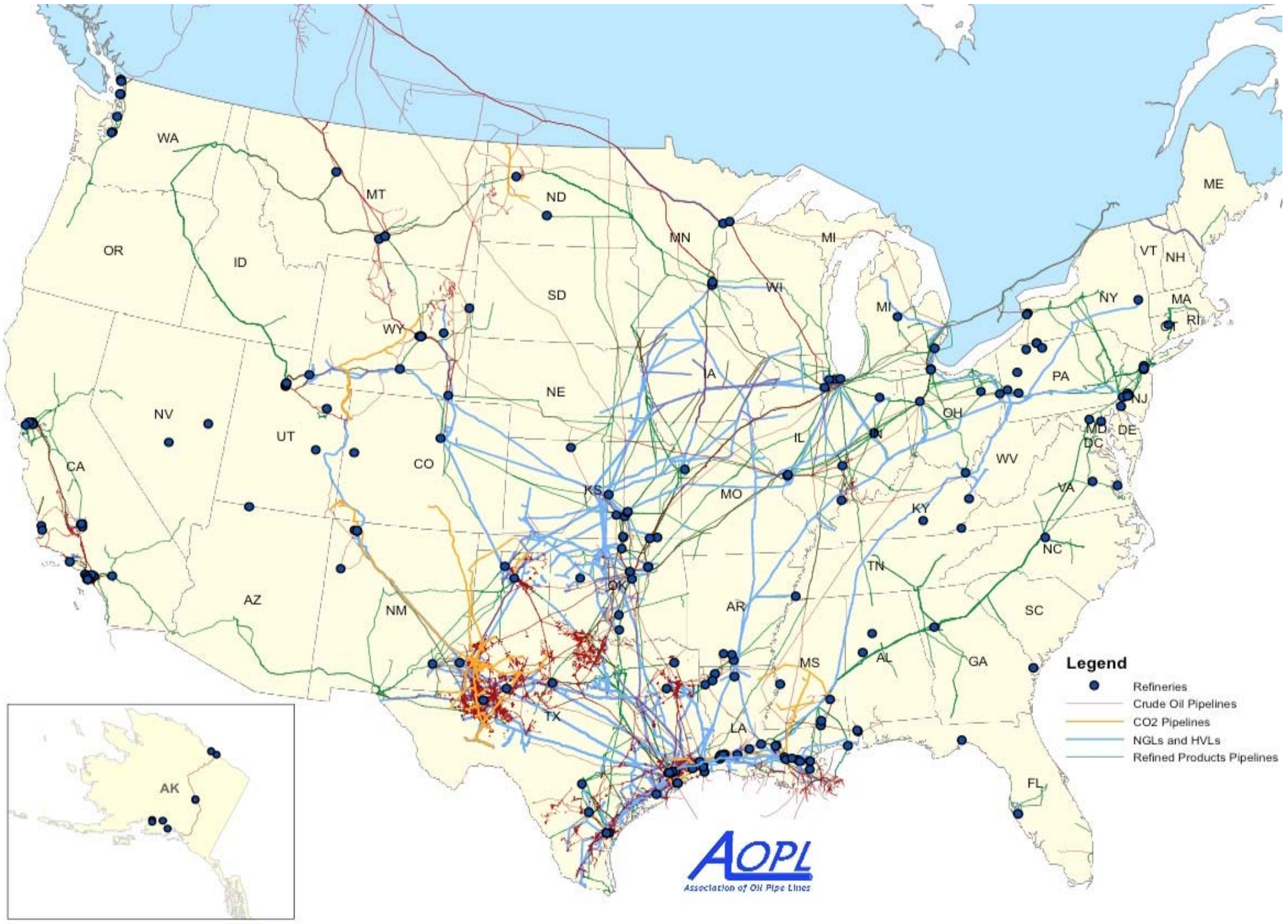


Note: Excluding VA

Crude Oil and Refined Products Pipelines

Within the OTR there are also a number of pipelines for transporting crude oil and refined products. Little information could be located regarding the number and makeup of pumping stations on those pipelines. The following map shows the relate pipeline system for the lower 48 states. It can be seen in the map that, relative to natural gas pipeline network system, the crude oil and refined products pipeline network is far less extensive in the OTR states.

