Final Report: Cost-Effective Reciprocating Engine Emissions Control and Monitoring for E&P Field and Gathering Engines

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Abstract

This final report describes a project intended to identify, develop, test, and commercialize emissions control and monitoring technologies that can be implemented by E&P operators to significantly lower their cost of environmental compliance and expedite project permitting. Technologies were installed and tested in controlled laboratory situations and then installed and tested on field engines based on the recommendations of an industry-based steering committee, analysis of installed horsepower, analysis of available emissions control and monitoring technologies, and review of technology and market gaps. The industry-recognized solution for lean-burn engines, a low-emissions-retrofit including increased airflow and pre-combustion chambers, was found to successfully control engine emissions of oxides of nitrogen (NO_X) and carbon monoxide (CO). However, the standard non-selective catalytic reduction (NSCR) system recognized by the industry was found to be unable to consistently control both NO_X and CO emissions. The standard NSCR system was observed to produce emissions levels that changed dramatically on a day-to-day or even hour-to-hour basis. Because difficulties with this system seemed to be the result of exhaust gas oxygen (EGO) sensors that produced identical output for very different exhaust gas conditions, models were developed to describe the behavior of the EGO sensor and an alternative, the universal exhaust gas oxygen (UEGO) sensor. Meanwhile, an integrated NSCR system using an advanced, signal-conditioned UEGO sensor was tested and found to control both NO_X and CO emissions. In conjunction with this project, advanced monitoring technologies, such as Ion Sense, and improved sensors for emissions control, such as the AFM1000+ have been developed and commercialized.

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Introduction

Forecasts of future U.S. natural gas demand of between 26 and 30 trillion cubic feet (Tcf) per year by 2035 (EIA, 2011) require up to 36% production growth from 2001 levels, with the majority of this increase expected from three primary areas: Offshore Gulf of Mexico, Rocky Mountains, and Canadian imports. Mature basins in the Southwest and Mid-Continent areas also will contribute to the total domestic supply, and maximizing their output will be necessary to meet the aggressive 30 Tcf gas demand target. Oil and gas production operations in the United States face a wide variety of environmental regulations that are imposed by multiple, sometimes overlapping, jurisdictions. In particular, onshore production must grapple with existing and emerging regulations that address National Ambient Air Quality Standards for NO_2, ozone, fine particulates, acid deposition, regional haze, and National Emissions Standards for Hazardous Air Pollutants for formaldehyde and carbon monoxide emissions from compressor engines. In addition, operators are now required to report greenhouse gas emissions and are expecting regulations regarding greenhouse gas emissions limits to be implemented sometime after 2016. (McCarthy, 2010) The scope of these regulations includes the wellhead and field gathering reciprocating engine-driven compressor equipment that is ubiquitous in E&P operations; in 2001 it was estimated that approximately 15 million horsepower were operating in upstream production applications (Hanover Compressor Company 2001 10-K Annual Report filing). At an average size of 250 HP, this implies a total E&P fleet of 60,000 engines. As more gas is drawn from unconventional wells, additional compression is required, and this compression is expected to be driven by additional, mostly smaller-sized, gas-fired engines. (Beshouri et al., *Report* 13, 2006)

Though in many oil and gas production areas the airshed emissions inventory is dominated by coal power plants, regulatory agencies continue to pursue incremental reductions in the total pollutant loading. Reciprocating engines have been identified as a meaningful source category. These engines are used to produce electricity for a leasehold, compress and re-inject natural gas for increased oil production, or compress natural gas so that it can be delivered to local gathering systems that feed ultimately into gas transmission pipelines.

At present, the region with the greatest confluence of emissions concerns is the Rocky Mountain and Intermountain West area. In these regions, significant concerns about regional haze control accelerated the implementation of NO_X and fine particulate regulations that are only pending in many other producing areas. However, the stricter national limits in emissions production promulgated by the Environmental Protection Agency's 2008 New Source Performance Standards for reciprocating engines and the incremental adoption of regulations state-by-state, as well as the proximity of many remote production areas in the Southwest to National Parks and Class I Wilderness Area (which are protected airsheds) may likely stimulate aggressive compressor engine controls in that and other production regions. Finally, the East Texas and Louisiana regions are subject to conventional ambient ozone concerns, and have promulgated strict NO_X controls for reciprocating engines. Oil and gas production from all states will be required for the U.S. to meet the expected 30 Tcf/year gas demand and to minimize the ongoing slide in domestic oil production. Therefore, impediments to production that are created by air quality permitting must be alleviated through focused R&D efforts.

Gas compressor operations are an essential element of oil and gas production. Increased emissions constraints on compressor operations affect oil and gas production in four distinct ways:

1) The length of time to obtain an emissions permit is increased as multiple jurisdictions evaluate the effects of various pollutants and attempt to define a mutually acceptable permit level for a given engine;
2) The capital and operating costs of compressor engine operation are increased as this equipment is physically modified and/or operated differently to comply with the air permits;
3) The capital and operating costs of compressor engine operation are increased when expensive and maintenance-intensive continuous emissions monitors are required, as is the case in parts of California. In many settings, the cost of this monitoring exceeds the cost of NO_X control; and
4) Compressor operators may be forced to limit the annual hours of operation to avoid exceeding a fixed annual ceiling on allowed emissions.

Each of these situations impedes oil and gas production by:

1) Deferring the start of wellhead production, thereby increasing the general business risk in price-volatile markets and increasing the carrying costs of various lease and development fees;
2) Directly increasing the cost of compression services used at the wellhead; or
3) Artificially limiting the annual take from a well due to constrained operations.

The net effect is reduced oil and gas production for a given cost within a fixed time period. Multiplying this through thousands of production sites will most certainly have a significant negative impact on the ability of U.S. operators to meet domestic energy demands and on the general productivity of the U.S. hydrocarbon resource base.

A focused effort has been made to develop cost-effective retrofit components, engine combustion controls, and engine performance-monitoring options that can reduce these economic and operating burdens to oil and gas operations. The project has examined various technologies for emissions controls and monitoring of compressor engines and identified cost-effective options, thus ensuring that compliance with air regulations does not prevent oil and gas operations from achieving their maximum productivity at competitive production costs.

Objective

The goal of this project is to identify, develop, test, and commercialize emissions control and monitoring technologies that can be implemented by E&P operators to significantly lower their cost of environmental compliance and expedite project permitting.

Basis of the Project

This project drew heavily on the experience gained from the interstate gas pipeline industry's experience with NO_X emissions reductions, and their efforts to develop cost-effective options for extensive deployment throughout their systems. A number of gas pipelines faced EPA statutory deadlines in 1994 and 1995 to achieve and certify dramatic reductions in compressor engine NO_X emissions across a very wide range of ageing and diverse, but critical, equipment. Even though typical pipeline reciprocating compressor engines range in size from 600 HP to 8,000 HP and are largely two- and four-stroke cycle integral compressors, there is some commonality in equipment types and operational concerns with the wellhead and gathering facilities under study in this project. Beginning in 1990, the pipeline industry embarked on a comprehensive R&D program that targeted significant (50%+) reductions in the cost of NO_X controls without any significant engine performance compromises. All of the technologies developed had to be field-retrofitable and commercially-supported. That program was a significant success and created a number of technical options that allowed up to 80% NO_X reductions in a cost-effective and operationally-acceptable manner. The individuals involved with this current project were key participants in that prior pipeline NO_X and formaldehyde reduction program.

The gas pipeline emissions control technology development effort was instructive in that it employed the following six distinct phases of activity, each of which was necessary for success:

1) Obtain an industry consensus for the:

    a) specific engine types and models on which to focus development efforts;

    b) installed cost targets; and

    c) realistic emissions levels to be achieved under all operating conditions.

2) Develop an inventory of installed horsepower to confirm initial industry guidance and to create a useful tool for impact analysis;

3) Create a coordinated, core team of engine technologists, regulatory experts, and industry representatives to ensure that engine design issues, regulatory drivers, and practical operating considerations always were addressed simultaneously;

4) Aggressively field test component and controls developments;

5) Characterize the fundamental relationships between engine operating parameters and exhaust emissions so that accurate, non-instrumented emissions monitoring systems could be deployed; and

6) Transfer technology results to organizations with an existing presence in the industry so that equipment could be provided on commercial terms, with emissions guarantees, and supported on an ongoing basis.

This project followed a similar broad outline with the expectation that the end product is a set of cost-effective emissions control and monitoring options that can be applied to a wide range of compressor engines in common use in oil and gas production. As a result of collaborations and information-sharing promoted through this project, new or improved emissions reduction controls are available for several types of engines that lacked effective control technology previously. In addition, lower-cost monitoring alternatives were investigated. This should allow operators to enjoy reduced costs of compliance, greater permitting certainty, reduced costs of emissions monitoring, and possible improved engine performance due to improved combustion stability. All of this will sum to increased production as wells are brought online more rapidly, compression equipment is run harder and longer to facilitate increased production, and cost savings are reallocated toward additional resource base development.

Summary of Results: Accomplishments

Phase 1: Industry-guided assessment of monitoring and controls

Tasks completed as a part of Phase 1 include the following:

1. Create an industry-based steering committee;
2. Develop a representative database of existing E&P reciprocating engine inventory;
3. Identify and assess commercial and emerging control and monitoring technologies;
4. Determine technology and market gaps between practical options and current and expected permitting requirements;
5. Conduct controlled tests to evaluate promising monitoring and control technologies identified in Tasks 3 and 4; and,
6. Determine on-engine control system and sensor requirements for remote emissions monitoring.

Create an Industry-Based Steering Committee

An industry steering committee was formed to guide the project in order to best meet the needs of the Exploration and Production (E&P) industry. The steering committee included members representing El Paso, BP, Chevron Texaco, Universal and Hanover Compression (which merged to form Exterran), Western Gas Resources, Williams, the Petroleum Technology Transfer Council (PTTC), and the American Petroleum Institute (API). Initially, the steering committee provided information regarding the E&P fleet, experiences with and perceptions of available and emerging emissions monitoring and control technologies, challenges that arise as additional regulations are implemented, and levels of investment reasonable to put into emissions monitoring and control technology. (Chapman, *Report 1*, 2003) As the project progressed, members of the steering committee provided cost share and funding to allow for needed additional testing of NSCR. (Chapman and Nuss-Warren, *Report 19*, 2007) In addition, members of the steering committee made their engines available to perform this testing and provided maintenance and upgrades. (Chapman and Nuss-Warren, *Report 17*, 2007) As results became available, the research team shared them with members of the steering committee through conference call updates and presentations at meetings, including the annual Gas Machinery Conference. It is expected that the availability of this information will encourage the transfer of effective technologies to field engines.

Some of the initial guidance from the steering committee that proved especially helpful in undertaking this project regarded industry perceptions about the most certain ways of meeting permitting requirements and the areas that needed further investigation. Initially, steering committee members believed that rich-burn engines fitted with non-selective catalytic reduction (NSCR) catalysts were the most certain way to achieve ever-decreasing permit limits, although this was known to reduce fuel efficiency, and therefore increase cost. Because the price of consumed gas and carbon dioxide produced were expected to become factors in the future, the steering committee felt additional investigation into minimizing emissions from more fuel-efficient lean-burn engines was warranted. (Chapman, *Report 1*, 2003) This influenced the research team's choice to begin by focusing on lean-burn engines. Rich-burn engines were further investigated once it became clear that the industry's perception regarding the consistent reduction of emissions to low levels by NSCR was unjustified. (Arney, 2006)

The steering committee also suggested that if increased monitoring was likely to be required, the large geographic area over which production engines are distributed would call for monitoring to be conducted remotely. In addition, committee members felt the cost of any required monitoring for emissions would be quite burdensome if no additional benefit could be derived. However, if monitoring could provide insight into engine operation so that engine performance could be improved and maintenance cost reduced, additional monitoring could become appealing. (Chapman, *Report 1*, 2003) This led the research team to look for ways in which a parametric emissions monitoring system (PEMS) that calculates emissions based on engine operating conditions could be implemented for E&P engines.

Finally, the industry steering committee provided guidance on what the most helpful form for a database of existing E&P engines would be. Specifically, the committee members felt that a frequency distribution of engines based on an appropriate sample of various geographic regions would be most helpful. (Chapman, *Report 1*, 2003) Thus, rather than spending time ensuring every single engine in use was included in the database, members of the research team were instead able to focus on using the trends from the frequency distribution to determine which technologies to focus on to provide retrofit options for the greatest number of engines.

Develop a Representative Database of Existing E&P Reciprocating Engine Inventory

Based on recommendations from the industry steering committee, the database of existing E&P engines characterized a sample of engines from major sources. This sample includes the State of Wyoming Engine Inventory Database, the EPA ICCR Database, the GTI/PRCI Engine and Turbine Database, and the Database of Colorado and New Mexico Engines from Universal Compression. (Chapman, *Report 2*, 2003) While these sources contain approximately 9,000 engines, all duplicates and engines used in capacities outside of exploration and production were removed, leaving a total of 4,729 engines, which was deemed to be an adequate sample. (Chapman, *Report 3*, 2003) However, the sources used typically document only permitted engines. Thus, lower-horsepower engines are underrepresented in the engine database. (Chapman and Nuss-Warren, *Phase 1 Report*, 2007)

For each engine the following information was tracked:

1. Make and Model,
2. Air-to-fuel ratio,
3. Cycle, and

4. Horsepower.

Information regarding geographical distribution was deemed unnecessary once the sources of engine data were examined. The complete database is in Appendix I, Table 8, "Gathering Engines in the DOE Project Database Sorted by Frequency." When listed by how frequently an engine is found on the inventory, the first 20 types of engines account for 85% of the total. (Chapman, *Report 3,* 2003) This implies that emissions reduction solutions for the most common types of engines will be solutions for the majority of the E&P fleet.

Table 1. Engine frequency by air-to-fuel ratio and cycle.

A/F ratio	Cycle	Total
Lean-burn	two-stroke	783
Lean-burn	four-stroke	2318
Rich-burn	four-stroke	1617
Unknown		11
Grand Total		4729

When sorted by air-to-fuel ratio and cycle, as shown in Table 1, it becomes clear that four-stroke cycle engines are more prevalent than two-stroke cycle engines and lean-burn engines outnumber rich-burn engines among those engines included in the database. However, because many engines rating less than 100 hp are not included, and the majority of these smaller units are four-stroke cycle rich-burn engines, rich-burn engines are actually underrepresented in the database. (Chapman and Nuss-Warren, *Phase 1 Report*, 2007) Because there are numerous four-stroke cycle lean-burn engines, four-stroke cycle rich-burn engines, and two-stroke cycle lean-burn engines, emissions solutions were investigated for all three of these engine types.

Table 2. Engine Frequency by Manufacturer.

Manufacturer	Total
Ajax	763
Caterpillar	1631
Ford	28
Superior	37
Waukesha	2232
Other	38
Grand Total	4729

Table 2 shows the engines sorted by manufacturer. The most prevalent manufacturers of engines in the E&P fleet are Waukesha and Caterpillar. Both manufacturers make four-stroke cycle rich- and lean-burn engines. The third most common manufacturer is Ajax, which makes two-stroke cycle lean-burn engines. (Chapman and Nuss-Warren, *Phase 1 Report*, 2007) Thus, emissions reduction technologies for four-stroke cycle lean- and rich-burn engines should be applicable to both Waukesha and Caterpillar models, and technologies for two-stroke cycle lean-burn engines only need to apply to Ajax engines. Solutions for engines made by these three companies apply to 98% of the total fleet.

Identify and Assess Commercial and Emerging Control and Monitoring Technologies

In order to effectively identify and assess commercial and emerging control and monitoring technologies, it is necessary to determine which emissions products are of regulatory concern for reciprocating engines used in natural gas exploration and production and to understand how those products are formed. Once the products have been identified and understood, emissions control technologies can be assessed in terms of

1. Scientific principles behind the emissions reduction;
2. Overall costs associated with implementation;
3. Recurring maintenance costs associated with use;
4. Incremental fuel costs resulting from use; and,
5. Required emissions monitoring and associated costs.

The research team approached this assessment by first determining baseline emissions levels for the engines identified as a result of analyzing the engine database. Then, the team identified emissions control technologies that could be applied to each of these engines. Next the researchers gathered technical, operational, and economic information for each control technology and the associated ancillary equipment. Finally, they analyzed the cost effectiveness of each technology for the E&P fleet.

Reciprocating Engine Emissions Production

Reciprocating engines in the natural gas exploration and production industry are typically spark-ignited engines fueled by natural gas from the production sources. Thus, the emissions of concern are typically oxides of nitrogen (NO_X) and carbon monoxide (CO), both of which are frequently regulated. Other regulated products of combustion include oxides of sulfur (SO_X), particulate matter (PM), and volatile organic compounds (VOCs). SO_x is not considered a product of natural gas combustion because it is formed only when the fuel contains sulfur, and natural gas does not contain significant amounts of sulfur. PM is not considered a product of natural gas combustion because it is typically produced by burning liquid or solid fuels. Few VOCs, or unburned non-methane hydrocarbons, are produced because natural gas consists mainly of methane and, therefore, contains few of these heavier hydrocarbons. Like all combustion engines, these engines produce carbon dioxide (CO_2) as a product of combustion. (Chapman, *Report 2*, 2003) While CO_2 must be reported as a greenhouse gas, it is not expected to be regulated for most natural gas production engines before 2016. (McCarthy, 2010) Because the amount of CO_2 produced depends on the amount of fuel burned, improving engine efficiency will reduce CO_2 emissions.

