

**Phase 1 Report: Cost-Effective Reciprocating Engine
Emissions Control and Monitoring
for E&P Field and Gathering Engines**

Topical Report

DOE Award DE-FC26-02NT15464

Author

Kirby S. Chapman, Ph.D., Kansas State University
Sarah R. Nuss-Warren, Research Associate, Kansas State University

Submitted by

Kansas State University
National Gas Machinery Laboratory
245 Levee Drive
Manhattan, KS 66502

February 2007

Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Abstract

This topical report discusses work completed during Phase 1 of the project Cost Effective Reciprocating Engine Emissions Control and Monitoring for E&P Field and Gathering Engines. In this report information, data, and results are compiled and summarized from quarterly reports 1 through 15. Results for each of the tasks in Phase 1 are presented.

Table of Contents

Disclaimer.....i

Abstract ii

Table of Contents..... iii

Introduction1

Basis of the Project3

Phase 1 Tasks4

Create an Industry-Based Steering Committee5

Identify and Assess Commercial and Emerging Control and Monitoring Technologies8

Determine Technology and Market Gaps between Practical Options and Current and Expected Permitting Requirements16

Determine On-engine Control System and Sensor Requirements for Remote Emissions Monitoring19

Conclusions21

Phase 2 Outlook22

Acknowledgements22

References22

Appendix I.....25

Appendix II32

Introduction

The objective of this project is to identify, develop, test, and commercialize emissions control and monitoring technologies that can be implemented by exploration and production (E&P) operators to significantly lower the cost of environmental compliance and expedite project permitting. The project team takes considerable advantage of the emissions control research and development efforts and practices that have been underway in the gas pipeline industry for the last 12 years. These efforts and practices are expected to closely interface with the E&P industry to develop cost-effective options that apply to widely-used field and gathering engines, and which can be readily commercialized.

The project is separated into two phases. Phase 1 work establishes an E&P industry liaison group, develops a frequency distribution of installed E&P field engines, and identifies and assesses commercially available and emerging engine emissions control and monitoring technologies. Current and expected E&P engine emissions and monitoring requirements are reviewed, and priority technologies are identified for further development. The identified promising technologies are tested on a laboratory engine to confirm their generic viability. In addition, a full-scale field test of prototype emissions controls will be conducted on at least ten representative field engine models with challenging emissions profiles. Emissions monitoring systems that are integrated with existing controls packages will be developed. Technology transfer/commercialization is expected to be implemented through compressor fleet leasing operators, engine component suppliers, the industry liaison group, and the Petroleum Technology Transfer Council.

Forecasts of future U.S. natural gas demand of 30 trillion cubic feet (Tcf) /yr by 2015 require 36% production growth from 2001 levels. Demand growth will be addressed by both conventional gas and coal-bed methane. The majority of the increase in conventional gas production is expected from three primary areas: Offshore Gulf of Mexico, Rocky Mountains, and Canadian imports. Mature basins in the Southwest and Mid-Continent areas will also 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 ozone, fine particulates, and NO₂; regulations regarding acid deposition and regional haze; and pending air toxics regulations. All these issues will limit emissions from compressor engines. NO_x and formaldehyde will be the likely focus. The scope of these regulations will include the assessment of the need for emissions controls on the wellhead and field gathering reciprocating engine-driven compressor and pumping equipment that is ubiquitous in E&P operations. Current estimates are that approximately 15 million horsepower are presently 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.

Though in many oil and gas production areas the air shed emissions inventory is dominated by coal power plants, regulatory agencies continue to pursue incremental reductions in total

pollutant loading. Reciprocating engines have been identified as a meaningful source category. This is evident in Federal and State actions, as well as Environmental Impact Statements associated with new development. These engines are used to produce electricity for a leasehold, compress and re-inject natural gas for increased oil production, compress natural gas so that it can be delivered to local gathering systems that ultimately feed into gas transmission pipelines, and drive smaller-load equipment such as pump jacks.

At present, the region with the greatest confluence of emissions concerns for small internal combustion (IC) engines 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 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 air-sheds) may likely stimulate aggressive compressor engine controls in that and other production regions, as well. Finally, the East Texas and Louisiana regions are subject to conventional ambient ozone concerns, and have promulgated strict NO_x controls for reciprocating engines. In addition, EPA has proposed regulations that impact smaller IC engines in all applications throughout the U.S. These rules include a New Source Performance Standard for IC engine, as well as air toxics standards for: (1) area sources (i.e., engines at smaller facilities), and (2) engines 500 hp and smaller at major sources.