Lower 48 States Crude Oil and Refined Products Pipelines, 2009



Source: Petroleum Geographics Corporation 2012

Attachment 2

2010 FERC Form 2 and Form 2A Data

OTR Natural Gas Compressors

State	Service	Facility Name/Location	No. Compressors	Total HP	Gas Compressor 2010 Fuel Use (MMBTU/yr)	Compressor 2010 Operating Hrs	Electric Compressor 2010 Power Usage (kwhr)
CT	Transmission	Chaplin Compressor Station, Chaplin, CT	2	13900	287115	4417	0
CT	Transmission	Cromwell Compressor Station, Cromwell, CT	8	21400	647985	27190	0
CT	Transmission	Oxford Compressor Station, Oxford, CT	3	37700	285982	3258	0
CT	Transmission	Brookfield Compressor Station, Brookfield, CT	2	18010	754008	11737	829750
CT	Transmission	Milford Compressor Station, Milford, CT	2	20620	260736	3101	509640
MA	Transmission	#261 - Agawam, MA Electric/Gas	5	17110	112038	6598	3199914
MA	Transmission	#264 - Charlton City, MA	2	12552	740495	7674	0
MA	Transmission	#266A - Mendon, MA	3	9170	167252	6769	0
MA	Transmission	#267 - Hopkinton, MA	5	5000	48126	728	0
MD	Transmission	Rutledge, MD	3	12000	0	7984	17053583
MD	Undrgrd Strg	Accident, MD	2	11000	86106	5212	1167552
MD	Transmission	No. 190 Ellicott City, Maryland	12	29250	1980798	96310	0
ME	Transmission	Baileyville Compressor Station,ME	2	16622	258129	3550	0
ME	Transmission	Richmond Compressor Station, ME	2	16622	208448	3108	0
ME	Transmission	Wood Chopping Ridge Compressor Station, ME	1	18085	367363	3323	0
ME	Transmission	Brewer Compressor Station, ME	1	18085	233651	2494	0
ME	Transmission	Searsmont Compressor Staion, ME	1	18085	123360	553	0
ME	Transmission	Westbrook Compressor Station, ME	2	26666	129882	1418	0
ME	Transmission	Eliot Compressor Station, ME	1	8960	20775	256	0
NH	Transmission	#270B1 - Pelham	1	6053	7959	97	0
NJ	Transmission	Hanover Compressor Station, Hanover, NJ	3	22000	193007	6245	0
NJ	Transmission	#325 - Sussex, NJ	2	14991	276720	5675	0
NJ	Transmission	Franklin (Freehold), NJ	1	5000	0	12	356417
NJ	Transmission	Hanover, NJ	1	6500	168087	6	180960
NJ	Transmission	Lambertville, NJ	7	24600	509431	22921	6818612
NJ	Transmission	Linden, NJ	3	6150	228305	13840	363520
NJ	Transmission	No. 205 Lawrenceville, New Jersey	3	30200	0	3333	31162606
NJ	Transmission	No: 207 Sayreville, New Jersey	2	10000	1806	4519	16011555
NJ	Transmission	No. 505 Centerville, New Jersey	8	16000	132840	8776	0
NJ	Other	No. 240 Hackensack Meadows, New Jersey	5	4320	148182	11445	0
NY	Transmission	Southeast Compressor Station, Southeast, NY	5	40010	1299694	14952	0
NY	Transmission	Stony Point Compressor Station, Stony Point, NY	7	38800	870835	13768	0
NY	Transmission	Corning, NY	1	1000	5904	2551	0
NY	Undrgrd Strg	Dundee, NY	3	1880	618	2133	0
NY	Undrgrd Strg	North Greenwood, NY	1	1000	0	0	0
NY	Undrgrd Strg	Quinlan, NY	2	4740	57565	2085	0
NY	Undrgrd Strg	Woodhull, NY	8	14700	260074	14522	0
NY	Transmission	Borger, NY	3	21910	236330	4100	0
NY	Transmission	Brookmans Corner, NY	1	7300	11139	114	0
NY	Transmission	Lockport, NY	0	0	0	0	0
NY	Transmission	Utica, NY	7	9500	34762	3813	0