NO_X is the pollutant of primary concern for natural-gas-fuelled, spark-ignited engines. NO_X refers to combined NO and NO_2. For spark-ignited, reciprocating engines, NO_X is typically reported and regulated in terms of the mass of pollutant produced for the amount of work done by an engine, which is measured in units of g/bhp-hr. This allows emissions from different-sized engines to be compared. NO_X can also be reported in terms of parts per million (ppm) by volume. (Chapman, *Report 2*, 2003)

NO_X can be formed in three different ways during combustion. The first and most common formation mechanism is thermal NO_X. Thermal NO_X refers to the reaction of nitrogen and oxygen in the air at high temperatures. Typically, this occurs along the flame front during combustion, where the temperatures are highest. The higher the flame temperature and the longer the temperature remains high, the more NO_X will be formed. (Chapman, *Report 11*, 2005) The second formation mechanism is prompt NO_X. Prompt NO_X is formed early in the combustion process when nitrogen from the air reacts with hydrocarbon radicals in the fuel. Prompt NO_X accounts for very little of the NO_X formed in typical combustion. Finally, fuel-bound NO_X is the least significant formation mechanism in natural-gas-fuelled engines. Fuel bound NO_X is formed by nitrogen that is part of the hydrocarbon structure of the fuel. Since natural gas contains almost no nitrogen, fuel-bound NO_X is not a concern for natural-gas-fired engines. (Chapman, *Report 2*, 2003)

CO is formed through incomplete combustion. The combustion reaction cannot be completed if there is not enough oxygen, so an overly rich air-to-fuel mixture can lead to high levels of CO. In addition, whenever temperatures are not high enough for a long enough duration, the reaction will remain incomplete. This can happen when the cooler walls quench the combustion reaction or when the combustion gases are cooled during the exhaust process, which can also quench the reaction. (Chapman, *Report2,* 2003)

Control Technologies

Any effective control technology must be able to reduce the levels of NO_X and CO from an engine's baseline production. There are two general approaches to this process. The first, combustion control, requires modification of the conditions within the engine's cylinder so that less NO_X and CO are actually produced in the combustion reaction. In post-combustion control, however, the engine exhaust passes through a catalyst of some sort where the pollutants in the exhaust undergo further chemical reactions to form standard air constituents. Promising technologies of both types are discussed below and compared in Table 9 of Appendix II.

Combustion Control

Since the NO_X produced by reciprocating, spark-ignited, natural-gas-fired engines is primarily thermal NO_X, reducing the combustion temperature will result in less NO_X production. Thus, the main strategy for combustion control is to reduce the combustion temperature. This is most easily done by adding air above and beyond that required for complete combustion of the fuel. This additional air raises the heat capacity of the gases in the cylinder so that for a given amount of energy released in the combustion reaction, the maximum temperature will be reduced. Any time excess air is introduced into the cylinder, and the engine is said to be "lean." Lean air-to-fuel ratios have a normalized air-to-fuel ratio (λ) greater than 1.

$$\lambda = \frac{AFR_{actual}}{AFR_{stoichiometric}}$$

Lean-burn technology as a method to reduce NO_X emissions typically uses 50 – 100% excess air (λ from 1.5 to 2). As long as engine stability remains good, lean combustion produces higher engine output and efficiency. However, with such lean air-to-fuel ratios, it becomes more difficult to light the mixture, and combustion instability can become a problem. Not only does unstable combustion decrease the output of the engine, it can also result in higher CO and unburned hydrocarbon levels due to incomplete combustion. The challenge of lean-burn technology as a means for emissions control is to provide sufficient air to reduce the temperature and NO_X levels but to maintain combustion stability. This is often achieved by increasing the ignition energy provided to the mixture. Thus, most combustion control technologies either provide a way to increase air flow to the engine, increase the ignition energy available, or reduce temperatures while maintaining combustion stability with improved mixing or slightly less lean mixtures. (Chapman, *Report 2*, 2003)

Retard Ignition Timing – Ignition timing retardation is a low cost option applied to achieve small decreases in NO_X emissions of up to 10%. When the spark timing is decreased, the peak firing temperature and pressure will be lower, reducing NO_X emissions. A few degrees of timing adjustment can give a significant change in NO_X output. The trade-off is reduced engine efficiency. (Chapman, *Report 2*, 2003) However, this is a minor adjustment with a very low cost to implement and can be tuned for best results when used in conjunction with other combustion control technologies, such as increased air-to-fuel ratio.

Lean-burn combustion with low-emissions retrofit – For a lean-burn, low emissions retrofit to be effective, additional air must be provided to the engine. Typically, turbochargers are added to increase the air pressure at the engine intake so that more air is pulled into the cylinder. This increases the in-cylinder air-to-fuel ratio. Turbochargers also increase the temperature of the air they compress, so intercooling is typically needed where a turbocharger is installed. In cases where turbochargers cannot be fit to an engine, other changes to the intake of the engine can be made. In some cases, changes to the exhaust of an engine that cannot be turbocharged can provide increased air pressure in the cylinder. (Cameron Compression, 2010) Reductions of up to 90% in NO_X emissions are possible, giving brake-specific emissions in the range of 0.5 to 2.0 g/bhp-hr. (Chapman, *Report 2*, 2003) Along with the reduced NO_X emissions come increased fuel economy and a possible increase in CO compared to slightly richer, but still lean, combustion conditions. The turbocharger, intercooler, and other changes to the air intake systems for an engine account for the majority of the cost of this technology, but there will typically be changes made to the ignition system as well. A complete retrofit can cost from $500K to $2 million and requires significant changes to the engine, but the NO_X reductions are robust. (Chapman, *Report 3*, 2003)

High Energy Ignition Systems – High energy ignition refers to systems that deliver a hot spark, long spark duration, or multiple sparks. The basic concept behind these technologies is the ability to ignite a leaner air/fuel mixture within the power cylinder than would be possible with a standard ignition system. (Chapman and Adriani, *Report 6*, 2004) This technology, when used to ignite lean mixtures, can produce a system with NO_X emissions in the range of 2.5 to 3 g/bhp-hr. (Chapman, *Report 4*, 2003) However, this ignition technology is only useful when combined with increased air flow to the engine, and is not used for the very leanest mixtures. It can require special sparkplugs and electrical equipment and would typically be included in the cost of a lean-burn combustion retrofit for low emissions. (Chapman, *Report 2*, 2003)

Pre-Combustion Chamber (PCC) – Pre-combustion chambers (sometimes referred to as jet cells) are used to ignite extremely lean air/fuel mixtures. A secondary fire chamber is integrated into the power cylinder head. These systems use a secondary fuel supply to richen the pre-chamber's lean mixture to an easily ignitable mixture. The integral design assures proper cooling and eliminates problems with water leaking into the power cylinder. NO_X levels around 1.0 g/bhp-hr can be achieved with an integral PCC when combined with increased air flow to the engine. This is usually installed as part of a lean-burn combustion retrofit for low emissions, but will tend to make for a more expensive and intensive retrofit process because the engine head must be replaced with one containing an integral PCC. Additionally, a secondary fuel system is required for the use of a PCC. (Chapman, *Report 2*, 2003)

Micro Pre-Combustion Chamber – This approach is a hybrid between high energy ignition systems and pre-combustion chambers. It reduces NO_X by providing sufficient energy to ignite a lean air/fuel mixture, but is not typically used with the very leanest mixtures. This system is typically a spark plug fitted with a small fuel supply line directed at the spark plug's electrode. Similar to a pre-combustion chamber, the secondary fuel is fed through a check valve in the cavity in and around the spark plug's electrodes. As the piston rises, the secondary fuel mixes with the cylinder's air/fuel mixture to generate a localized rich mixture. When the spark is initiated, the localized rich mixture ignites and provides sufficient energy to continue the combustion process through the remaining lean mixture in the cylinder. This technology can limit NO_X emissions to the 2 – 4 g/bhp-hr range when combined with increased air flow to the engine. A micro PCC would be installed as part of a lean-burn combustion retrofit for low emissions. While it still requires a secondary fuel system, a micro PCC would tend to cost less to install than an integral PCC, but requires special replacement spark plugs. (Chapman, *Report 2*, 2003)

Screw-in Pre-Combustion Chamber – Screw-in pre-combustion chambers affect combustion and emission performance similarly to integral pre-combustion chambers (NO_X levels around 1 g/bhp-hr) when used with increased air-flow to the cylinder. These systems are retrofit options that provide additional ignition energy from a separate rich-burning chamber capable of firing a lean air/fuel mixture in the main chamber. Again, a secondary fuel supply is used to "richen" a localized mixture. The difference is that the PCC is simply screwed into the normal spark plug port in the cylinder head. However, this means a secondary cooling system must be installed for the PCC. Again, the cost is part of the lean-burn combustion retrofit for low emissions and is expected to be lower in cost than using an integral PCC. (Chapman, *Report 2*, 2003)

Pre-Stratified Charge – The pre-stratified charge system is an option available for four-stroke cycle, rich-burn, carbureted engines. In general, a secondary air supply for dilution is piped into the fuel manifold for each cylinder. The dilution air is maintained at a slightly higher pressure than the pressure of the carbureted mixture. While the cylinder fuel valve is closed, fresh air is forced into the fuel header pushing the carbureted mixture back. Once the fuel valve opens, the fresh air and a leaner-than-normal mixture are the first to enter the cylinder and move toward the piston. The dilution air is displaced, and the carbureted mixture continues flowing into the cylinder. This results in the richer, carbureted mixture filling the top of the cylinder, where the spark plug is located. Once the fuel valve closes and the spark plug is ignited, the richer, carbureted mixture ignites and begins burning downward into the lean mixture. The combination of rich then lean reduces the combustion temperature and subsequently NO_X emissions. (Chapman, *Report 2*, 2003) NO_X emissions levels of 2 g/bhp-hr are achievable, but the engine power may be de-rated by up to 20%. (Chapman, *Report 4*, 2003) While this control strategy does not require a turbocharger and intercooling, it does require significant changes to the air-intake system, so costs are expected to be significant.

Advanced In-Cylinder Mixing – Advanced in-cylinder mixing can be applied to non-turbocharged lean-burn engines. The goal of advanced in-cylinder mixing, typically using high-pressure fuel injection, has been to develop a system than can be retrofitted to an engine that will significantly improve the emission signature of that engine without the expense of adding a turbocharger. Poor in-cylinder mixing due to ineffective fuel delivery can lead to combustion variability and be problematic. Commercially available options for advanced in-cylinder mixing include high pressure fuel injection and supersonic injection into the power cylinder. (Chapman, *Report 2*, 2003) This technology can reduce NO_X levels from 30 – 70%, but is not expected to reduce to levels of 2 g/bhp-hr alone. Because turbocharging and intercooling are not required, costs are expected to be less than that of technologies that require major changes to air-intake systems. However, changes to the fuel system are necessary and high-pressure fuel must be available in some cases. (Chapman, *Report 4*, 2003)

Exhaust Gas Recirculation (EGR) – EGR replaces some of the excess air in a lean-burn engine with cooled exhaust gasses. (Chapman and Adriani, *Report 6*, 2004) Because the exhaust gas has more water vapor than average air, and water vapor has a higher specific heat capacity than other major components of air, the exhaust gas also has a higher specific heat capacity than air. Thus, for an equal amount of energy released into the cylinder, the temperature will increase less than for typical lean combustion. This lower temperature results in lower NO_X emissions. This technology is still under development for natural-gas-burning engines, but it is expected to give similar NO_X reduction to lean-burn combustion as an emissions reduction technology. Implementing this technology for natural gas engines would require significant changes to the air-delivery system and the exhaust system, as well as significant development and testing, so it is not expected to be a cost effective option at this time. (Chapman and Nuss-Warren, *Phase 1 Report*, 2007)

Homogeneous Charge Compression Ignition (HCCI) – HCCI is an alternative piston engine combustion process that can provide efficiencies similar to compression-ignition direct injection (CIDI) engines, commonly known as diesel cycle engines, with very low NO_X and particulate emissions. HCCI engines operate on the principle of having a dilute, premixed charge that reacts and burns volumetrically throughout the cylinder as it is compressed by the piston. It is said to incorporate the best features of both spark-ignition and compression-ignition engines. As in an SI engine, the charge is well mixed, which minimizes particulate emissions. As in a CIDI engine, the charge is compression ignited and has no throttling losses, which leads to high efficiency. But unlike either conventional engine, combustion occurs simultaneously throughout the volume rather than in a flame front. This important attribute of HCCI avoids high peak temperatures around the flame front and consequently dramatically reduces NO_X. Because HCCI is still in the research and development phase, actual NO_X reductions and costs are unknown. Any implementation of this technology will also include significant development. (Chapman, *Report 3*, 2003)

Hydrogen/Natural Gas blended fuel –By blending hydrogen with natural gas as a fuel, a leaner mixture can be consistently lit in the combustion chamber. This is because hydrogen gas has a wider flammability limit than natural gas. In addition hydrogen diffuses three times faster than methane, so improved in-cylinder mixing can be achieved. However, using too much hydrogen in the blend could cause unwanted local hot spots that could lead to backfiring and premature ignition. (Chapman, Nuss-Warren, and Van Norden, *Report 20*, 2007) Blends of up to 20% hydrogen can show NO_X reductions of 40 -50% with no increase in CO when used with lean combustion. In addition, hydrogen blending has been able to improve engine operation. Using a hydrogen blend could remove the need for a pre-combustion chamber when using lean combustion. However, hydrogen would need to be available in the field, and significant changes must be made to the fuel delivery system to blend the natural gas and hydrogen before delivery. Because this technology is still under development, the costs to implement it would include the cost of developing hydrogen production in the field. (Chapman et al., *Report 22*, 2008)

Air-to-Fuel Ratio Controller (AFRC) – An AFRC controls the amount of fuel allowed into the engine depending on the amount of air that is being used. Typically, an oxygen sensor is used to determine the actual air-to-fuel ratio during combustion. This signal feeds back to the controller, which then allows more or less fuel into the combustion chamber to provide the desired air-to-fuel ratio during combustion. Although an AFRC could theoretically be used to provide finesse in combustion emissions control, it is usually used in conjunction with catalysts to provide the appropriate chemical mixture for successful post-combustion control. Without additional technologies, such as increased air flow to the engine or a post-combustion catalyst, very little emissions benefit can be expected. The benefit is that associated with the working control system including the AFRC. To use an AFRC, changes must be made to the fuel- and/or air-delivery system. The cost to install and AFRC can range from a few thousand dollars for smaller engines up to $30K for larger engines that require more sophisticated controls. (Chapman and Nuss-Warren, *Phase 1 Report*, 2007)

Post-combustion Control

Post-combustion emissions controls reduce pollutants to standard air constituents. They rely on enhancing the rates of the chemical reactions that the pollutants undergo, thereby allowing a significant quantity of pollutant to break down in minutes. Although the reactions occur slowly in nature, when the exhaust is sent through a catalytic converter, the precious metal compound or injected chemicals increase the speed of the chemical process. Unfortunately, this process works efficiently only when the right mixture of chemicals enters the catalyst and the mixture is at the correct temperature. This requires precise control of the engine's air-to-fuel ratio and/or the rate at which chemicals are injected into the exhaust stream. In many cases, the precise mixture needed for these catalytic converters to work limits the kinds of engines to which the technology is applicable. (Chapman and Nuss-Warren, *Phase1 Report*, 2007)

Non-Selective Catalytic Reduction (NSCR) or Three-way Catalyst (TWC) – NSCR enhances the rate of the reduction of NO_X to N_2, oxidation of CO to CO_2, and oxidation of any remaining hydrocarbons to CO_2 and H_2O. Because these reactions take place only in low-oxygen, or reducing, atmospheres, the exhaust must contain less than 0.5% O_2. This means that NSCR systems can function only on stoichiometric or rich-burn engines, and they require precise control of the air-to-fuel ratio in order to maintain satisfactory catalysis. Additionally, if the catalyst is exposed to unburned fuel or lubricants, it can become poisoned and lose effectiveness. (Chapman, *Report* 2, 2003) While NSCR can reduce NO_X and CO emissions by more than 90%, with total NO_X emissions levels at less than 1 g/bhp-hr, this simultaneous control can be achieved only over a very small range of air-to-fuel ratios. In fact, current models cannot necessarily control both pollutants continuously. Systems tend to drift rich or lean and control one of the two main pollutants effectively while levels of the other increase dramatically. In addition, under rich conditions where NO_X levels are well-controlled, ammonia is produced in the catalyst. (Chapman and Nuss-Warren, *Report 24*, 2008) However, much of the instability in NSCR systems appears to be the result of oxygen sensors and control strategies for AFRCs. A more advanced control system for NSCR has been developed that mitigates some of the difficulties in NSCR control. (Beshouri and Huschenbett, 2010) Installing an NSCR system requires changes to the fuel intake and exhaust systems of an engine. In addition, catalysts and sensors must be replaced as they are damaged or wear out. Catalysts are typically replaced after around 20,000 hours of operation, (Chapman, *Report 4*, 2003) and advanced oxygen sensors are expected to need replacement after a maximum of 6,000 hours. (Beshouri and Huschenbett, 2010) This increases maintenance cost. In addition there is a fuel efficiency penalty incurred by running an engine in the proper operating range. While the cost to install an NSCR system can vary greatly, it tends to be fairly high due to the precious metals in the catalysts and changes to the engines. (Chapman, *Report* 2, 2003) Because the system is challenging to implement effectively, the lowest-cost option may not necessarily provide the most effective, and therefore most cost-effective, emissions control.