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, and 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 affects oil and gas production in four distinct ways:

- 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. Furthermore, permitting may become impossible when performance targets for application of emission controls to small engines are inappropriately established at levels that are technically infeasible or only achievable based on expenditures well in excess of forecasts of the implementing agencies.
- 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.
- 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.
- 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:

- Deferring the start of wellhead production, thereby increasing the general business risk in current price-volatile markets and increasing the carrying costs of various lease and development fees,
- Directly increasing the cost of compression services used at the wellhead,
- 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.

In addition, application of controls may result in emissions tradeoffs that can result in other deleterious environmental effects if not properly considered. These issues may be exacerbated by presumptions of technology performance that have not been proven for the engine sizes or operating applications present in oil and gas operations.

These economic and operating burdens to oil and gas operations can be reduced through a focused effort to develop cost-effective retrofit components, engine combustion controls, and engine performance monitoring options. This project strives to significantly improve the cost-effectiveness of implementing NO_x controls and monitoring on compressor engines, while characterizing emissions tradeoffs to ensure that compliance with air regulations does not prevent oil and gas operations from achieving their maximum productivity at competitive production costs.

Basis of the Project

This project draws 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 1994/1995 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 bhp to 8,000 bhp 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 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:

- Obtain an industry consensus for

- specific engine types and models on which to focus development efforts;
 - installed cost targets; and
 - realistic emissions levels to be achieved under all operating conditions.
- Develop an inventory of installed horsepower to confirm initial industry guidance and to create a useful tool for impact analysis;
 - 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;
 - Aggressively field test component and controls developments;
 - Characterize the fundamental relationships between engine operating parameters and exhaust emissions so that accurate, non-instrumented emissions monitoring systems could be deployed; and
 - 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. Operators will enjoy reduced costs of compliance, greater permitting certainty, reduced costs of emissions monitoring, and possible improved compressor performance due to improved combustion stability. All of this sums to increased production as wells are brought online more rapidly, compression equipment is run harder and longer to facilitate increased production, and lifting cost savings are reallocated toward additional resource base development.

Phase 1 Tasks

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. Moved to Phase 2a of this project (Conduct controlled tests to evaluate promising monitoring and control technologies identified in Tasks 3 and 4)
6. Determine on-engine control system and sensor requirements for remote emissions monitoring

Create an Industry-Based Steering Committee

The formation of the industry steering committee, which fulfills several purposes, is essential to the success of the project. The committee's main purpose is to ensure that the project meets the needs of the industry. In order to do this, the committee provided information about the current state of exploration and production (E&P) fleets, expressed concerns about regulation trends that could limit production under static emissions reduction technology, and gave realistic estimates about how much companies could afford to invest in emissions control at meetings held during the initial stages of the project. Another purpose of the committee is to provide contact points to arrange field testing. The final purpose of the steering committee will be to provide a link to industry to facilitate technology transfer.

The steering committee consists of E&P industry representatives, as well as individuals from compressor fleet rental companies. The committee members are:

Richard Sumner, El Paso Corporation
Reid Smith, BP
Mike Milliet, ChevronTexaco
Brad Bengel, Universal Compression
Jim LaBounta, Western Gas Resources
Jack Kopfman, Williams
Rob Rice, Hanover Compression
Don Duttlinger, PTTC
Terry Twyman, API (Ad Hoc member)

Contact with the industry steering committee proved very constructive and provided important information about what should be included in the database, the current state of emissions reduction technology in the field, and trends in emissions controls. The most important information to include in the database was determined to be the number of each kind of engine, especially in regions experiencing growth.

Discussion on the state of current technology showed a fairly limited number of typical controls on engines. For rich-burn engines these were limited to air-to-fuel-ratio controllers (AFRC) and non-selective catalyst reduction. On the other hand, lean-burn engines typically had pre-combustion chambers and improved scavenging technology. Committee members expressed interest in oxidation catalysts for lean-burn engines, but recognized that costs would need to be reduced for the option to be feasible. A concern expressed was that engine manufacturers specify low emissions values, but these values are difficult or impossible to achieve at typical operating conditions. Another consideration was that certain emissions control techniques work well only at certain loads and speeds. However, wells require less power at later stages, and emissions control technology or engines may have to be changed. Thus, flexibility remains very important.