NY	Transmission	Oakfield NY	2	20620	20134	220	262560
NY	Transmission	Croghan Compressor Station, Croghan, NY	2	17180	333832	4548	702880
NY	Transmission	Wright Compressor Station, Wright, NY	2	14302	436558	7607	513456
NY	Transmission	Athens Compressor Station, Athens, NY	1	10028	228932	2667	442080
NY	Transmission	Boonville Compressor Station, Boonville, NY	1	18371	206107	1533	620320
NY	Transmission	Dover Compressor Station, Dover, NY	1	18371	330391	2510	948538
NY	Transmission	Corning Millenium, NY	1	15000	0	1611	0
NY	Field	Field Compressor St - Appalachian Field	1	450	8262	8112	186221
NY	Undrgrd Strg	Beech Hill	3	8350	12113	8068	388560
NY	Undrgrd Strg	Derby	1	75	400	1832	9183
NY	Undrgrd Strg	Independence	4	5000	104882	10801	324800
NY	Undrgrd Strg	Limestone	1	800	31525	4328	97680
NY	Undrgrd Strg	Nashville	3	3320	20434	4543	292000
NY	Undrgrd Strg	Porterville	4	600	30413	5721	116682
NY	Undrgrd Strg	Tuscarora	2	1440	40840	4876	101496
NY	Undrgrd Strg	Zoar	8	1200	39286	18824	150880
NY	Transmission	#224 - Clymer, NY	4	8000	309015	18570	0
NY	Transmission	#229 - Hamburg, NY	6	8400	529074	46324	0
NY	Transmission	#230C - Lockport, NY	4	18000	8213	327	0
NY	Transmission	#233 - Geneseo, NY	2	7000	148178	3463	0
NY	Transmission	#237 - Clifton Springs, NY	3	8000	346521	13720	0
NY	Transmission	#241 - Lafayette, NY	5	18400	591170	20342	0
NY	Transmission	#245 - West Winfield, NY	12	19700	698051	44411	0
NY	Transmission	#249 - Carlisle, NY	4	16200	616398	18652	0
NY	Transmission	#254 - Nassau, NY	7	18710	410132	9804	0
NY	Transmission	#405A - CONNEXION NEW ENGLAND	1	7700	244347	4404	0
PA	Transmission	Artemas #2, PA	3	3670	0	1270	0
PA	Transmission	Delmont, PA	2	1954	56852	9200	0
PA	Transmission	Downingtown, PA	2	12000	0	7096	25681552
PA	Transmission	Eagle, PA	4	8050	255513	18536	0
PA	Transmission	Easton, PA	3	2890	11615	1225	0
PA	Transmission	Ellwood City, PA	2	1000	10570	1886	0
PA	Transmission	Gettysburg, PA	4	7500	233265	7969	0
PA	Transmission	Greencastle, PA	4	7070	265821	9314	0
PA	Transmission	Hellertown, PA	2	2200	21718	2502	0
PA	Transmission	Marietta, PA	3	4050	0	6281	0
PA	Transmission	McClellandtown, PA	1	225	0	0	0
PA	Transmission	Milford, PA	2	680	0	9	0
PA	Transmission	Renovo, PA	5	3370	30348	16619	0
PA	Transmission	Rimersburg, PA	1	320	13299	4692	0
PA	Transmission	Salisbury, PA	5	5480	458179	31623	0
PA	Transmission	Waynesburg, PA	5	5400	470930	22856	0
PA	Undrgrd Strg	Artemas #1, PA	2	4000	177424	8242	0
PA	Undrgrd Strg	Donegal, PA	2	2000	41653	4975	0
PA	Undrgrd Strg	Holbrook, PA	1	130	0	0	0
PA	Extraction	Hutchinson, PA	2	250	0	3564	130880
PA	Undrgrd Strg	Boom, PA	2	5200	3745	26	0
PA	Undrgrd Strg	Ellisburg, PA	8	18400	298419	24948	0
PA	Undrgrd Strg	Greenlick, PA	4	13600	394904	12019	0
PA	Undrgrd Strg	Harrison, PA	6	11100	84666	11300	0