Selective Catalytic Reduction (SCR) – SCR reduces NO_X to N_2 in the presence of a reducing agent, which is typically ammonia or aqueous urea. The reagent is injected into the exhaust stream before the catalyst to maintain the continuously uniform mixture of chemicals necessary for the reduction reaction. The amount of NO_X reduction depends on the amount of reagent used but can be reduced by 80 – 90%. However, ammonia can be released out of the catalyst, creating additional environmental concerns. To add an SCR system, a catalyst must be added to the exhaust, and infrastructure to inject ammonia must be installed. An SCR system significantly increases operating costs because of the need to supply and store ammonia, which is a hazardous chemical, replacement of catalysts, and increased maintenance. (Energy Nexus Group, 2002)

Oxidation Catalysts – Oxidation catalysts increase the oxidation rate of CO and hydrocarbons to CO_2 and H_2O in the presence of excess O_2. As such, they require excess O_2 and can only be used with lean-burn engines. While oxidation catalysts do not reduce NO_X levels, they can reduce CO and heavier hydrocarbon emissions levels by as much as 98 - 99%. (Energy Nexus Group, 2002) A catalyst needs to be added to the engine exhaust to use this technology, but no additional changes to the engine intake system are required. However, the catalyst can cause backpressure on the engine. The cost of using oxidation catalysts to control emissions arises primarily from purchasing and replacing the catalyst.

Lean-NO_X Catalysts – Lean-NO_X catalysts require a hydrocarbon reductant, such as the engine fuel, to be injected before the catalyst in order to reduce NO_X. This results in a notable increase in fuel use, which depends upon the amount of NO_X to be reduced. Lean-NO_X catalysts risk poisoning by both lube oil and fuel sulfur, but the risk can be quite low when the correct lubricant is selected. This technology can reduce NO_X levels by 80% and CO and heavier hydrocarbons by about 60%. It requires a catalyst to be added to the engine exhaust, which creates backpressure on the engine, and that infrastructure to deliver fuel to the catalyst be installed. The cost to use a lean- NO_X catalyst will be impacted by the use of additional fuel, which can reduce fuel economy by 3%. (Energy Nexus Group, 2002) It will also include the cost of the catalyst, catalyst replacement, and special lubricants.

Monitoring Technologies

Monitoring technologies are used to determine the emissions levels produced by an engine. In some cases, permits require monitoring to show that limits are not exceeded. In other cases, a monitoring system can be used to improve engine operation through closed-loop controls or readily detect minor maintenance issues before they become more serious. Table 10 in Appendix II compares the various monitoring technologies described below.

Continuous Emissions Monitoring System (CEMS) or Continuous Process Monitoring System (CPMS) – A CEMS must measure all variables needed to completely and continuously determine the mass flow rate of pollutants under changing external and combustion conditions. For example, a system might measure fuel flow and exhaust stack concentrations of pollutants and oxygen. The system consists of a gas-sampling interface that is permanently installed and an emissions analyzer. The gas-sampling interface can either extract gas from the stack and transport it to the analyzer or support and protect the analyzing equipment such that it remains in contact with the exhaust stream at all times. The analyzer typically uses an optical method to measure gas concentration. An analyzer using an opacity monitor measures light scattering and absorption in the sample, whereas a non-dispersive infrared analyzer measures light absorbed by various pollutant molecules in the sample. Chemiluminescence analyzers measure the light emitted by chemical reactions that occur in the sample. (Jahnke, 2000) Although this technology is commercially available, the analyzer itself and the infrastructure needed to permanently install it are relatively expensive. It does not measure any combustion conditions and cannot easily be used to improve engine operation or maintenance. It can be used with any control technology, but systematic errors are possible with some emissions products and must be considered carefully. (Chapman and Nuss-Warren, *Phase 1 Report*, 2007)

Portable Emissions Analyzers – A portable emissions analyzer is typically used to perform periodic checks on emissions for many different sources. Such an analyzer will have a sampling probe that can be easily inserted into the exhaust stream for a short period of time. It uses electro-chemical cells to measure gas concentration. These cells create a small voltage as a result of the chemical reaction that occurs when the pollutant molecule is absorbed. As a result, the cell wears out over time or with overexposure to the chemical being monitored. (Chapman and Nuss-Warren, *Phase 1 Report*, 2007) Portable monitors with an automatic “rinse” function that exposes the electrochemical cells to fresh air, can be used to measure emissions “semi-continuously.” Such a monitoring cycle would consist of 15 minutes of monitoring followed by 45 minutes of “rinse” or 10 minutes of monitoring followed by 10 minutes of “rinse.” However, using such an analyzer in this way requires fairly regular maintenance and favorable environmental conditions. The analyzer must operate at a constant temperature to maintain accuracy, and electrochemical cells need to be replaced after overexposures. A portable analyzer in semi-continuous mode is not comparable to a CEMS. (Chapman et al., *Report 25*, 2009) The emissions concentration data acquired using a portable analyzer can be converted to a mass flow rate only if the fuel consumption or exhaust flow rate of the source is known. Analyzers are commercially available for around $10,000, but the additional infrastructure to install an analyzer for semi-continuous monitoring could cost several thousand dollars, and replacement cells typically cost around $100 each. Portable analyzers cannot measure combustion conditions, so they cannot easily be used to improve engine operation or maintenance. While these analyzers can be used with any control technology, high emissions levels, even temporarily, can easily overexpose the cells.

Parametric Emissions Monitoring Systems (PEMS) – A parametric emissions monitoring system measures engine parameters that directly affect emissions. Data on these parameters is then fed into a combustion model for the engine to predict the emissions produced. Parameters that are necessary for a full determination of emissions include engine torque and speed, air-to-fuel ratio, ignition timing and air-manifold temperature and pressure. Although many of these parameters are directly measured, air-to-fuel ratio can also be determined using other methods, such as an in-cylinder pressure measurement or ion sense signal. In addition to emissions information, a PEMS can provide information that can enhance engine operation. (Beshouri, 1998) This type of system is commercially available for engines with combustion controls for emissions. However, it is being developed for use with post-combustion controls as well. The cost to implement a PEMS will depend on the specific sensors used, but is typically expected to be a few thousand dollars. (Chapman and Nuss-Warren, *Phase 1 Report*, 2007)

Solid State NO_X Sensor – A solid state NO_X sensor is a small, self-contained unit that can be installed in an exhaust stream to continuously monitor NO_X. Those produced by NGK-Locke, which are used in NO_X modules sold by ECM, create a reducing atmosphere in an ion-conductive metal-oxide chamber that measures oxygen produced as NO_X decomposes. (Orban, 2005) These sensors have a cross-sensitivity to ammonia and must be operated at a constant temperature for accurate results. (ECM, 2011) They could be used with any control technology, but the cross-sensitivity to ammonia makes them less accurate for engines with rich air-to-fuel ratios or in situations where ammonia may be created in a catalyst, such as with NSCR or SCR systems. These sensors do not give information about combustion conditions but are a relatively low-cost monitoring option. The sensor and associated electronics can be installed for only a few thousand dollars and the sensor can be replaced for under a thousand dollars.

Exhaust Gas Oxygen (EGO) or Lambda (λ) Sensor – This sensor measures the oxygen concentration in the exhaust gas or the ratio of oxygen to hydrocarbons to determine a normalized air-to-fuel ratio (λ). The output signal depends on "net" oxygen rather than free oxygen in the exhaust and has sensitivity to reducing species such as hydrogen, carbon monoxide, and hydrocarbons. (Peyton Jones and Jackson, 2003) Though most are designed specifically for rich-burn operation, some, such as the universal exhaust gas oxygen (UEGO) sensor, can be used in lean-burn applications as well. For a four-stroke cycle engine, the exhaust oxygen concentration determines exactly the in-cylinder air-to-fuel ratio with little uncertainty. However, for a two-stroke cycle engine the exhaust oxygen concentration will be a function of scavenging efficiency as well as the burned-gas oxygen concentration, and the reading will not be directly proportional to the in-cylinder air-to-fuel ratio. These sensors could be used with any control technology but are most often used as an input for post-combustion control technologies. (Chapman and Nuss-Warren, *Phase 1 Report*, 2007) The cross-sensitivity to reducing species requires special care be taken when using this sensor to find the in-cylinder air-to-fuel ratio. (Chapman and Nuss-Warren, *Report 24*, 2008) The cost to add EGO sensors and the associated electronics to an engine is typically a few thousand dollars.

Ion-Sense – Ion sensing measures the electrical conduction between two electrodes. Studies have shown that it is possible to infer the gaseous species concentrations within the cylinder during the combustion and post-combustion processes by sensing the conducted current. With this technique, it is possible to determine the in-cylinder air-to-fuel ratio and the engine average air-to-fuel ratio. It is also possible to identify combustion anomalies, which can help operators improve engine operation and maintenance. Ultimately, this same process can be used to determine NO_X production within the cylinder and eventual emissions of NO_X. Ion sense has been demonstrated on rich- and lean-burn gas-fired engines, so it can be used with virtually any emissions control technology. (Beshouri, 2006). It is expected to be commercially available for natural gas engines in the United States in the near future, and the costs are primarily determined by the cost of shielded ignition coils and signal processing equipment. (Chapman and Nuss-Warren, *Phase 1 Report*, 2007)

Determine Technology and Market Gaps between Practical Options and Current and Expected Permitting Requirements

Most Promising Options

Based on the analysis of the available technologies discussed above, the most promising options for lean-burn engines appears to be increasing the air-to-fuel ratio while utilizing pre-combustion chambers to increase the ignition energy. Where turbocharging is possible, this is a fairly well-understood process, but where no turbocharging is possible, such as on Ajax engines, this process required additional investigation. For rich-burn four-stroke cycle engines, an NSCR system appears to be the best choice. However, concerns about the consistency of emissions reduction in NSCR systems required additional investigation, as well. In terms of monitoring, a parametric monitoring system is preferred.

Regulatory Picture

Currently the National Ambient Air Quality Standards (NAAQS) for ozone, fine particulate matter (PM), and nitrogen dioxide (NO_2) affect the natural gas industry. Combustion of natural gas produces oxides of nitrogen (NO_X), including NO_2, that are precursors to ozone and PM formed in the atmosphere, so states limit NO_X production by reciprocating engines to meet national ozone and PM limits. States implement emissions permitting for new, modified, or even existing reciprocating engines. The permitted levels vary by state, location of the engine, and the region's NAAQS attainment status. States with the most stringent requirements typically include California and New York.

In California, all permitted sources must use Best Achievable Control Technology (BACT) and limits are low: NO_X at 0.15 g/bhp-hr, VOC at 0.15 g/bhp-hr, CO at 0.6 g/bhp-hr, and PM at 0.02 g/hp-hr. While the size of engines to be permitted in California is at the discretion of the local district, the California Air Resources Board (CARB) indicates that 50 bhp is an appropriate threshold for permitting. In addition CARB suggests that an initial performance test followed by periodic monitoring is a reasonable monitoring requirement.

New York's Reasonably Achievable Control Technology (RACT) rule limits NO_X emissions from natural-gas fired engines to 1.5 g/bhp-hr in non-attainment areas. Alternatively, an engine may comply by showing a 90% reduction in NO_X from the unit's 1990 baseline or using a "system" averaging plan that shows equivalent reductions for all equipment affected by the plan. As in California, compliance must be demonstrated through testing. (Beshouri et al., *Report 13*, 2006)

In addition, New Source Performance Standards for reciprocating internal combustion engines directly regulate engines' emissions of carbon monoxide (CO) and NO_X regardless of the state in which the engine is located. The published rules in 2008 place limits on NO_X, CO, and VOC (excluding formaldehyde) for all new, modified, or reconstructed engines, regardless of size. The stricter of the two incremental limits published in 2008 came into effect in 2010 or 2011 depending on the type of engine. New engines 100 hp and larger are regulated to 1.0 g/hp-hr NO_X and 2 g/bhp-hr CO while new engines 25 hp to 100 hp are regulated to 2.8 g/bhp-hr combined NO_X + hydrocarbons and 4.8 g/bhp-hr CO. Reconstructed or modified engines 25 hp and greater are regulated to 3.0 g/bhp-hr NO_X and 4.0 g/bhp-hr CO, or 5.0 g/bhp-hr CO for engines rated less than 100 hp.

Formaldehyde and CO are also regulated through the National Emissions Standards for Hazardous Air Pollutants (NESHAP). For major sources over 100 hp, two-stroke cycle lean-burn engines must produce less than 225 ppm CO at 15% exhaust oxygen concentration, while four-stroke cycle lean-burn engines must remain under 47 ppm CO at 15% oxygen. Four-stroke cycle rich-burn engines must remain under 10.3 ppm formaldehyde at 15% oxygen. For area sources over 500 hp, the limits for four-stroke cycle lean-burn engines are also 47 ppm CO at 15% oxygen, but four-stroke cycle rich-burn engines are limited to 2.7 ppm formaldehyde at 15% oxygen. Smaller engines are regulated by "work practice" or "management practice," which means that detailed maintenance plans and records showing oil changes or analysis and inspection and replacement of spark plugs, belts, and hoses after a given number of operating hours (1,440 hours for four-stroke engines and 4,320 hours for two-stroke lean-burn engines) or at least yearly must be kept. (McCarthy, 2010)

Technology Gaps

To meet the California permitting requirements, post-combustion controls are needed, including NSCR for rich-burn engines and a combination of both SCR and oxidation catalysts for lean-burn engines. Outside of California, regulated limits will also typically require NSCR for rich-burn engines. However, an NSCR system is not necessarily able to maintain consistent control. Experimental studies have found that emissions output levels with NSCR can vary greatly within hours or days. (Chapman and Nuss-Warren, *Report 24*, 2008) In addition, a catalyst operated at a constant condition for too long can begin to lose functionality. An integrated AFRC and sensor system using an UEGO sensor with improvements in AFRC control strategies can minimize the frequency and level of excursions, particularly when a downstream solid state NO_X sensor is used to preemptively detect conditions leading to out of control operation so they can be addressed by an operator. Even these more advanced systems require both NO_X and CO to react. If there are limits on both these emissions products, the ratio of CO to NO_X should be high enough to assure nearly complete reaction of the NO_X. A 6:1 ratio of CO-to-NO_X has been suggested to maintain successful operation. (Beshouri and Huschenbett, 2010) Where regulated limits do not allow for such a ratio, successful reduction of NO_X is likely to be unachievable. In addition, integrated AFRC systems are currently at the stage where they are being specifically built and tuned to a given engine. While this technology is likely to be available on the market soon, most off-the-shelf AFRC systems are not integrated, so they should not be expected to consistently control to California limits. While they should be expected to meet national limits, excursions are likely to occur. Operator intervention is typically necessary to bring systems back into control. Without a self-detection system, it is difficult to know when such interventions are necessary.

For lean-burn engines outside of California, the NO_X levels permitted in regulations are typically achievable through the use of increased air-flow and PCCs. However, most NO_X for a lean engine using a pre-chamber is actually formed in the PCC. The level of NO_X formed can be reduced by controlling the air-to-fuel ratio in the pre-combustion chamber itself. (Chapman and Nuss-Warren, 2007) Manufacturers quote less than 2 g/bhp-hr NO_X for integral and screw-in PCCs, (Taliaferro, July 13, 2011) so the national NO_X emissions limit is met for retrofits. However, a method for controlling air-to-fuel ratio in the pre-chamber may be required to meet the 1 g/bhp-hr NO_X limit for new engines in some cases. The CO limits implemented by NESHAP should be achievable in most cases for two-stroke cycle lean-burn engines without post-combustion controls. If a two-stroke cycle engine cannot meet this limit without post-combustion controls, and for the more stringently regulated four-stroke cycle engines, oxidation catalysts will enable the engines to meet the limits. (McCarthy, 2010)

Market Gaps

As demand for natural gas continues to increase and the depletion of many existing fields continues, gas prices will increase. Following this increase in price, a significant increase in drilling has occurred. Although newly-drilled traditional wells often have high pressures and do not need compression, “unconventional” sources, such as coal-bed methane, begin with lower pressures and require significant compression for produced gas to enter into the pipeline grid. Additionally, with prices high, it becomes profitable to continue to use depleted wells longer. On these wells, the produced gas also requires significant compression. Thus, as long as gas prices remain high, there will be an increased usage of compressors. Because most locations are remote, compressors driven by internal combustion engines typically remain most economically feasible.