Trends in the industry generally indicated an expectation of higher costs to meet more restrictive limits. For example, it appeared that very low NO_x levels (0.15 g/bhp) were achievable only

with NSCR catalysts on rich-burn engines, which are less fuel-efficient. As natural gas prices have increased, the fuel-efficiency has become a greater concern. A concern that 8-hr O₃ standards and regional haze issues would create the need for control in formerly uncontrolled rural regions was raised, as were the implications of eventual control of greenhouse gasses. The need for increased emissions monitoring was identified as a particularly costly aspect to more limiting regulations. The committee indicated that members could justify investing in additional monitoring only if it had additional benefits, such as the potential to increase engine performance.

The key outcome of consultation with the steering committee was that the E&P industry perceived that rich-burn engines coupled with an exhaust catalyst is the easiest path to satisfying potential EPA regulations. Ideally, though, a retrofit control and monitoring technology would take advantage of lean-burn engines to achieve increased performance and eliminate the backpressure caused by the catalyst. A parametric monitoring system that could infer emissions from engine data, which could be used to maintain excellent engine performance, would be preferred over a more-costly system that gave only emissions data.

Although the creation of the industry steering committee was completed during the first phase of this project, and much fruitful input has already been gained, the steering committee's role has not ended. The committee will play a vital role during phase two to expedite field testing by providing access to information and sites. Finally, the steering committee will be an essential part of technology transfer when each member is exposed to the results and conclusions of this project and shares them with his or her associates.

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

Rather than compiling a complete database, upon the suggestion of the industry steering committee the current fleet was sampled in order to characterize the makes and models that are used in the E&P industry. This information was used to prioritize the work in Tasks 3 and 4.

The initial sampling of engines was developed from lists of engines typically used in E&P operations. The frequency sampling was also used to determine horsepower ranges. Geographical distribution was determined to be non-essential after initial examination.

Items tracked in the database include:

- Make and model
- Cycle
- Horsepower
- NA/T/TA
- Rich/lean

The project team collected information on approximately 9,000 engines used in E&P operations. The information was compiled into a single database shown in Appendix I, Table 1. The sources of engine lists are provided in Table 1. Because many of these sources mainly include permitted

engines, not all low horsepower engines are included. Thus, low horsepower engines are underrepresented in the database.

As shown in Table 2, four-stroke-cycle engines are most prevalent, and among high horsepower engines lean-burn engines outnumber the rich-burn engines. However, since many of the less

Table 1. Sources of engine data and information.

Database	Number of Engines
State of Wyoming Engine Inventory Database	3,372
EPA ICCR Database	5,000*
GTI/PRCI Engine and Turbine Database	300 Gathering Engines
Database of Colorado and New Mexico Engines from Universal Compression	500

***Some of the engines in this database are used in interstate natural gas transmission and were removed.**

than 100 horsepower engines, which are primarily four-stroke, rich-burn engines, were not included in the sources, the four-stroke, rich-burn engines appear less prevalent than they really are.

Table 2. Engine frequency by air-to-fuel-ratio and cycle.

A/F ratio	Cycle	Total
Lean-burn	2-stroke	783
Lean-burn	4-stroke	2318
Rich-burn	4-stroke	1617
Unknown		11
Grand Total		4729

The four-stroke-cycle engine inventory is dominated by Caterpillar and Waukesha, both of which build both lean- and rich-burn four-stroke-cycle engines. On the other hand, the two-stroke-cycle engine inventory is dominated by Cameron Ajax, which builds only two-stroke-cycle, lean-burn engines. The prevalence of these and other manufacturers is shown in Table 3.

Table 3. Engine frequency by manufacturer.

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

Identify and Assess Commercial and Emerging Control and Monitoring Technologies

In completing the third task, the project team identified, categorized, and assessed commercially available and emerging emissions control and monitoring technologies. This process requires an understanding of emissions formation in engines and the science underlying reduction methods. This understanding can then be applied to available emissions reduction technologies, and the appropriate technologies can be identified as suitable for retrofits in the fleet of gas engines in natural gas E&P applications.