PA	Undrgrd Strg	Leidy, PA	13	25800	427133	38719	0
PA	Undrgrd Strg	Lincoln Heights, PA	2	510	6367	9330	0
PA	Undrgrd Strg	North Oakford, PA	0	0	0	0	22730086
PA	Undrgrd Strg	North Summit. PA	2	6400	114736	4468	0
PA	Undrgrd Strg	Oakford, PA	15	43800	309724	44620	0
PA	Undrgrd Strg	Sabinsville, PA	8	12870	218612	13035	0
PA	Undrgrd Strg	South Oakford, PA	4	24200	122824	20655	28479000
PA	Undrgrd Strg	State Line, PA	4	4650	63271	5396	0
PA	Undrgrd Strg	Tioga, PA	2	8400	55413	3679	0
PA	Transmission	Ardell, PA	1	15000	304790	1822	0
PA	Transmission	Ardell 2 PA	2	3550	0	8767	0
PA	Transmission	Beaver, PA	4	12800	539427	23243	0
PA	Transmission	Bedford-TE, PA	0	0	0	0	10541707
PA	Transmission	Big Run, PA	1	1775	81786	8637	0
PA	Transmission	Centre,PA	2	12400	17980	298	0
PA	Transmission	Chambersburg, PA	4	24800	91016	5402	15584000
PA	Transmission	Chambersburg-TE, PA	0	0	0	0	5303820
PA	Transmission	Cherry Tree, PA	2	1520	84100	16146	0
PA	Transmission	Connellsville-TE, PA	0	0	0	0	0
PA	Transmission	Crayne, PA	2	15600	604644	10636	0
PA	Transmission	Finnefrock, PA	6	17500	721073	30509	0
PA	Transmission	Helvetia, PA	1	330	14608	5966	0
PA	Transmission	J.B. Tonkin, PA	1	6000	313000	7796	0
PA	Transmission	Little Greenlick, PA	3	11135	202960	8515	0
PA	Transmission	Luthersburg, PA	2	880	34281	8730	0
PA	Transmission	NFG-Ellisburg, PA	0	0	0	0	0
PA	Transmission	Perulak, PA	1	4735	99400	3674	0
PA	Transmission	Punxsutawney, PA	3	13132	397058	13087	0
PA	Transmission	Rochester Mills, PA	3	1320	69928	19079	0
PA	Transmission	Rock Springs, PA	2	4740	127	102	0
PA	Transmission	Rural Valley, PA	2	5325	104902	6433	0
PA	Transmission	Sabinsville, PA	1	5800	0	17	0
PA	Transmission	South Bend, PA	6	12000	262572	14602	0
PA	Transmission	Stoney Run, PA	3	1152	31542	9646	0
PA	Transmission	Uniontown-TE, PA	0	0	0	0	18220824
PA	Undrgrd Strg	Hartson-Washington County, PA	3	3300	114572	12354	0
PA	Transmission	Pratt-Greene County, PA	5	4800	179718	23494	0
PA	Field	Mt. Morris-Greene County, PA	2	220	4007	8826	0
PA	Field	Ryerson-Greene County, PA	1	41	0	0	0
PA	Field	Waynesburg-Greene County, PA	2	3600	203445	15651	0
PA	Undrgrd Strg	Boone Mountain	2	300	10583	318	36313
PA	Undrgrd Strg	Carter Hill	2	765	2270	678	45687
PA	Undrgrd Strg	Ellisburg	4	9445	0	19892	0
PA	Undrgrd Strg	Henderson	2	2700	125012	9575	193240
PA	Undrgrd Strg	Queen	4	450	14507	12611	51636
PA	Undrgrd Strg	Summit	2	880	14606	2324	123250
PA	Undrgrd Strg	Wellendorf	1	325	259	528	0
PA	Transmission	East Fork	5	3060	40543	9332	82669
PA	Transmission	Eldred	2	300	14770	10710	60186
PA	Transmission	Heath	1	1160	1489	7107	385200