If prices of emissions monitoring and control technology rise too steeply, it could make production less economically feasible, resulting in a lower supply of gas and increased gas prices. Thus, it becomes advisable to identify the lowest-cost, most effective NO_X controls. For engines where replacement of major equipment, such as cylinder heads and turbochargers, is necessary capital costs account for most of the cost of control. However, engineering labor, construction project management, testing, permitting, and lost production from downtime must also be considered. If a successful retrofit can be achieved without major changes to equipment, this becomes a significant advantage. For instance, where a screw-in pre-combustion chamber will successfully allow for lean combustion, it would be inadvisable to install an integral pre-combustion chamber. Additionally, the cost for increased monitoring will be a large burden for operators unless monitoring contributes additional functionality or control. Thus, a technology like ion sense could be used to monitor the quality of combustion as well as NO_X emission. This data on combustion quality could allow for adjustments that improve engine operation. Overall, the system would be far more beneficial than a system that only monitored emissions. On the other hand, if actual emissions monitoring is necessary on a continuous basis, the cost of monitoring must be very low for it to be economically feasible. This would make solid-state sensors more promising than traditional solutions. (Beshouri et al., *Report 13*, 2006)

Conduct Controlled Tests to Evaluate Promising Monitoring and Control Technologies

Testing on KSU Ajax

Based on the engine database and the idea that technologies that work on two-stroke cycle lean-burn engines typically work on four-stroke cycle lean-burn, the research team chose to use an Ajax DP-115 engine to conduct controlled tests that would help to evaluate various technologies. The DP-115 used for testing was built in 1966 without the low emissions controls that current engines have built-in. It is a one-cylinder, horizontal, reciprocating engine with a bore of 13.25 inches and a stroke of 16 inches, rated at 360 rpm and 1605 ft-lb of torque. Like all two-stroke cycle engines, the Ajax requires forced air flow through the engine in order to effectively scavenge out exhaust gases. While many two-stroke cycle engines use crank-case compression, pump scavenging, or turbocharging to produce air flow, Ajax engines use an air chest that surrounds the lower portion of the cylinder and reed valves in the air intake system. Thus the engine cannot be turbocharged to increase the air flow rate. (Chapman, *Report 11,* 2005)

The test bed for this engine included equipment and sensors needed to measure a plethora of data. Using the test cell, it was possible to measure various temperatures and pressures, including in-cylinder pressure, engine speed, torque, power, air and fuel flow rates, and in-cylinder ion sense traces. In addition, emissions concentrations were measured with a portable analyzer. These data allowed the research team not only to evaluate the effectiveness of various emissions control technologies, but also to evaluate the engine operating conditions and to trouble-shoot any difficulties that were unrelated to the emissions control technologies. (Chapman and Adriani, *Report 10*, 2005)

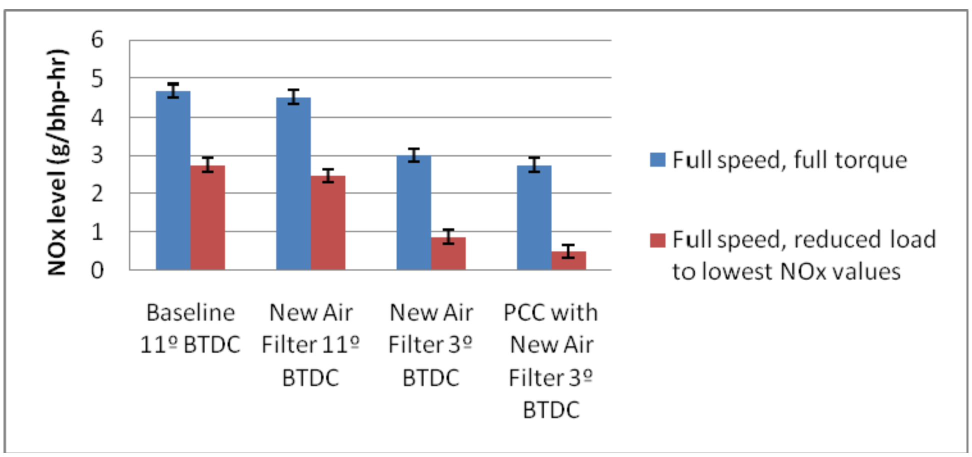
The first tests conducted established an emissions and operating baseline for the engine. As shipped and overhauled, the engine came equipped with an oil-bath air filter, which is typical of older Ajax engines, although new engines use paper air filters. At full load, full torque conditions, the engine NO_X emission rate was 4.69 ± 0.18 g/bhp-hr, which nearly agrees with the published OEM Ajax data of 4.4 g/bhp-hr. (Chapman and Adriani, *Report 10*, 2005)

The next set of tests involved adjusting the air-to-fuel ratio, retarding the spark timing, and increasing ignition energy with a screw-in PCC. Since this engine could not be turbocharged, the load was adjusted to vary the air-to-fuel ratio and changing the air filter. These results are summarized in Table 3 and Figure 1. Running the engine at part load to adjust the air-to-fuel ratio resulted in significant reduction of NO_X levels at the cost of increased engine instability as measured by the standard deviation of the peak pressure (SDPP) and, for all but the baseline configuration, increased brake-specific fuel consumption (BSFC). Increasing the air-to-fuel ratio by changing the air filter resulted in meaningfully reduced NO_X emissions only when the engine ignition was retarded or a pre-combustion chamber was used to improve ignition. Using the standard deviation of peak pressure as a measure of engine stability, it can be seen from **Error! Reference source not found.** that using a PCC with retarded ignition timing can keep the engine stability the same as its baseline stability while providing emissions benefits. (Chapman and Adriani, *Report* 10, 2005)

Table 3. Summary of New Air Filter and PCC Test Results.

Test type	Full speed, full torque			Lowest NO_X full speed operating range			
	NO_X level (g/bhp-hr)	SDPP (% of peak pressure)	BSFC (btu/bhp-hr)	Lowest NO_X operating range (% of full load)	NO_X level (g/bhp-hr)	SDPP (% of peak pressure)	BSFC (btu/bhp-hr)
Baseline 11º BTDC	4.69 ± 0.18	7	9,800	near 90	2.75 ± 0.18	13	9,800
New Air Filter 11º BTDC	4.54 ± 0.18	14	9,200	near 94	2.47 ± 0.18	21	9,500
New Air Filter 3º BTDC	3.01 ± 0.18	9	9,800	74 – 88	0.86 ± 0.18	21	10,300
PCC with New Air Filter 3º BTDC	2.75 ± 0.18	7	9,500	74 – 88	0.48 ± 0.18	14	10,200

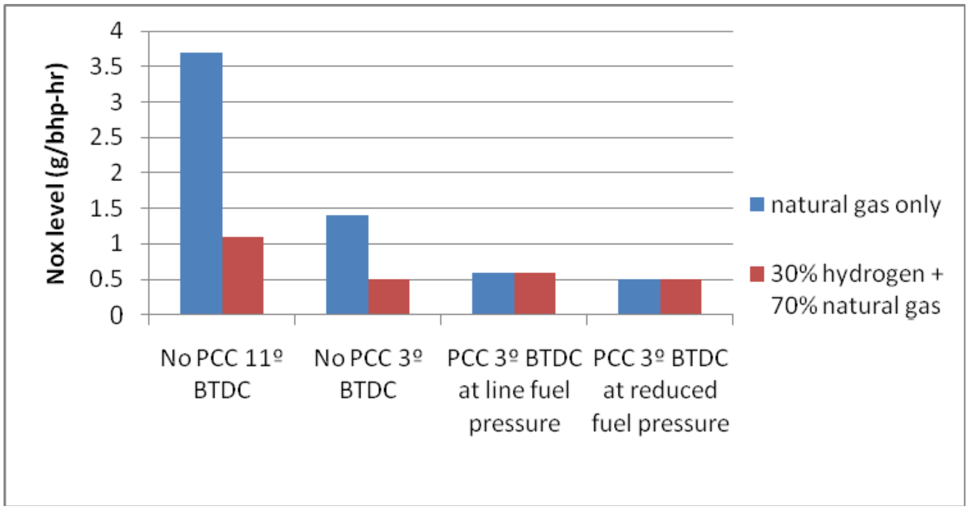
Figure 1. NO_X levels on the KSU Ajax DP-115 for varying conditions.



Later testing of PCCs indicated that reducing the fuel pressure to the pre-combustion chamber reduced the NO_X levels emitted by the KSU Ajax. (Chapman and Nuss-Warren, *Report 18*, 2007) This is likely because limiting the fuel to the PCC reduced the air-to-fuel ratio and the temperature in the pre-chamber allowing less NO_X to be formed in the PCC.

In another set of tests, hydrogen blended fuel was used instead of natural gas alone. For these tests up to 30% hydrogen was added to the natural gas. As the percent of hydrogen added increased, the engine ran at leaner in-cylinder air-to-fuel ratios and produced less NO_X while no significant change in CO emissions was evident. In addition, the engine was far more stable with hydrogen than with natural gas alone. When blended fuel was used with a PCC, the NO_X reduction was not significant compared to the NO_X reductions provided by the PCC alone. However, the use of the PCC did create a slight increase in CO emissions. These results are summarized in Figure 2. (Chapman et al., *Report 22*, 2008)

Figure 2. NO_X levels on the KSU Ajax for Hydrogen and Natural Gas Blended Fuel.

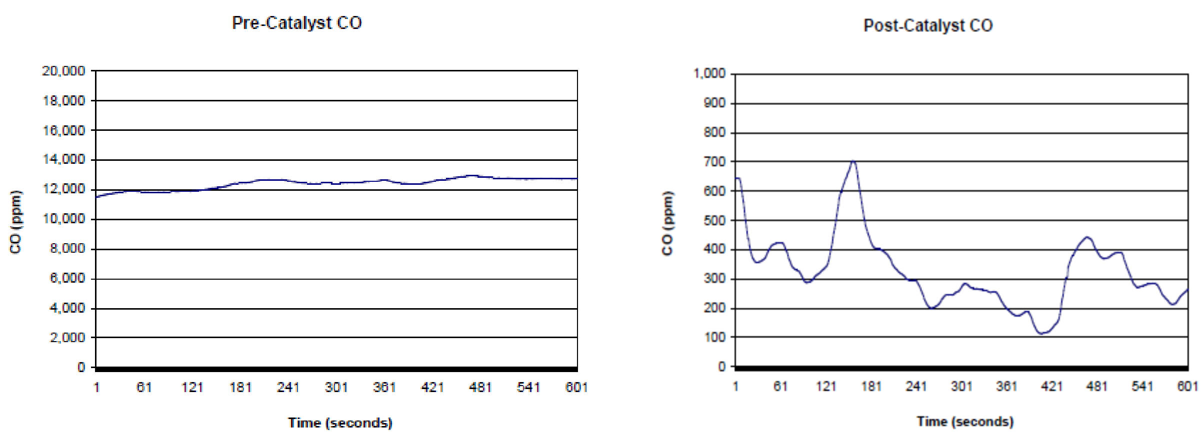


NSCR Characterization

Additional testing was conducted on four-stroke cycle rich-burn engines equipped with NSCR once it became evident that NSCR systems were not as robust a solution as operators thought when the industry-based steering committee first met. Initial testing of several engines showed that an NSCR system could maintain compliance when it was operating correctly. However, this testing also showed that emissions variations can occur with changes in load and that out of control operation can occur with changes in ambient temperature. It also showed that monitoring temperature rise and pressure drop across the catalyst is not sufficient to determine out of control operation and that any AFRC used must have full-authority control. That is, the fuel valve must be able to change the amount of fuel supplied to the engine so that it reaches the leanest and richest limits of catalyst operation at all ambient conditions. (Chapman and Adriani, *Report 5*, 2004) Later tests showed that an NSCR system on a California engine was not able to maintain NO_X limits below 1g/bhp-hr without entering out-of-control operation upon ambient temperature or humidity changes. (Chapman and Nuss-Warren, *Report 14*, 2006).

The next step in the testing of NSCR-equipped four-stroke rich-burn engines was to characterize typical NSCR systems. The goal of these tests was to determine the stable operating limits an NSCR-equipped engine could achieve and to determine whether NSCR was effective for smaller engines. This was done in part by using a Compressco GasJack at KSU. The GasJack is an integral compressor that uses a standard V-8 Ford 460 cubic inch four-stroke engine. One bank of four cylinders is modified into a reciprocating compressor. The engine was instrumented to determine various temperatures and pressures, air and fuel flow rates, engine speed, torque, and power. (Chapman et al., *Report 20*, 2007) The emissions concentrations were measured with a portable analyzer and used to determine emissions mass flow rates based on the engine air and fuel flow rates. By measuring emissions concentrations before and after the catalyst, it was determined that while pre-catalyst NO_X concentration was relatively constant over a period of 10 minutes, the post-catalyst NO_X concentration varied by 10 times as much, even when the overall NO_X reductions of 98% occurred. This tendency is even more pronounced with CO emissions. Before the catalyst, the concentration was relatively constant for 10 minutes, with a slight overall drift, but after the catalyst the CO concentration varied by 13 times as much. The post-catalyst changes in concentration do not show the same trends as any changes in pre-catalyst concentration. While the pre-catalyst CO concentration may show a slight drift, the post-catalyst CO concentration varies almost periodically as can be seen in Figure 3. Although the pre- and post-catalyst emissions were not measured simultaneously, the shown figures are typical of all data collected. These post-catalyst fluctuations are explained by the storage and release of oxygen onto the catalyst surface. When oxygen is absorbed, less is available to convert CO to CO_2, which decreases conversion efficiency. When oxygen is released, more is available and the conversion efficiency increases. (Chapman et al., *Report 22*, 2008) This behavior is likely important to understanding emissions excursions leading to out-of-control operation in the tests already discussed.

Figure 3. Pre- and post-catalyst CO concentrations for 10 minutes (not measured simultaneously).



Another interesting result of these tests was that the AFRC set the valve to different positions to obtain the same EGO sensor output (777 mV) even at nearly the same speed as seen in Table 4. This indicates that the EGO signal is most likely not a repeatable measure of air-to-fuel ratio.

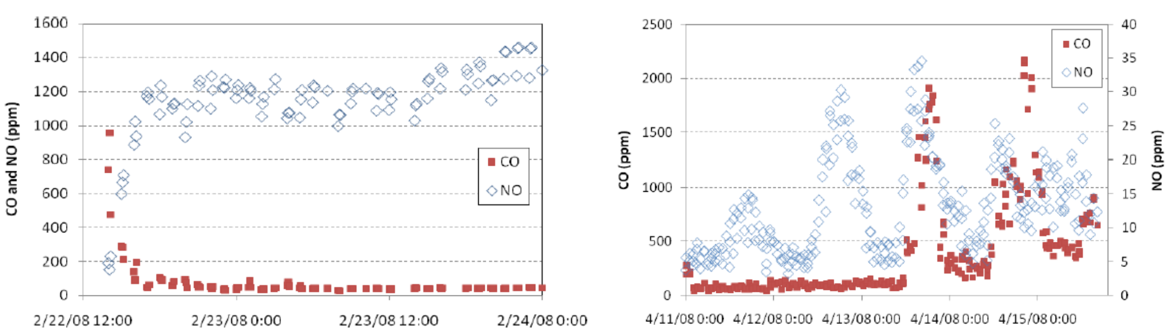
Table 4. AFRC valve positions to obtain a 777 mV EGO output at 1800 and 2000 rpm.

Engine speed (rpm)	1793.2	1802.7	1796.8	1997.5	1993.7	2004.2
Valve Position (steps open from 0 - 250)	133	115	116	214	186	208

Additionally, in this test it was observed that as the engine speed increased, the pre-catalyst oxygen level decreased, and CO conversion dropped under these overly rich conditions. However, the EGO set point was not changed for these higher-speed, higher-power operating conditions. This supports the conclusion that the EGO sensor signal is not providing accurate feedback to control the level of oxygen to the engine at all operating conditions. Overall, the tests showed conversion efficiencies of NO_X of 99.2% on average with an average emissions rate of 0.20 ± 0.05 g/bhp-hr. The conversion rate for CO was 92% on average with an average emissions rate of 3.8 ± 1.1 g/bhp-hr. However, conversion efficiencies for CO at higher-power operating conditions ranged from just 32.1 % to 87.1 %. The controlled testing at the KSU lab indicated that while NO_X and CO levels can be controlled under *certain conditions*, the variance in the post-catalyst emissions and the non-repeatability of the EGO signal with respect to valve position and pre-catalyst oxygen concentration indicate issues that could seriously undermine consistent control in the field. (Chapman et al., *Report 22*, 2008)

Another portion of the NSCR characterization was to examine collection engines equipped with NSCR systems in the field over a considerable span of time. Three four-stroke cycle rich-burn engines site-rated at 57 hp, 23 hp and 1,467 hp were equipped with monitoring technology that allowed the research team to determine operating and ambient conditions including fuel flow, engine speed and power, EGO output, and emissions concentration. While conditions other than emissions concentration were recorded continuously, because portable analyzers were used in auto-refresh mode, emissions were collected for only 15 minutes (and later 30 minutes) out of an hour. The data was stored in an on-site instrumentation controller and downloaded via a cellular modem to the KSU lab every four hours. In addition, periodic testing with an additional portable analyzer to confirm results and determine ammonia levels was conducted every few months. Finally, the 57 hp engine emissions were mapped over varying air-to-fuel ratios. (Chapman et al., *Report 25*, 2009) Overall, data was collected over the course of 383 days, including warm, intermediate, and cold seasons, for a total of nearly 190,000 minutes on all three engines. (Chapman et al., *Report 27*, 2009)

Figure 4. NO_x and CO concentrations at the 57 hp engine over several days in February and April, 2008.