Reciprocating Engine Emissions Production

Exhaust emissions from all reciprocating engines include pollutants such as oxides of nitrogen (NO_x), carbon monoxide (CO), and volatile organic compounds (VOCs), which consist of unburned, non-methane hydrocarbons. Other pollutants, including oxides of sulfur (SO_x) and particulate matter (PM) depend on the specific fuel used. SO_x emissions are dependent on the sulfur content of the fuel. Because natural gas normally has low levels of sulfur, engines operating on natural gas typically emit insignificant levels of SO_x. While PM is a pollutant of concern for engines using liquid fuels, it is not typically a concern for natural-gas-burning engines.

Nitrogen Oxides (NO_x) – NO_x is formed by three processes during the combustion of a hydrocarbon. First, NO_x can be formed when fuel has nitrogen bound to hydrocarbons, which is insignificant for combustion using natural gas. Additionally, NO_x can be formed in the combustion reaction on the flame front where extra energy is available. However, the flame zone is small, and this does not account for much of the total NO_x formation. The most significant contribution to NO_x produced in an internal combustion engine is thermal NO_x.

Thermal NO_x is created when nitrogen and oxygen remaining after initial combustion react due to the excess energy available as a result of high post-combustion temperature (Heywood, 1988).

Thermal NO_x formation is described by the Zeldovich mechanisms. The Zeldovich mechanisms are the primary chemical mechanisms for thermal NO production, (Borman and Ragland, 1998):



The reaction mechanisms are shown in the order in which they occur. The first equation dominates the reaction, and the remaining two reactions cannot occur until the first one is complete.

As stated above, NO_x formation is a function of temperature. When the combustion temperature is lowered, the first equation reaction rate reduces significantly. The rate of formation for the first reaction is given by the following two equations (Heywood, 1988):

$$\frac{d[\text{NO}]}{dt} = k_{+1}[\text{O}][\text{N}_2] - k_{-1}[\text{NO}][\text{N}] + k_{+2}[\text{N}][\text{O}_2] - k_{-2}[\text{NO}][\text{O}] + k_{+3}[\text{N}][\text{OH}] - k_{-3}[\text{NO}][\text{H}] \quad (4)$$

$$\frac{d[\text{N}]}{dt} = k_{+1}[\text{O}][\text{N}_2] - k_{-1}[\text{NO}][\text{N}] - k_{+2}[\text{N}][\text{O}_2] + k_{-2}[\text{NO}][\text{O}] - k_{+3}[\text{N}][\text{OH}] + k_{-3}[\text{NO}][\text{H}] \quad (5)$$

The variables k_{\pm} are the forward and reverse rate constants.

Temperature, molecular surface area, and concentration all influence the activation energy level (Kuo, 2005). Since the goal is to reduce NO, NO₂, and other NO_x, and the physical surface area of the molecule cannot be changed, temperature and concentration become the controlling factors. Consequently, lower temperatures result in lower activation energy in the mixture, thereby lowering the NO that is formed.

When the reaction rate is reduced by temperature, the first mechanism reduces the concentration of NO and N. This then reduces the potential reactants in the second mechanism. Therefore, a temperature reduction in the first reaction introduces a limiting factor for NO_x emissions. For that reason, the goal of combustion control technology for NO_x reduction is to reduce thermal NO_x by lowering the reaction temperature. The reaction temperature can be reduced by adding excess air to the combustion products, thus leaning the mixture. As the air-to-fuel ratio becomes progressively more lean, the extra air serves as a dilutant that absorbs energy that is released from the fuel, decreasing the combustion temperature.

Carbon Monoxide (CO) – Carbon monoxide results from incomplete combustion. This occurs when oxygen supplied is insufficient to convert all carbon in the fuel to carbon dioxide. Incomplete combustion can also occur if the temperature is not high enough to complete the reaction. When cooling occurs at the combustion chamber walls or the reaction is quenched in the exhaust process additional CO can be formed (Energy Nexus Group, 2002).

Volatile Organic Compounds – Unburned or volatile hydrocarbons are also called volatile organic compounds (VOC). The designation typically includes any non-methane hydrocarbon in the exhaust stream. Some of these compounds are hazardous, or can react in the atmosphere to create hazardous chemicals. The VOCs are typically a result of incomplete combustion (Energy Nexus Group, 2002). However, as the engines typically used in gathering and production operation run on natural gas, the amount of VOCs they produce remains low.