PA	Transmission	Island Run	4	615	17527	11507	130386
PA	Transmission	Kaylor	1	145	10879	8091	13776
PA	Transmission	Knox	4	1968	64031	20087	124617
PA	Transmission	Lamont	8	1490	51257	30288	263200
PA	Transmission	Roystone	12	5500	189451	62384	149443
PA	Transmission	Sackett	4	675	28152	25532	125954
PA	Transmission	Van	2	476	5750	9346	7766
PA	Transmission	Concord	5	11250	23546	1276	332000
PA	Transmission	Costello	2	1440	0	14985	28074
PA	Transmission	Ellisburg	5	11450	491390	11450	812700
PA	Transmission	Lockport	4	18000	41925	0	0
PA	Transmission	Boone Mountain	1	280	0	5269	0
PA	Transmission	Nashville	1	225	0	3471	0
PA	Transmission	Reynoldsville	1	150	7720	6891	40903
PA	Transmission	Bowen	1	1340	360	65	23825
PA	Undrgrd Strg	#313 - Coudersport, PA	14	24270	1051775	69136	0
PA	Transmission	#219 - Mercer, PA	14	21550	867950	63824	0
PA	Transmission	#307 - Pigeon, PA (Kane)	6	15500	661587	29745	0
PA	Transmission	#313A Elllisburg, PA	2	4730	131993	8594	0
PA	Transmission	#315 - Wellsboro, PA	1	9300	70305	589	0
PA	Transmission	#317 - Troy, PA Electric	1	13000	4355	1588	7303548
PA	Transmission	#319 - Wyalusing, PA	2	9000	165676	3426	0
PA	Transmission	#321 - West Clifford, PA	3	14100	275679	7815	0
PA	Transmission	#323A - Hawley, PA (Stagecoach) Electric	1	13400	740	3918	32003200
PA	Transmission	Armagh, PA	1	22000	429957	1631	150900
PA	Transmission	Bechtelsville, PA	4	33500	1353738	20510	744902
PA	Transmission	Bedford, PA	11	33880	307777	29591	47453065
PA	Transmission	Bernville, PA	2	41800	953347	4919	591360
PA	Transmission	Heidlersburg, PA	1	16000	0	2325	14020634
PA	Transmission	Chambersburg, PA	2	41300	0	3595	16217920
PA	Transmission	Delmont, PA	12	46400	1901482	55591	2034669
PA	Transmission	Entriken, PA	1	22000	344877	1476	333840
PA	Transmission	Grantville, PA	4	33500	1571988	20018	875712
PA	Transmission	Holbrook, PA	15	58800	1908009	49712	2164622
PA	Transmission	Leidy, PA	4	8100	0	12443	189160
PA	Transmission	Lilly, PA	4	34800	1601960	22505	679680
PA	Transmission	Marietta, PA	7	23960	756327	17906	757200
PA	Transmission	Perulack, PA	4	34800	1594479	25627	1628800
PA	Transmission	Phoenixville,PA/Eagle, Pa	1	4000	0	1497	1605646
PA	Transmission	Shermans Dale, PA	2	41800	1062290	5403	531520
PA	Transmission	Uniontown, PA/Connelsville	8	79200	1293221	16995	72090151
PA	Transmission	Waynesburg, PA	1	5000	169717	4395	111200
PA	Undrgrd Strg	Leidy, PA	13	25800	242377	38719	0
PA	Undrgrd Strg	Oakford, PA (Oakford)	15	43800	358108	44620	0
PA	Undrgrd Strg	Oakford, PA (South Oakford)	4	24200	137830	20655	0
PA	Undrgrd Strg	Oakford, PA (Lincoln Heights)	2	510	9203	9330	0
PA	Undrgrd Strg	No. 530 Leidy-Tamarack Storage Field, PA	0	0	2243866	0	0
PA	Undrgrd Strg	No. 535 Wharton Storage Field, PA	5	8500	121644	20106	0
PA	Transmission	No. 195 Delta, Pennsylvania	5	19460	906501	35626	0
PA	Transmission	No. 200 Malvern, Pennsylvania	13	30860	2044206	100036	0

PA	Transmission	No. 515 Bear Creek, Pennsylvania	6	32000	423899	12281	0
PA	Transmission	No. 517 Benton, Pennsylvania	4	38500	245552	2459	0
PA	Transmission	No. 520 Salladasburg, Pennsylvania	7	35200	483089	10580	0
RI	Transmission	Burrillville Compressor Station, Burriville, RI	5	22000	599629	11360	0
RI	Transmission	#265E - Burrillville, RI (Rise)	1	7170	332999	7550	0
VA*	Transmission	Loudoun, VA	9	15190	185470	10858	0
VA*	Transmission	Loudoun, VA	3	12000	205510	8434	0
VA*	Transmission	Leesburg, VA	3	14200	357748	10089	0
VA*	Transmission	No. 185 Manassas, Virginia	10	20000	1182138	74626	0
		Total	721	2442801	55239677	2393711	414001868

*FERC 2 and 2A compressor stations in OTR area of VA

2010 OTR Natural Gas Compressors
FERC Form 2 and Form 2A Data

State	No. Compressors	Total Horsepower
CT	17	111630
MA	15	43832
MD	17	52250
ME	10	123125
NH	1	6053
NJ	35	139761
NY	123	406057
PA	472	1469533
RI	6	29170
VA*	25	61390

*OTR area of VA only