When the semi-continuous emissions data is examined, it is clear that the NSCR systems did not simultaneously control NO_X and CO levels effectively for the majority of the time. Emissions levels were not consistent day-to-day or even over the course of a few hours, as shown in Figure 4. Typically, as one emissions product was better controlled, the level of the other increased. While the first graph in Figure 4 shows a long-term drift toward overly lean conditions, the second graph shows the kinds of short-term variations seen on the KSU GasJack. If the first graph in Figure 4 is examined carefully, the short term-variance can also be observed, but it is less obvious due to the large overall drift. (Chapman and Nuss-Warren, *Report 24*, 2008)

As a means of summarizing all the data collected, the emissions levels maintained for each engine along with the error in determining the percent of time for which that engine maintained the emissions level are shown in Table 5, Table 6, and Table 7. For instance, the 23 hp engine was able to maintain NO_X levels below 0.5 g/bhp-hr at all CO levels for 63% of the time monitored, but it was able to maintain this NO_X level with CO levels below 2 g/hp-hr for only 14 % of the time and with CO levels between 2 and 4 g/hp-hr for only 4 % of the time. In summary, for the smallest two engines, NO_X was controlled to less than 0.5 g/bhp-hr while CO was controlled to less than 2 g/bhp-hr for only 14 % of the time. At the largest engine, NO_X and CO were controlled to these levels for 38 % of the time. NO_X was controlled to less than 2 g/hp-hr while CO was controlled to less than 4 g/hp-hr for 46 % of the time on the smallest engine, 40 % of the time on the 57 hp engine, and 65% of the time on the largest engine. On the other hand, NO_X levels were rather high (greater than 2 g/bhp-hr) on the 23 hp engine for 7 % of the time, on the 57 hp engine for 26 % of the time and on the 1,467 hp engine for 34 % of the time. For the two smaller engines, CO levels were rather high (over 4 g/bhp-hr) for 47 % of the time while at the larger engine CO levels were at these levels for just 0.9 % of the time. Similar levels indicated in the table were not necessarily collected at consecutive times as can be determined from Figure 4. (Chapman et al., *Report 27*, 2009)

Table 5. Percent of time various emissions levels were maintained on the 23 hp engine.

	CO < 2 g/hp-hr	2 < CO < 4 g/hp-hr	CO > 4 g/hp-hr	All CO levels
NO_X < 0.5 g/hp-hr	14 (± 2)%	4 (± 1)%	45 (+ 1 or -8)%	**63 (+2 or -10)%**
0.5 < NO_X < 1 g/hp-hr	11 (± 3)%	0.3 (+0.7 or -0.1)%	1 (+ 7 or - 0.3)%	**12 (+11 or – 3)%**
1 < NO_X < 2 g/hp-hr	16 (± 2)%	0.3 (+ 0.2 or - 0.1)%	1 (+ 2 or - 3)%	**18 (+ 2 or - 3)%**
NO_X > 2 g/hp-hr	7 (+ 2 or – 1)%	0.10 (- 0.02)%	0.10 (± 0.02)%	**7 (± 2)%**
All NO_X levels	**48 (+ 4 or - 0.4)%**	**5 (- 0.9)%**	**47(+ 0.6 or – 0.8)%**	**100.0%**

Table 6. Percent of time various emissions levels were maintained on the 57 hp engine.

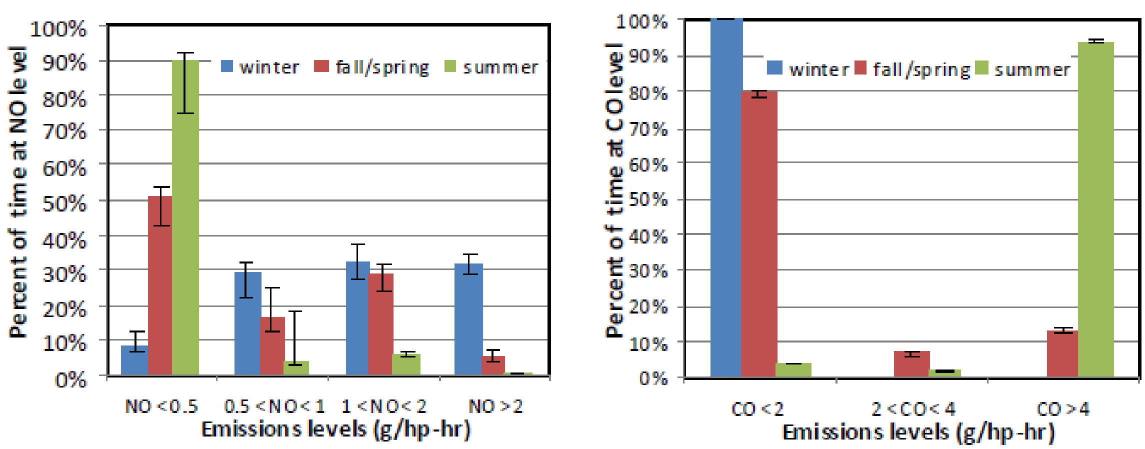
	CO < 2 g/hp-hr	2 < CO < 4 g/hp-hr	CO > 4 g/hp-hr	All CO levels
NO_X < 0.5 g/hp-hr	14 (+1or -2) %	9 (+0.4 or - 2) %	8 (±1) %	**31 (+2 or - 5)%**
0.5 < NO_X < 1 g/hp-hr	6 (+2 or – 1) %	1 (+2 or – 0.3) %	7 (+2 or – 1) %	**14 (+ 6 or – 3) %**
1 < NO_X < 2 g/hp-hr	8 (+0.6 or – 0.5) %	2 (±0.2) %	19 (±1) %	**29 (±2) %**
NO_X > 2 g/hp-hr	12 (±0.2) %	1 (+0.07 or – 0.06) %	13 (+0.8 or – 0.6) %	**26 (± 1) %**
All NO_X levels	**40 (± 0.4)%**	**13 (+0.5 or – 0.4) %**	**47 (+0.2 or – 0.1) %**	**100.0%**

Table 7. Percent of time various emissions levels were maintained on the 1,467 hp engine.

	CO < 2 g/hp-hr	2 < CO < 4 g/hp-hr	CO > 4 g/hp-hr	All CO levels
NO_X < 0.5 g/hp-hr	38 (+2 or -4) %	1.0 (±0.2) %	0.9 (+0.1 or – 0.2) %	**40 (+2 or -4) %**
0.5 < NO_X < 1 g/hp-hr	15 (+4 or -3) %	0.0 (+0.1) %	0.0 (+0.1) %	**15 (+4 or -3) %**
1 < NO_X < 2 g/hp-hr	11 (+2 or - 1) %	0.0 (+0.007 or – 0.001) %	0.0 (+0.002) %	**11 (+2 or -1)%**
NO_X > 2 g/hp-hr	34 (±1) %	0.11 (±0.01) %	0.0 (+0.01) %	**34 (±1) %**
All NO_X levels	**98 (±0.1) %**	**1.1 (- 0.2)%**	**0.9 (±0.1) %**	**100.0%**

The data collected were examined for seasonal variations. Because emissions levels were typically different for the engines during different seasons, as shown for the smallest engine in Figure 5, the relationship between temperature and emissions level was examined. For all three engines, a rise in NO_X levels was found as temperatures decreased. This is expected because at colder temperatures, air density increases, and for the same valve opening, a leaner air-to-fuel ratio can be achieved. However, a corresponding decrease in CO with temperature increase was found only for the smallest engine. This could indicate that at the set points chosen for control the NO_X was more sensitive to changes in oxygen than the CO, which is the opposite the trend seen on the KSU lab GasJack, but the same trend seen in the mapping data still to be discussed. (Chapman et al., *Report 27*, 2009) Another possibility is that short-term variations in the CO emissions levels that did not correspond to changes in ambient temperature were simply much greater than any temperature-dependent variance in CO levels.

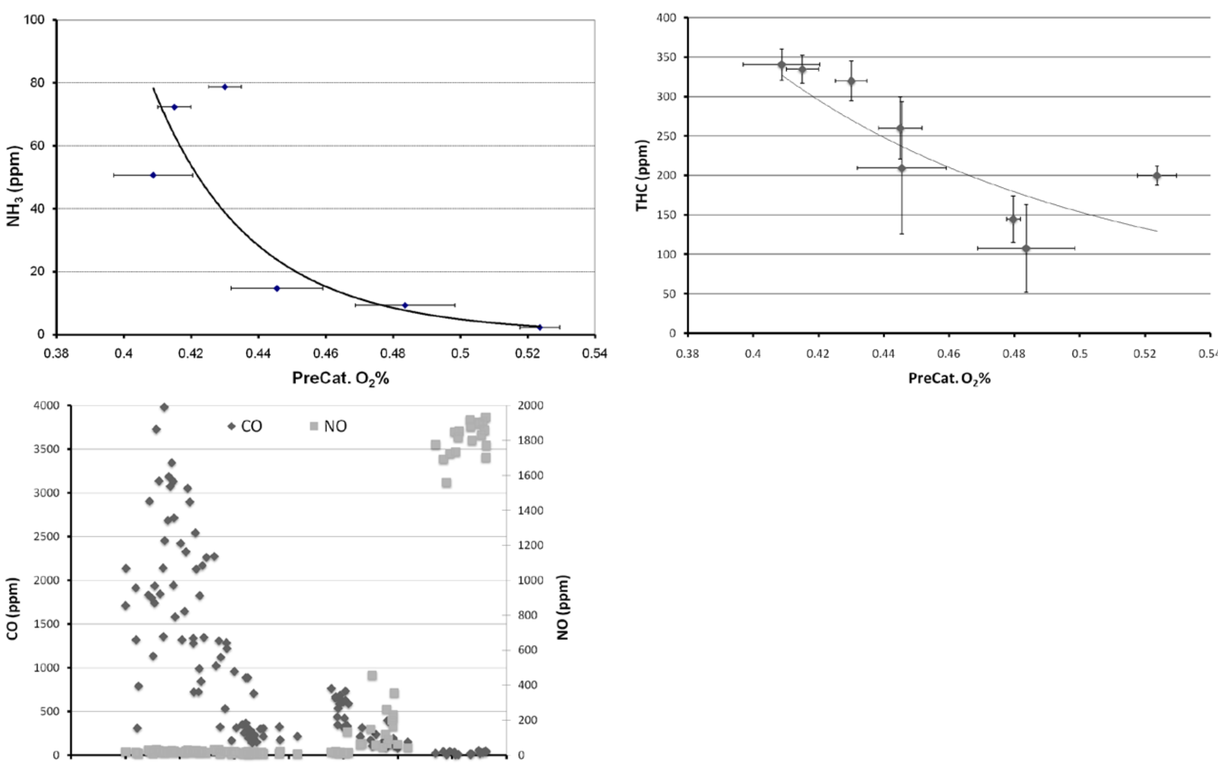
Figure 5. Seasonal variations in NO and CO levels at the 23 hp engine.



Periodic data collected over the course of this long-term monitoring indicated that ammonia (NH_3) was present when the post-catalyst CO was not negligible. This was found to be true for all three engines tested. In addition, these tests indicated that the NO_2 emissions were negligible, and thus can be ignored for total NO_X levels, except when the NSCR system is out of control in a “failed lean” condition that produces NO levels of over 2,000 ppm. For instance, even at 421 ppm of NO_X, the highest “in control” level found during periodic testing (NO_X levels of 2.3 g/bhp-hr) the NO_2 produced was consistent with zero. (Chapman et al., *Report 25*, 2009)

During the mapping test, the air-to-fuel ratio for the 57 hp engine was varied over its complete control range, and emissions were measured before and after the catalyst with FTIR and an EPA reference method analyzer and a flame ionization detector for total hydrocarbons (TCH). The post-catalyst emissions were also measured with the portable analyzer normally used for semi-continuous monitoring to verify that its readings were consistent with those of the reference method. (Chapman et al., *Report 25*, 2009)

Figure 6. Influence of pre-catalyst oxygen level on ammonia, total hydrocarbons, CO, and NO_x.



The mapping test confirmed that both NO_X and CO emissions were highly dependent on the pre-catalyst free oxygen concentration. However, there was some inconsistency in the dependence of the emissions on the “net oxygen” as measured by the EGO sensor. For instance, two tests taken with the same EGO set-point and similar, relatively stable EGO readings, had wildly different emissions values. One showed relatively rich operation where NO_X was controlled to less than 100 ppm and CO varied from 300 to 800 ppm (still relatively well controlled) and the other showed lean operation where NO_X ranged from 1000 to 2000 ppm and CO was controlled to less than 100 ppm. This suggests that the EGO sensor may not be the appropriate sensor to provide feedback to the AFRC since emissions levels are not repeatable for a given EGO control or output value. The EGO sensor also produced the same output at different oxygen levels. This raises the question of what in the exhaust affects the sensor response besides oxygen and motivates the EGO modeling work presented later. (Chapman et al., *Report 25*, 2009)

In addition, the mapping test found that ammonia was produced within the catalyst during rich operation. Post-catalyst ammonia levels were as high as 79 ppm and always higher than the pre-catalyst ammonia levels, which were typically around 2 ppm. The amount of ammonia produced depended strongly upon the pre-catalyst oxygen level as shown in the first graph in Figure 6. As more oxygen was present, less ammonia was produced. This is the same trend seen for total hydrocarbons, as shown in the second graph of Figure 6, and CO as shown in the third graph of Figure 6. However, the NO_X emitted from the catalyst actually increases as pre-catalyst oxygen increases, as also shown in the third graph of Figure 6. Thus, there is a trade-off between NO_X and CO, NH_3, and THC. The more tightly NO_X is controlled, the more CO, NH_3, and THC will be produced. The test also examined formaldehyde produced. Pre-catalyst levels ranged from 15 to 33 ppm while post-catalyst levels went from below the detection limit of 0.2 ppm to about 0.6 ppm. The NSCR catalyst is capable of reducing formaldehyde emissions. (Chapman et al., *Report 25*, 2009)

Determine On-engine Control System and Sensor Requirements for Remote Emissions Monitoring

For both two-stroke cycle and four-stroke cycle lean-burn engines the control system is low emissions combustion using the appropriately lean air-to-fuel ratio with a pre-combustion chamber that can provide sufficient ignition energy to ignite this mixture. It is essential that lean-burn engines maintain the proper air-to-fuel ratio to maintain effective emissions control. An effective way to verify these conditions is through a parametric monitoring system. This system could use sensors to detect air-manifold pressure and fuel flow rate or fuel-manifold pressure, which could be tied into an automated control system. Such a system could maintain the proper air-to-fuel ratio and log the information or produce an alarm status when the proper ratio could not be maintained. (Chapman et al., *Report 29*, 2010) This control strategy could also include a pressure sensor on the PCC fuel line and ion sense for each cylinder. The PCC fuel line pressure would serve to verify that the fuel pressure was maintained at the value to provide optimum emissions and engine stability or evidence of PCC check valve failure. (Chapman and Nuss-Warren, *Report 14*, 2006 and Chapman and Nuss-Warren, *Report 18*, 2006) The ion sense would serve to detect misfires or other combustion problems and to verify that all engine cylinders are firing at the desired air-to-fuel ratio. (Dettwyler and Beshouri, 2007)

For four-stroke cycle rich-burn engines, the control technology is an NSCR catalyst combined with an AFRC including advanced control strategies integrated with an upstream UEGO sensor that produces signal-conditioned output. To detect out-of-control operation, downstream monitoring with a solid-state NO_X and O_2 sensors should be used with an on-board diagnostic system. The on-board diagnostic system should be able to interpret the various signals available from post-catalyst sensors, the AFRC, and other critical measures to effectively analyze every component of the NSCR system. This will require sophisticated and robust analytical and diagnostic software tools. (Beshouri and Huschenbett, 2010)

Phase 2: Field Testing and Commercialization

Tasks completed as a part of Phase 2 include the following:

1. Install selected technologies on selected engines in the field; and,
2. Model NSCR for enhanced controller tuning.

Install Selected Technologies on Selected Engines in the Field

For two-stroke cycle and four-stroke cycle lean-burn engines, the chosen control technology was increased air-flow with pre-combustion chambers. Specifically, for existing engines, it was determined that screw-in PCCs could provide benefits equivalent to integral pre-combustion chambers. Thus, either screw-in or integral pre-combustion chambers were tested based on the availability of engines using each technology.