Carbon Dioxide (CO₂) – Although CO₂ is non-hazardous, it is considered a significant greenhouse gas and is of concern due to its potential for global warming. Any combustion produces CO₂, but the amount produced is a function of fuel carbon content and engine efficiency. Because natural gas has less carbon per unit energy extracted, it will produce less CO₂ than oil or coal (Energy Nexus Group, 2002).

Technology Identification and Assessment

The focus of most control technology is to reduce the NO_x and CO that are produced by an engine. Both chemicals pose a health risk in high enough concentrations, and NO_x is a precursor to other potentially hazardous pollutants such as ozone and fine particulates. As such, technologies that appear to have potential to reduce NO_x and CO production were characterized.

Characterizing technologies includes:

- Understanding the underlying science of each option;
- Identifying the overall costs to retrofit the technology and associated equipment;
- Estimating the recurring maintenance costs to operate in compliance;
- The incremental fuel costs; and
- Emissions monitoring requirements (and expenses).

The project team pursued an approach including:

- Describing baseline information on emissions of gas engines;
- Identifying applicable retrofit technologies for the class of engines to be addressed;
- Gathering technical, operational, and economic information on available technologies and ancillary equipment; and

- Analyzing technologies based on cost effectiveness and applicability to the E&P fleet of engines

This task was separated into two subtasks. The first focuses on monitoring techniques, and the second focuses on emissions control techniques. In most cases, monitoring techniques are essential for precise emissions control.

Monitoring Technologies

Monitoring technologies are used to quantify emissions produced by an engine. In some cases a monitoring system is required to demonstrate continuous compliance. In other cases, the monitoring can be used for closed-loop control of combustion modifications or post-combustion emission control technology.

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 which 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. Chemiluminescence analyzers measure the light emitted by chemical reactions that occur in the sample (Jahnke, 2000).

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. Vendors claim that portable analyzers could be used for semi-continuous monitoring, which would include about 15 minutes of emissions data every hour, with minimal maintenance. 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.

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 available in Europe and through some distributors in the US, create a reducing atmosphere in an ion-conductive metal-oxide chamber that measures oxygen produced as NO_x decomposes. Though these sensors degrade over time, it may be possible to detect the degradation rate or place the sensors such that NO_x can be accurately monitored (Orban, 2005).

Parametric Emissions Monitoring Systems (PEMS¹) – 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 be determined using other methods as well, such as an in-cylinder pressure measurement or ion sense. For direct measurement of air-to-fuel ratio, an oxygen sensor can be used. In addition to emissions information, a PEMS can provide operational information that can enhance engine operation (Beshouri, 1998).

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 an air-to-fuel ratio (λ). 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 trapped air-to-fuel ratio.

Ion-Sense – Ion sensing measures the electrical conduction between two electrodes. By sensing the conducted current, studies have shown that it is possible to infer the gaseous species concentrations within the cylinder during the combustion and post-combustion processes. With this technique, it is possible to determine the in-cylinder air-to-fuel ratio, the engine average air-to-fuel ratio, and also identify combustion anomalies. Ultimately, this same process can be used to determine NO_x production and emission within the cylinder. Ion sense has been demonstrated on rich- and lean-burn gas-fired engines (Beshouri, 2006).

For effectiveness, cost, and other information see Table 1 in Appendix 2.

Control Technologies

Controls are separated into two groups: combustion process control, which changes the dynamics of combustion to reduce the amounts of pollutants created, and post-combustion controls, which chemically convert pollutants to standard air constituents. Combustion process control, mostly through reducing combustion temperature, has been the principal focus in gas engines. Unfortunately, combustion process controls require trade-offs. High temperatures produce complete combustion and low levels of CO and VOCs. However, they also produce the most NO_x. As the temperature decreases, the combustion quality may suffer as well, which could reduce efficiency. Additionally, for very lean mixtures, incomplete combustion can occur, creating CO. Post-combustion controls have trade-offs as well. In many cases, with post-combustion controls the engine must operate at a precise air-to-fuel ratio that may not be the

¹ The acronym PEMS is sometimes referred to as the Predictive Emissions Monitoring System. However, this is incorrect terminology because it does not represent the true nature of a parametric monitoring system. The word “predictive” implies that one can forecast into the future – this is not the intent of a PEMS.

most efficient. Other post-combustion emission controls require additional energy input to function, thereby reducing the overall efficiency of the system.