The prevalent Ajax engines, such as the one tested at the NGML, could not be turbocharged, but emissions were effectively controlled in laboratory tests with pre-combustion chambers. Ajax chose to refine and field-test a new-style screw-in PCC for legacy engines based on tests conducted on the NGML Ajax DP-115. The pre-combustion chamber has been fully tested on the Ajax models DPC-115, DPC-105, and DPC-140. In completing these tests Ajax has found that emissions are equivalent to an engine using a standard, or integral, pre-combustion chamber, which they typically quote to be less than 2 g/bhp-hr. Ajax is still testing models DPC-81 and DPC-60 to confirm the results for even smaller engines. (Taliaferro, July 13, 2011) While the same fuel-control orifice and ignition timing have been successfully used for all engine sizes tested, the fuel pressure to the PCC is adjusted in each situation to provide optimal engine operation and emissions control. (Taliaferro, July 14, 2011)

To demonstrate the effectiveness of pre-combustion chambers and increased air flow for two-stroke cycle lean-burn engines that can be turbocharged a Clark TLA-6 rated at 2000 hp was field-tested. This engine used screw-in PCCs and upgraded turbochargers as a low-emissions combustion retrofit. These controls effectively maintained the air-to-fuel ratio and, as a result, NO_X emissions remained well controlled within permit limits over the course of 6 days. Overall, the NO_X levels tended to remain under 1 g/bhp/hr, but diurnal effects caused peaks as much as 25% above the baseline. Even during these excursions, the maximum peak stayed under 3 g/bhp-hr, which was below the permitted limit, and these peaks were much smaller than variations typical for NSCR-fitted rich-burn engines. CO levels remained under 3.5 g/bhp-hr for this engine, but tended to be near 1.5 g/bhp-hr when the engine was most stable and all PCCs on the engine were well-balanced. (Chapman et al., *Report 29*, 2010)

To test four-stroke cycle lean-burn engines using increased airflow and pre-combustion chambers as a control strategy, two sets of field tests were conducted. Five identical Enterprise HVA-16-C6 compressor engines, rated at 5,500 hp each, were controlled with integral PCCs and high-output turbochargers. An additional five identical compressor engines, Ingersoll-Rand model 412-KVS, rated at 2,000 hp each, were also controlled with integral PCCs and high-output turbochargers. Both sets of engines were monitored for emissions levels using a parametric emissions monitoring system, but data for this project was collected using a reference method and CEMS, which the PEMS were compared to for regulatory purposes. Due to the regulatory requirements, approximately 720 hours of continuous data were collected for both sets of engines. For the larger engines the emissions levels were maintained on average at 90% of the target emissions level, which was below 2 g/bhp-hr. However, excursions of up to twice the typically maintained level were observed, primarily during start-up, shut-down, and part-load operation. In particular, the long-term average remained well within permitted limits. The smaller engines were over-controlled due to an overly simplistic air-to-fuel ratio OEM control mechanism. Thus, these engines maintained an average emissions level at 60% of the set point, which was well below the 2 g/bhp-hr emissions limit. However, this over-control resulted in lower-efficiency operation and higher (unregulated) CO levels. Diurnal changes of up to 150% of the set-point (still within permitted limits) were observed. For both sets of engines, while excursions were observed, they were small compared to the excursions seen during operation of engines with typical NSCR systems, which can easily increase to 10 times the typical emissions levels during an excursion. (Chapman, et al., *Report 29*, 2010)

Field-testing of four-stroke cycle rich-burn engines was challenging due to instability problems in standard systems. Satisfactorily consistent control could be achieved only by using an upstream signal-conditioned UEGO with a full authority AFRC. Field tests of two different AFRC systems were installed on two identical KVG-10 pipeline engines. The first engine included an integrated control and diagnostic system that included the following parts:

- An AFM1000+ sensor upstream of the catalyst;
- An EPC-100e controller using the upstream sensor for control;
- An ECM NOxCAN sensor for downstream monitoring of the NO_X to CO ratio and O_2; and,
- AETC's NSCR OBD+ onboard diagnostics monitoring system.

The AFM 1000+ sensor is a UEGO that has been modified by adding additional signal conditioning to give a linear output with oxygen concentration in natural gas exhaust. In addition, the signal conditioning accounts for long-term changes in signal due to exposure to hydrogen. The NOxCAN sensor is used to monitor emissions and send the signal to the onboard diagnostics and monitoring system so that any out-of-control operation can quickly be detected and remedied. The second control system simply installed an AFM1000+ sensor in upstream control and the NOxCAN for monitoring with a legacy controller, the Woodward Geco Controller, in upstream control. For both controllers, NO_X and CO had clear monotonic trends when plotted versus the AFM1000+ signal, so the optimal control set-point could be found easily. In addition, the downstream NOxCAN sensor was able to accurately show trends in NO_X production for both engines. Finally, when using the advanced sensor, both controllers were able to maintain consistent control for an extended period. However, understanding changes in emissions levels was more challenging without the integrated control system. (Beshouri et al., *Report 35*, 2011)

NSCR Modeling and Enhanced Controller Tuning

The challenges encountered standard NSCR systems were tested called for explicit models of the system to be developed. Specifically, the EGO sensor was the focus of these models because the signal did not appear to be repeatable at similar engine conditions. In addition, indications that a properly conditioned UEGO sensor can provide better control calls for a model of this sensor, as well. The models can be used to understand the operation of the sensors in natural gas exhaust and may be used to provide improved signal conditioning. Because the sensors respond differently depending on the species in the exhaust, a model of a four-stroke cycle rich-burn, natural-gas-fired engine was developed, as well. The emissions output of this model are used as an input to the model of the sensors so that the output of the sensors can be examined at different engine operating conditions.

Four-stroke cycle Engine Model

The four-stroke cycle engine model takes into account the flow of air and fuel to the engine and the flow of exhaust out of the engine. It uses these flow rates and the chemical process of combustion to determine the formation and emission of exhaust components as a function of time. The formation of NO_X, hydrocarbons, and CO was included. (Chapman et al., *Report 28*, 2009)

The flow of air and fuel into the engine is determined by the flow of mixtures past intake and exhaust poppet valves. This flow was calculated at various crank angles, which correspond to different valve openings, using the compressible flow equation. The flow primarily depends on area through which the gas moves, the discharge coefficient of the poppet valve, and the difference in pressure of the volumes between which the gas is moving. Because the discharge coefficient for the intake valve changes in discontinuous ways as the valve lift increases, this detailed model is vital to determining how the fresh charge mixes and how the exhaust gases are purged from the cylinder. (Chapman et al., *Report 28*, 2009)

The combustion process is modeled to determine the formation of various emissions species. Once the intake process has been modeled, the pressure and temperature of the trapped gases during compression and before the ignition is determined using the ideal gas law, where neither the mass of the gases, nor the fraction that is fuel is changing. Heat transfer during the intake, compression, and combustion is calculated using a Nusselt-Reynolds number relation for turbulent convection. Combustion is modeled in three separate zones: burned, unburned, and boundary. In this case, the fraction of the fresh charge that has been burned is represented by an exponential function of the crank angle, called the Wiebe function. (Annand and Roe, 1974) This is used to determine the heat released as combustion proceeds. Mass and energy can also be transferred between adjacent zones. (Chapman et al., *Report 28*, 2009)

The combustion conditions determined by the combustion model can be used to calculate the formation of NO_X. NO forms wherever there are high-temperature burned gases, both in the flame front and in post-flame regions. It is formed by reactions between nitrogen and oxygen that do not attain chemical equilibrium. The initial rate of NO production depends on temperature and the concentrations of nitrogen and oxygen. NO in the flame zone can be converted into NO_2, and NO_2 can also dissociate into NO and oxygen. (Chapman et, al., *Report 28*, 2009)

The combustion conditions also determine the hydrocarbons produced by an engine. Hydrocarbon emissions generally result when some of the fuel does not combust. This happens where there is not enough oxygen to react with the hydrocarbons or flame cannot reach the fuel, such as in small crevices, near the piston rings or head gasket, or where the reaction is quenched by cooler surroundings. Typically quenching occurs near the cylinder walls. Therefore the hydrocarbon emissions depend upon the air-to-fuel ratio and the surface area of the cylinder, which can be determined using engine bore and stroke. Hydrocarbon emissions also depend upon what mass fraction of the fuel has been burned when the exhaust ports open. While these mechanisms allow unburned hydrocarbons to escape into the exhaust, the high exhaust temperatures contain enough energy to allow some of these hydrocarbons to oxidize into carbon dioxide and water. The portion of hydrocarbons that are oxidized in the exhaust depends primarily upon the oxygen concentration in the exhaust stream. (Chapman et al., *Report 29*, 2009)

The carbon monoxide produced by an engine was also modeled. Because the in-cylinder gases are not allowed to reach equilibrium before the exhaust ports are opened, the formation rates for creation of CO are needed. In addition, as with hydrocarbons, carbon monoxide can oxidize to CO_2 in the exhaust. Thus, the reaction rates for this oxidation are needed. Both reaction rates are found from the equilibrium constants for the species given the combustion conditions, and the result is dependent upon the air-to-fuel ratio in the cylinder. (Chapman et al., *Report 30*, 2010)

The models for formation of CO and total hydrocarbons were compared to experimental data. The CO model, which included cycle-resolved in-cylinder temperature and pressure compared well to field data collected from a Cooper GMVC engine when plotted as a function of air-to-fuel ratio. Results from the model had an average deviation of ±1.441 ppm compared to the experimental data. The model for total hydrocarbons produced had good agreement with the shape of the experimental data, but was initially high. When a factor indicating additional oxidation of hydrocarbons in the exhaust stream was incorporated, agreement between the model and the experimental hydrocarbon emissions of an Arrow VRG 330 matched well. Thus, the model can be used to determine the emissions at different engine conditions, and the output can be used as input for the oxygen sensor models.

EGO Sensor Model

The EGO sensor typically used in standard NSCR systems is a switch-type EGO sensor, also called a Nernst cell. The important feature of this sensor is that its output is linear over only a small range due to the logarithmic nature of the Nernst equation, which gives the output voltage. While this sensor had been modeled extensively for gasoline exhaust, no modeling for natural gas exhaust had been completed. Since natural gas exhaust constituents are likely to include reducing species, such as methane, which are expected to affect EGO sensor output, this additional effort was necessary. Thus, the research team undertook detailed modeling of this sensor for natural gas exhaust following the principles previously used for gasoline. (Chapman et al., *Report 26*, 2009) The sensor, as shown in Figure 7, was modeled in three parts: the outer protective layer through which exhaust species must diffuse to arrive at the electrode surface, the surface reactions at the electrode, and the transport of ions through the electrolyte. This followed the process laid out by Auckenthaler's (2002) model for the response of the sensor to gasoline exhaust.

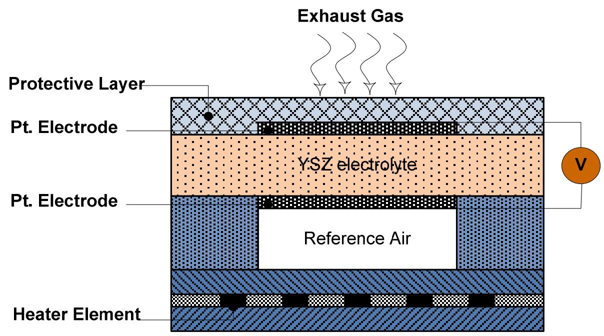


Figure 7. Schematic diagram of switch-type EGO sensor.

In modeling the protective layer, the main concern was to accurately track the diffusion of different exhaust gas species through the layer. Each specie will diffuse through the protective layer at a rate that depends upon the total concentration of the species, the gradient of the concentration of that species, and the flow of other species through the protective layer. Because the concentration and gradient of concentration are important, the absorption and desorption of the various species onto the platinum electrode affect the rates of diffusion. (Chapman et al., *Report 32*, 2010)

When the exhaust gas species arrive at the platinum electrode, they undergo catalytic reactions after they adsorb to the surface, and the reaction products later desorb from the surface. The rates of these reactions depend on the species present, the percent of possible sites that are occupied by that species, and on the temperature of the surface. This, in turn, determines how many unoccupied sites, or vacancies, exist on the surface of the platinum electrode. (Chapman et al., *Report 29*, 2010)

The charge imbalance on the electrodes that occurs when each electrode has a different concentration of vacancies determines the voltage across the electrolyte and the flow of charges across the electrolyte. The imbalance in vacancies therefore determines the output voltage of the sensor. The voltage is calculated using the Nernst equation. The Nernst equation depends logarithmically upon the ratio of vacancies at the exhaust gas electrode to the vacancies at the reference air electrode. The factors that affect the vacancy concentration include the gradient of oxygen concentration between the electrode and the electrolyte as well as the chemical potential of the reduction-oxidation reactions that occur on the electrode. Because species other than oxygen can also be reduced, the concentrations and reduction-oxidation reactions of CO, H_2, and methane (CH_4) must also be included. (Chapman et al., *Report 30*, 2010 and Chapman et al., *Report 31*, 2010)

When these parts of the model are combined, the voltage output of the EGO sensor given the exhaust gas composition can be determined. Comparing the new model to the data obtained by Baker and Verbrugge (1994), showed the correct shape for the output and a slight shift toward leaner values when methane reduction was included in the model compared to a model with no methane reduction as can be seen in Figure 8. (Chapman et al., *Report 32*, 2010)

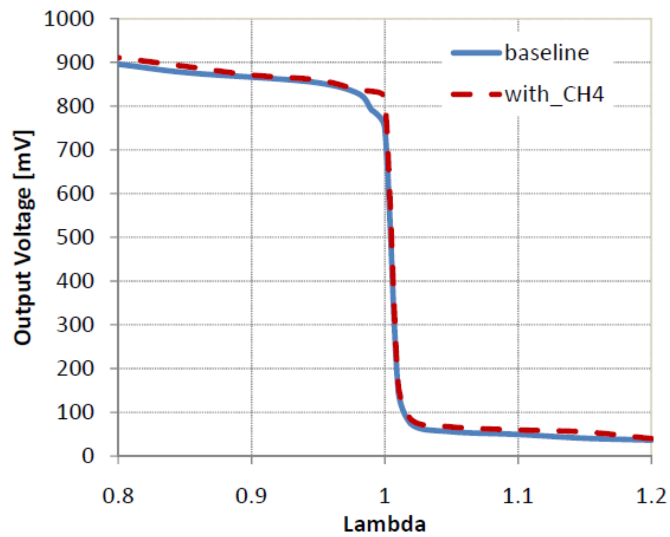


Figure 8. Comparison of modeled EGO output for models with and without methane reduction.

When the exhaust gas concentrations from the NSCR characterization study were examined, the puzzling points with identical EGO readings and very different emissions characteristics were explained. While the effects due to methane remained relatively small because of low concentrations, as in Figure 8, the effects due to hydrogen and carbon monoxide in the exhaust were significant. When these species were present in the exhaust, the voltage increased, even though a decrease would have been expected given the increase in oxygen concentration. (Chapman and Toema, *Report 33*, 2011)

UEGO Sensor Model

In the amperometric EGO sensor, oxygen is pumped from one side of the electrolyte to the other by the application of an external potential to the cell (Peyton Jones and Jackson, 2003). Figure 9 shows a comparison between the Nernst cell "potentiometric sensor" and the pumping cell "amperometric sensor." In the Nernst cell, the open-circuit voltage is produced as a result of the potential difference in the equilibrium oxygen concentration between the sensor electrodes. However, in the pumping cell, which is based on the well know limiting current principle, an external voltage is applied on the cell causing a pumping current of oxygen ions to flow through the solid electrolyte.

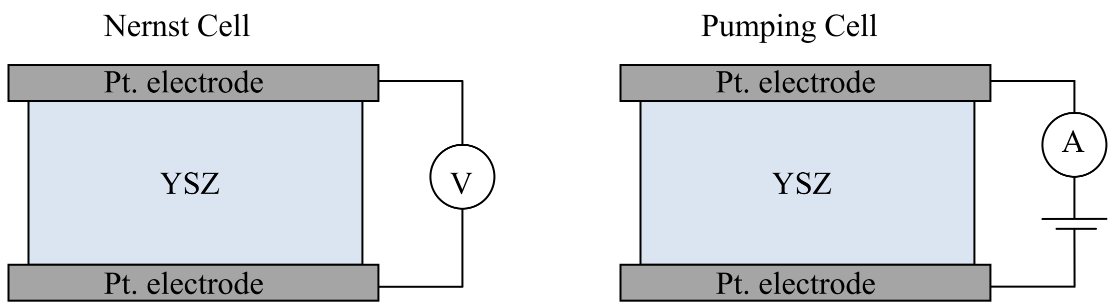


Figure 9. Nernst cell versus pumping cell

A diffusion barrier (e.g. a porous layer or a gap in front of the electrode) limits the access of oxygen molecules to the electrode which causes the generated limiting current to be independent of the applied pumping voltage. On a certain range of pumping voltage, the limiting current is proportional to the diffusion of oxygen molecules through the diffusion barrier and, therefore, proportional to the oxygen concentration in the exhaust gas. Figure 10 shows the current-voltage characteristics of a limiting current amperometric sensor. This figure shows that for a specific value of applied pumping voltage (e.g. 0.5 V) the limiting current is mainly dependent on the air-to-fuel ratio.

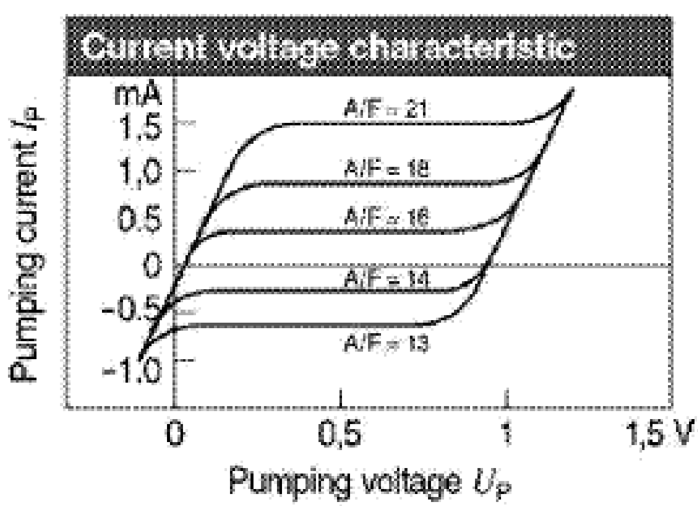


Figure 10. Pumping cell voltage-current relations [2]

A single pumping cell generates a defined signal characteristic in a lean burn exhaust gas ($\lambda>1$). For rich operation ($\lambda<1$), the relation between the pumping current and the air-to-fuel ratio will be ambiguous: the limiting current will increase with decreasing lambda.

To avoid the undesired behavior of a single amperometric cell, a dual cell type is now becoming the most widely used UEGO sensor. The dual cell sensor consists of two cells as its name indicates. These two cells are the limiting current pumping cell and the Nernst-type “potentiometric cell.” Figure 11 shows the configuration of a planar UEGO sensor. In this sensor design, an internal diffusion barrier is enclosed between the pumping cell and the sensing “Nernst” cell. The sensing cell operates in the potentiometric mode and the output emf is used to control the pumping current by using a closed loop electronic circuit as shown in Figure 11.

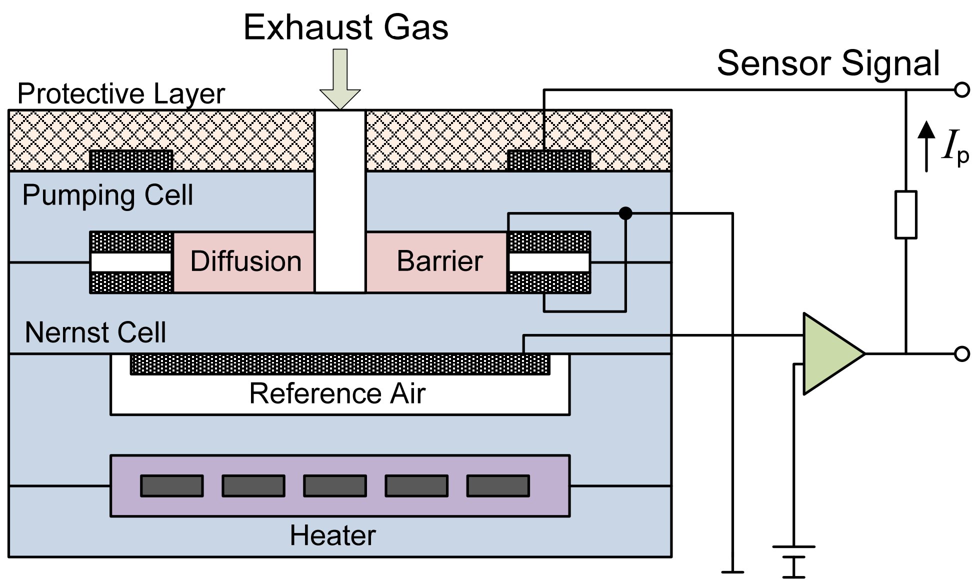


Figure 11. Dual cell wide range EGO sensor (Moos, 2005)

The feedback circuit enables the Nernst cell to keep the oxygen partial pressure in the internal diffusion gap constant always around the stoichiometric air-to-fuel ratio. Thus, depending on the polarity of the pumping voltage, oxygen can either be pumped out of or into the diffusion gap volume. Therefore, the electronic circuitry modulates the voltage supply to maintain the composition of the gas in the diffusion gap at a consistent λ equal to one. The pump cell corresponds to lean exhaust by discharging oxygen from the diffusion gap to the outside, but reacts to rich exhaust by pumping oxygen from the surrounding exhaust gas into the diffusion gap, reversing the direction of the current. Because the pumping current is also proportional to the oxygen concentration and/or oxygen deficiency, it serves as an index of the excess air-factor of the exhaust gas. (Chapman and Toema, *Report 34*, 2011)

Our modeling efforts have been focused on predicting the pumping current for different AF, and have built upon the work of Peyton Jones and Jackson (Peyton Jones and Jackson, 2003) and Moos. (Moos, 2005) The pumping current is directly related to the molar flow rate of oxygen through the diffusion barrier required to maintain stoichiometry. The molar flow rate of oxygen is equal to the oxygen excess of deficiency of the components entering the cell from the exhaust gas. For example, when reducing species like CO or CH_4 enter the cell, they react with oxygen on the electrode so the molar flow rate of oxygen is essentially decreased. We can take this effect into account by expressing the molar flow rate of oxygen in terms of all reducing and oxidizing species entering the cell from the exhaust gas.

The key to modeling the UEGO sensor response to gas concentration, then, is to accurately predict the diffusion of all species through the diffusion barrier. To represent diffusion, we have use the Maxwell-Stefan equation. This equation is generally believed to be the most reliable tool to model mass transfer in multi-component systems. (Taylor, 1993; Wesselingh, 2006)

This approach was used to simulate the sensor response (I_p) to different λ values. Figure 12 shows the results or our simulations as compared to result reported in the literature.

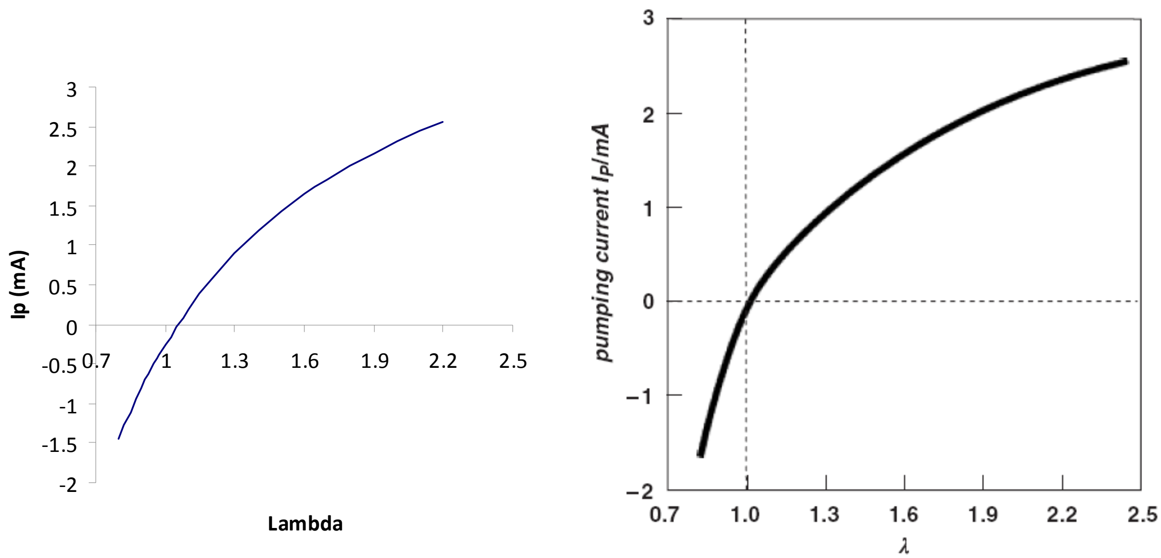


Figure 12. Pumping current as a function of lambda a) Our calculated results b) Results reported by Murase (Murase, 1998).

As seen in Figure 12, our calculations capture the expected trend of I_p with lambda. The values are very close to that reported by Murase. (Murase, 1998) One notable difference is that our calculations do not give exactly zero pumping current at 1 as one would expect. This is due to slight differences in the diffusion coefficients of methane and oxygen: methane diffuses faster so a slightly higher AFR is needed before the molar fluxes of methane and oxygen are equal which gives I_p equal to zero.

These calculations show that our approach can be used to model the UEGO sensor. Our next step is to explore the impact of different reducing and oxidizing species on the sensor response. It is expected that the presence of species like H_2 and CO will substantially change the sensor response since these species react with oxygen on the electrode. The final step of the UEGO sensor modeling is to validate the model with field data that give the output of an UEGO sensor as a function of exhaust gas composition. Gregg Arney with the Pipeline Research Consortium International has offered to facilitate obtaining some of these data, potentially from an engine at the Easter Municipal Water District.

Conclusions: Summary of Successful, Commercially Available, Cost-Effective Retrofit Emissions Reduction and Monitoring Equipment

Technologies Shown to Be Successful

In this study technologies were found to successfully control NO_X and CO emissions for natural-gas-fired engines typically used in the gas exploration and production industry. First, a low-emissions-combustion retrofit works well for both two-stroke cycle and four-stroke cycle lean-burn engines. Typically, the air flow to the engine is increased with a turbocharger. This leaner mixture requires additional energy to ignite, so a pre-combustion chamber, which can be screw-in or integral to the cylinder head, is used. The pre-combustion chamber can also reduce emissions for two-stroke cycle engines that cannot be turbocharged, such as the Ajax models, so long as the engines have increased air flow through improved air-intake filters and scavenging. Because this is a combustion control, the emissions can be calculated based on the operating conditions of the engines. Thus, a parametric monitoring system, which also gives valuable information that can improve engine operation and maintenance, is the preferred way to measure emissions. Because air-to-fuel imbalance in the different pre-combustion chambers and cylinders can adversely affect emissions, an advanced control strategy, which can be incorporated with the parametric monitoring system, is recommended. This control strategy should actively adjust and balance the air-to-fuel ratio in all cylinders. Incorporating ion sense into the parametric monitoring and the control strategy can be one effective way to ensure that all cylinders are firing with nearly identical air-to-fuel ratios.

The technology that effectively controls NO_X and CO emissions for four-stroke cycle rich-burn engines is an integrated NSCR system that includes a signal-conditioned UEGO sensor in upstream control and a full-authority air-to-fuel ratio controller as well as an NSCR catalyst. Care must be taken when implementing this technology. When an NSCR-controlled system runs out-of-control, emissions can be ten times higher than the intended level. While the use of the signal-conditioned UEGO greatly improves the situation and allows for consistent control, the whole NSCR system must be set up carefully to ensure no out-of-control operation. To detect changes in operation that could lead to out-of-control operation and the diagnosis of problems, the use of a NOxCAN sensor, a solid-state sensor that is sensitive to the NO_X-to-CO ratio, in an advanced on-board diagnostic system, such as the one demonstrated by AETC, is recommended.

Technologies Requiring Further Development

While the NSCR system using the signal-conditioned UEGO sensor can provide consistent NO_X and CO control, more work is required to ensure the robustness of this system. The UEGO sensor model developed as part of this project could be incorporated into an integrated NSCR control system and used in the diagnostic algorithms. In addition, a complete NSCR model for natural gas exhaust should be developed and integrated into an NSCR control system. By including these models, the control and diagnostic algorithms could become more effective and robust, which would improve the function of NSCR systems at all emissions levels.

Commercialization of Technologies

While this project has been underway, several technologies have become commercialized or nearly ready for commercialization. Ion sense, which was only available in Europe at the beginning of this study, has been developed for the natural gas industry in the United States by AETC. (Chapman et al., *Report 29*, 2010) In addition, the AFM1000+, an advanced oxygen sensor that is basically a signal-conditioned UEGO, has been developed by AETC. (Beshouri, 2010) Cameron Ajax is nearly ready to release screw-in pre-combustion chambers quoted at less than 2 g/bhp-hr for its small, two-stroke cycle lean-burn engines, as well. (Taliaferro, July 13, 2011)

While the technologies discussed above were successful at reducing emissions levels, some incremental changes are still needed. For low levels of NO_X, most of the NO_X from an engine using a pre-combustion chamber is actually produced in the PCC. This could be improved by fixing the few problems with PCCs. For instance PCC air-to-fuel ratio control could be improved, as could the balance of air-to-fuel ratio for PCCs on all engine cylinders. Finally, because stuck and damaged check valves cause many of the fuelling imbalances and PCC malfunctions, improving PCC check-valves or finding a better method for quickly identifying and replacing stuck or damaged check-valves could make a difference in emissions levels. Finally, longer averaging times for emissions levels, as opposed to one-hour emissions level averages, could more accurately reflect the long-term effectiveness of emissions control.

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Appendix I

Table 8. Gathering Engines in the DOE Project Database Sorted by Frequency.

Gathering Engines in the DOE Project Database Sorted by Frequency						
Manufacturer	***Model***	**Air Fuel Ratio**	**Cycle**	**Horsepower**	**Total**	**% of Total**
Waukesha	H 24 GL	Lean-burn	four-stroke	530	937	19.8%
Caterpillar	G 3408 TA	Rich-burn	four-stroke	400	536	11.3%
Waukesha	F 18	Lean-burn	four-stroke	400	327	6.9%
Caterpillar	G 3516 TALE	Lean-burn	four-stroke	1340	323	6.8%
Ajax	DPC 280	Lean-burn	two-stroke	280	295	6.2%
Waukesha	L 7044 GSI	Rich-burn	four-stroke	1680	270	5.7%
Ajax	DPC 2802 LE	Lean-burn	two-stroke	316	221	4.7%
Waukesha	3524 GSI	Rich-burn	four-stroke	840	197	4.2%
Waukesha	L 5790 GL	Lean-burn	four-stroke	1215	169	3.6%
Caterpillar	G 3412 LE	Lean-burn	four-stroke	585	142	3.0%
Waukesha	VRG 330	Rich-burn	four-stroke	50	104	2.2%
Caterpillar	G 3412 TALE	Lean-burn	four-stroke	585	99	2.1%
Waukesha	L 7042 GSI	Rich-burn	four-stroke	1000-1478	86	1.8%
Caterpillar	G 3304	Rich-burn	four-stroke	80	72	1.5%
Caterpillar	G 3516 LE	Lean-burn	four-stroke	1340	60	1.3%
Caterpillar	G 3516	Lean-burn	four-stroke	1200	38	0.8%
Superior	825	Rich-burn	four-stroke	500-800	35	0.7%
Waukesha	L 7042	Lean-burn	four-stroke	1400	35	0.7%
Ajax	DPC 360	Lean-burn	two-stroke	360	32	0.7%

Gathering Engines in the DOE Project Database Sorted by Frequency						
Manufacturer	<u>*Model*</u>	**Air Fuel Ratio**	**Cycle**	**Horsepower**	**Total**	**% of Total**
Ajax	DPC 2803 LE	Lean-burn	two-stroke	600	30	0.6%
Waukesha	L 7042 GL	Lean-burn	four-stroke	1000	30	0.6%
Ajax	DPC 60	Lean-burn	two-stroke	60	28	0.6%
Caterpillar	G 399 TA	Rich-burn	four-stroke	700-900	25	0.5%
Ford	LSG 875	Rich-burn	four-stroke	60	25	0.5%
Ajax	DPC 140	Lean-burn	two-stroke	140	24	0.5%
Caterpillar	G 3512 TALE	Lean-burn	four-stroke	585	24	0.5%
Caterpillar	G 3306	Rich-burn	four-stroke	165	22	0.5%
Caterpillar	G 342	Rich-burn	four-stroke	185	22	0.5%
Ajax	DPC 300	Lean-burn	two-stroke	300	21	0.4%
Caterpillar	G 3608 TALE	Lean-burn	four-stroke	2222	20	0.4%
Caterpillar	G 398	Rich-burn	four-stroke	550	20	0.4%
Caterpillar	G 398 TA	Rich-burn	four-stroke	450-700	20	0.4%
Ajax	DPC 115	Lean-burn	two-stroke	115	18	0.4%
Ajax	DPC 180	Lean-burn	two-stroke	180	17	0.4%
Ajax	DPC 600 LE	Lean-burn	two-stroke	600	17	0.4%
Caterpillar	G 3512	Lean-burn	four-stroke	850	16	0.3%
Waukesha	L 7042	Rich-burn	four-stroke	750	15	0.3%
Caterpillar	G 3306 TA	Rich-burn	four-stroke	165	14	0.3%
Caterpillar	G 3606 TALE	Lean-burn	four-stroke	1803	13	0.3%
Clark	RA	Lean-burn	two-stroke	300-500	13	0.3%
Ajax	DPC 230	Lean-burn	two-stroke	230	12	0.3%

Gathering Engines in the DOE Project Database Sorted by Frequency						
Manufacturer	*Model*	**Air Fuel Ratio**	**Cycle**	**Horsepower**	**Total**	**% of Total**
Caterpillar	G 3612	Lean-burn	four-stroke	3335	12	0.3%
Waukesha	VRG 310	Rich-burn	four-stroke	50	12	0.3%
Caterpillar	G 3306 NA	Rich-burn	four-stroke	145	11	0.2%
Caterpillar	G 3304 NA	Rich-burn	four-stroke	95	10	0.2%
Caterpillar	G 3412 C LE	Lean-burn	four-stroke	627	10	0.2%
Ajax	DPC 30	Lean-burn	two-stroke	30	9	0.2%
Caterpillar	G 379	Rich-burn	four-stroke	400	9	0.2%
Ajax	DPC 360 LE	Lean-burn	two-stroke	360	8	0.2%
Caterpillar	G 333	Rich-burn	four-stroke	127	8	0.2%
Caterpillar	G 3406 TA	Rich-burn	four-stroke	325	8	0.2%
Caterpillar	G 3412		four-stroke	550	8	0.2%
Caterpillar	G 3412 CLE	Lean-burn	four-stroke	585	8	0.2%
Clark	HLA8	Lean-burn	two-stroke	1885	6	0.1%
Ingersoll-Rand	412 KVS	Lean-burn	four-stroke	1910	6	0.1%
Waukesha	F 1197	Rich-burn	four-stroke	100-300	6	0.1%
Caterpillar	G 342 NA	Rich-burn	four-stroke	165	5	0.1%
Caterpillar	G 3512 LE	Lean-burn	four-stroke	920	5	0.1%
Caterpillar	G 398 NA	Rich-burn	four-stroke	450	5	0.1%
Waukesha	F 18 GL	Lean-burn	four-stroke	400	5	0.1%
Waukesha	L 5790	Lean-burn	four-stroke	700-1200	5	0.1%
Waukesha	L 7042 GU	Rich-burn	four-stroke	800	5	0.1%
Waukesha	LRZB	Rich-burn	four-stroke	330	5	0.1%

Gathering Engines in the DOE Project Database Sorted by Frequency						
Manufacturer	*Model*	**Air Fuel Ratio**	**Cycle**	**Horsepower**	**Total**	**% of Total**
Ajax	DPC 280 LE	Lean-burn	two-stroke	280	4	0.1%
Ajax	DPC 42	Lean-burn	two-stroke	42	4	0.1%
Ajax	DPC 600	Lean-burn	two-stroke	600	4	0.1%
Caterpillar	G 3408 TA	Rich-burn	four-stroke	400	4	0.1%
Caterpillar	G 3408 NA	Rich-burn	four-stroke	255	4	0.1%
Caterpillar	G 342 TA	Rich-burn	four-stroke	200	4	0.1%
Caterpillar	G 3606	Lean-burn	four-stroke	1665	4	0.1%
Caterpillar	G 3608	Lean-burn	four-stroke	2222	4	0.1%
Caterpillar	G 379 TA	Rich-burn	four-stroke	300-400	4	0.1%
Cooper	GMVH-10	Lean-burn	four-stroke	2250	4	0.1%
Waukesha	145	Rich-burn	four-stroke	216	4	0.1%
Ajax	DPC 140 LE	Lean-burn	two-stroke	140	3	0.1%
Ajax	DPC 160	Lean-burn	two-stroke	160	3	0.1%
Ajax	DPC 2804 LE	Lean-burn	two-stroke	700	3	0.1%
Ajax	DPC 80	Lean-burn	two-stroke	80	3	0.1%
Ajax	DPC 800	Lean-burn	two-stroke	720	3	0.1%
Caterpillar	G 3412 TAHCR	Rich-burn	four-stroke	465	3	0.1%
Caterpillar	G 399	Rich-burn	four-stroke	665	3	0.1%
Ford	CSG	Rich-burn	four-stroke	60	3	0.1%
Ingersoll-Rand	LVG	Rich-burn	four-stroke	485	3	0.1%
Ajax	DPC 800 LE	Lean-burn	two-stroke	650	2	0.0%
Caterpillar	G 3406	Rich-burn	four-stroke	280	2	0.0%

Gathering Engines in the DOE Project Database Sorted by Frequency						
Manufacturer	*Model*	**Air Fuel Ratio**	**Cycle**	**Horsepower**	**Total**	**% of Total**
Caterpillar	G 3406 NA	Rich-burn	four-stroke	215	2	0.0%
Caterpillar	G 3408	Rich-burn	four-stroke	350	2	0.0%
Caterpillar	G 3408 LE	Lean-burn	four-stroke	425	2	0.0%
Caterpillar	G 3508		four-stroke	500	2	0.0%
Caterpillar	G 3508 LE	Lean-burn	four-stroke	515	2	0.0%
Caterpillar	G 3512 C LE	Lean-burn	four-stroke	945	2	0.0%
Caterpillar	G 3516 TA	Rich-burn	four-stroke	1085	2	0.0%
Caterpillar	G 3616 LE	Lean-burn	four-stroke	1340	2	0.0%
Caterpillar	G 379 NA	Rich-burn	four-stroke	400	2	0.0%
Caterpillar	G 399 TALCR	Rich-burn	four-stroke	930	2	0.0%
Generac	133 GTA	Rich-burn	four-stroke	297	2	0.0%
Ingersoll-Rand	KVG	Rich-burn	four-stroke	625	2	0.0%
Superior	2408	Lean-burn	four-stroke	1600	2	0.0%
Waukesha	F 135	Rich-burn	four-stroke	35	2	0.0%
Waukesha	F 2895	Rich-burn	four-stroke	600-700	2	0.0%
Waukesha	F 817	Rich-burn	four-stroke	100-350	2	0.0%
Waukesha	L 36 GL	Lean-burn	four-stroke	785	2	0.0%
Waukesha	L 5794 GSI	Rich-burn	four-stroke	1385	2	0.0%
Ajax	DPC 105	Lean-burn	two-stroke	105	1	0.0%
Ajax	SB 330	Lean-burn	two-stroke	330	1	0.0%
Caterpillar	G 3412 TA	Rich-burn	four-stroke	400	1	0.0%
Caterpillar	G 342 HAHCR	Rich-burn	four-stroke	225	1	0.0%

Gathering Engines in the DOE Project Database Sorted by Frequency						
Manufacturer	*Model*	**Air Fuel Ratio**	**Cycle**	**Horsepower**	**Total**	**% of Total**
Caterpillar	G 342 TALCR	Rich-burn	four-stroke	265	1	0.0%
Caterpillar	G 3512 GSI	Rich-burn	four-stroke	520	1	0.0%
Caterpillar	G 3516 LETA	Lean-burn	four-stroke	1170	1	0.0%
Caterpillar	G 3516 SITA	Rich-burn	four-stroke	1085	1	0.0%
Caterpillar	G 3516 TALEHS	Lean-burn	four-stroke	1265	1	0.0%
Caterpillar	G 3518 LE	Lean-burn	four-stroke	630	1	0.0%
Caterpillar	G 3606 LE	Lean-burn	four-stroke	1665	1	0.0%
Caterpillar	G 3606 TA	Rich-burn	four-stroke	1615	1	0.0%
Caterpillar	G 3616	Lean-burn	four-stroke	1200	1	0.0%
Caterpillar	G 3616 TALE	Lean-burn	four-stroke	4705	1	0.0%
Caterpillar	G 379 TA LCR	Rich-burn	four-stroke	415	1	0.0%
Caterpillar	G 398 HCTA	Rich-burn	four-stroke	700	1	0.0%
Clark	HRA8	Lean-burn	two-stroke	800	1	0.0%
Cummins	GTA50G2				1	0.0%
Waukesha	12V-AT27GL	Rich-burn	four-stroke	3065	1	0.0%
Waukesha	F 11 GSI	Rich-burn	four-stroke	60	1	0.0%
Waukesha	L 5108	Lean-burn	four-stroke	1072	1	0.0%
Waukesha	L 5108 GL	Lean-burn	four-stroke	1122	1	0.0%
Waukesha	L 5108 GU	Rich-burn	four-stroke	600	1	0.0%
Waukesha	L 5790 GU	Rich-burn	four-stroke	877	1	0.0%
Waukesha	L 5794	Lean-burn	four-stroke	1250	1	0.0%
Waukesha	L 5794 LT	Lean-burn	four-stroke	1354	1	0.0%

Gathering Engines in the DOE Project Database Sorted by Frequency						
Manufacturer	*Model*	**Air Fuel Ratio**	**Cycle**	**Horsepower**	**Total**	**% of Total**
Waukesha	L 7042 GNA	Rich-burn	four-stroke	896	1	0.0%
Waukesha	VRG 22O	Rich-burn	four-stroke	42	1	0.0%
TOTAL					**4729**	**100.0%**

Appendix II

Table 9. Comparison of control technologies.

Control Technology	NOX Impact	Other Impacts	Combustion Impacts	Cost	Availability	Implementation	Technology Compatibility
Retard Ignition Timing	up to 10% reduction	decreased fuel economy, possible CO tradeoff	can only be adjusted a few degrees	very low	commercial	minor adjustment	all
Lean-burn Combustion with Low-Emissions Retrofit	up to 90% reduction	increased fuel economy, possible CO tradeoff	higher power, higher efficiency, restricted operation range, risk of unstable combustion	$500K to $2 million	commercial	requires significant changes to old equipment and installations of new equipment	requires higher air boost (turbochargers), higher ignition energy (PCC or HEIS), A/F ratio controller possible, possible SCR or oxidation catalyst (probably not cost effective)
High Energy Ignition System	2.5 - 3 g/bhp-hr range	possible CO tradeoff	improve combustion stability	part of retrofit cost	commercial	requires new ignition system, spark plugs	part of low emissions retrofit to lean engine to maintain stable combustion, A/F ratio controller possible, possible SCR or oxidation catalyst (probably not cost-effective)
Pre-combustion Chamber (integral)	1 g/bhp-hr range	possible CO tradeoff	improve combustion stability	part of retrofit cost	commercial by OEM	requires new cylinder head, secondary fuel system	part of low emissions retrofit to very lean engine to maintain stable combustion, A/F ratio controller possible SCR or oxidation catalyst (probably not cost-effective)

Advanced In-cylinder Mixing	Pre-stratified Charge	Pre-combustion Chamber (screw-in)	Micro Pre-combustion Chamber	Control Technology
30 - 70 % reduction	2 g/bhp-hr range	1 g/bhp-hr range	2 - 4 g/bhp-hr range	**NOX Impact**
increased fuel economy, possible CO tradeoff	possible CO tradeoff	possible CO tradeoff	possible CO tradeoff	**Other Impacts**
improve combustion stability	power de-rated by 20%	improve combustion stability	improve combustion stability	**Combustion Impacts**
less than major changes to air system required for very lean engine operation	cost of changes to air delivery system	part of retrofit cost, lower than integral PCC	part of retrofit cost, lower than integral PCC, increased replacement plug price	**Cost**
nearly commercial (retrofits available)	commercial	commercial by OEM and 3rd party	commercial	**Availability**
replace fuel delivery system, requires high pressure fuel	requires changes to fresh charge delivery system	requires secondary fuel system, secondary cooling system	requires secondary fuel system	**Implementation**
higher air boost to lean engine, SCR, NSCR could be applied (probably not cost-effective)	applicable only to four-stroke, rich-burn, carbureted engines, NSCR could be applied (probably not cost-effective)	part of low emissions retrofit to lean engine to maintain stable combustion, A/F ratio controller possible, SCR or oxidation catalyst could be applied (probably not cost effective)	part of low emissions retrofit to lean engine to maintain stable combustion, A/F ratio controller possible, possible SCR or oxidation catalyst (probably not cost-effective)	**Technology Compatibility**

Air-to-Fuel Ratio Controller	Hydrogen Blended Fuel	Homogeneous Charge Compression Ignition	Exhaust Gas Recirculation	Control Technology
that of the combustion or post-combustion controls it is used with	40% - 50% when used with lean combustion	unknown, expected to improve upon lean-burn combustion	expected to be similar to or improve upon lean-burn combustion	**NOX Impact**
that of the combustion or post-combustion controls it is used with	none	possible CO tradeoff	possible CO tradeoff	**Other Impacts**
that of the combustion or post-combustion controls it is used with	improves combustion stability	unknown, expected to improve upon lean-burn combustion	expected to be similar to or improve upon lean-burn combustion	**Combustion Impacts**
~$30K range	cost of mixing manifolds and on-site hydrogen generation, includes development	includes development	includes development	**Cost**
commercial	long term R&D	long term R&D	developing	**Availability**
requires changes to air and/or fuel delivery system	requires manifold to mix hydrogen and natural gas and on-site hydrogen	requires significant changes to equipment, controls difficult to implement	requires significant changes to air intake and exhaust	**Implementation**
could be used to control lean-burn with low emissions retrofit or with catalysts, not effective alone	requires lean-burn engine, removes need to increase ignition energy, so no added benefit to using PCC, unknown effects on post-combustion controls	no ignition system, control typically requires EGR, compatible with post-combustion controls (likely not cost-effective)	requires lean-burn engine, PCC or HEIS, not compatible with post-combustion controls due to exhaust temperature requirements	**Technology Compatibility**

Control Technology	Lean-NO_X Catalysts	Oxidation catalyst	Selective catalytic reduction (SCR)	Non-selective catalytic reduction (NSCR)
NO_X Impact	up to 80 % reduction	none	1 mole of NO_X is reduced 80-90% by .9 to 1 mole NH_3	up to 98% reduction, levels can be in range of 0.1 to 1.0 g/bhp-hr, but may not be continuously controlled
Other Impacts	reduces CO and non-methane HC by up to 60%, decreases fuel economy by up to 3%	reduces CO and non-methane HC by 98 - 99%, methane by 60 - 70%	requires storage of NH_3, unreacted NH_3 can be released	up to 97% reduction of CO and 80% reduction of VOCs, tradeoff between reduction of NO_x and CO, production of NH_3
Combustion Impacts	backpressure on engine	backpressure on engine	backpressure on engine	reduced fuel efficiency, backpressure on engine
Cost	cost of catalyst, catalyst replacement, increase operating costs (including extra fuel and special lubricants)	cost of catalyst, catalyst replacement	cost of catalyst, catalyst replacement, increase operating costs (including reagent supply)	cost of catalyst, catalyst replacement, A/F ratio controller, EGO sensor and replacement
Availability	nearly commercial	commercial	commercial	commercial, systems with improved control are under development
Implementation	requires addition of catalyst, injection of fuel into exhaust	requires addition of catalyst	requires addition of catalyst and ammonia injection to exhaust, storage for ammonia	Requires addition of catalyst, A/F ratio controller, and EGO sensor
Technology Compatibility	for lean-burn engine, requires low-sulfur fuel, compatible with lean-burn combustion controls	requires excess O2, compatible with lean-burn combustion controls	compatible with combustion controls	requires rich-burn combustion (exhaust oxygen levels <0.5%), not compatible with combustion controls

Table 10. Comparison of Monitoring Technologies

Monitoring Technology	Combustion	Cost	Availability	Implementation	Technology Compatibility
Continuous Emissions Monitoring System	none	high	commercial	sampling interface permanently installed (typically)	all, some emissions products can cause systematic errors which must be considered carefully
Portable Emissions Analyzer	none	up to $10K plus cost of replacement cells	commercial	requires port in exhaust stack	all, high levels of some emissions components can damage cells
Solid State NOX sensor	none	few thousand plus cost to replace sensor (~$800)	commercial	requires port in exhaust stack	all for monitoring, cross-sensitivity to NH_3 and require live calibration to get ppm
Parametric Emissions Monitoring System	gives information about combustion quality	depends on sensors used, a few thousand	some commercial, more developing	installation of sensors and software	works well with combustion controls
Exhaust gas oxygen sensor	gives combustion equivalence ratio for four-stroke engines	few thousand plus cost to replace sensor (few hundred)	commercial	installation of sensors and software	used extensively with post-combustion controls
Ion Sense	give information about combustion quality, in-cylinder equivalence ratio, NO_X levels	relatively low, signal processing equipment must be purchased, requires shielded ignition coils	nearly commercial	sensor is spark plug, requires signal processor box external to engine and software	all, especially effective for combustion controls