Lean-burn technology as a combustion emission control was developed and commercialized during the 1980s as a direct response to the need for cleaner burning gas engines. As discussed earlier, thermal NO_x formation is a function of both flame temperature and residence time. The focus of lean-burn developments was to lower combustion temperature in the cylinder using lean fuel/air mixtures. Lean combustion decreases the fuel/air ratio in the zones where NO_x is produced so that peak flame temperature is less than the stoichiometric adiabatic flame temperature, therefore suppressing thermal NO_x formation. Improvements in mixing may be accomplished through swirling and tumbling the air (or air/fuel mixture) within the cylinder, improving fuel injection or location, increasing fuel injection pressure, and enhancing flame speed. Most lean-burn engines use turbocharging to supply excess air to the engine and produce the homogeneous lean fuel-air mixtures. Lean-burn engines generally use 50 to 100% excess air (above stoichiometric).

An added performance advantage of lean-burn operation is higher output and higher efficiency, as long as the combustion process remains in an optimal region for both low NO_x production and engine stability. Optimized lean-burn operation requires sophisticated engine controls to ensure that combustion remains stable and NO_x reduction is maximized while minimizing emissions of CO and VOCs.

Combustion-based control technologies have been developed and demonstrated on several classes of gas engines. They include:

Retard Ignition Timing – Ignition timing retardation is a low cost option applied to achieve small decreases in NO_x emissions. 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.

High Energy Ignition – 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.

Pre-Combustion Chambers (PCC) – Pre-combustion chambers (some times 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 chambers lean mixture to an easily ignitable mixture. The integral design assures proper cooling and eliminates water leakage problems into the power cylinder.

Micro Pre-Combustion Chamber – This approach is a hybrid between the high energy ignition systems and a pre-combustion chamber. It reduces NO_x by providing sufficient energy to ignite a lean air/fuel mixture. 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.

Screw-in Pre-Combustion Chambers – Screw-in pre-combustion chambers affect combustion and emission performance similarly to integral pre-combustion chambers. 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.

Pre-Stratified Charge – The pre-stratified charge system is an option available for four-stroke cycle 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 air/fuel pressure. While the cylinder fuel valve is closed, fresh air is forced into the fuel header pushing the air/fuel mixture back. Once the fuel valve opens, the fresh air and lean mixture is the first to enter the cylinder and moves toward the piston. The dilution air is displaced and the carbureted mixture continues flowing into the cylinder, leaving near the top of the cylinder. 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.

Advanced In-Cylinder Mixing – The goal of advanced in-cylinder mixing, typically using high-pressure fuel injection, has been to develop a system that can be retrofitted to an engine that will significantly improve the emission signature of engines without compromising the economic advantages they currently exhibit. 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 super sonic injection into the power cylinder.

Exhaust Gas Recirculation (EGR) – EGR replaces some of the excess air in a lean-burn engine with cooled exhaust gasses. 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.

Homogeneous Charge Compression Ignition (HCCI) – HCCI is an alternative piston engine combustion process that can provide efficiencies as compression-ignition direct ignition engines (CIDI), 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.

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 A/F 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 equivalence 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.

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 reducing the time it takes for a significant quantity of pollutant to break down to minutes. Although the reactions slowly occur 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. This requires precise control of the engine's air-to-fuel ratio 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

There are several types of catalytic exhaust gas treatment processes that are applicable to gas engines:

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 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 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, the catalyst can become poisoned and lose effectiveness.

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 (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 (Energy Nexus Group, 2002). As such, they require excess O_2 and can only be used with lean-burn engines.

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 depend 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 (Energy Nexus Group, 2002).

For effectiveness, cost, and other information see Table 2 in Appendix 2.

Based on product offerings and performed retrofits, the typical providers of control options were determined. There are only a few original equipment manufacturer (OEM) retrofit providers: Caterpillar, Cameron (which builds Ajax engines), and Waukesha. However, there are more aftermarket providers, including Altronic, Continental Controls, Woodward Controls, Enginuity, Hoerbiger, REM Technology, EMIT technologies, and Miratech.

Generally, for a lean-burn engine, the most promising control strategy is to increase the air-to-fuel ratio to its leanest limit and then use technologies such as the screw-in pre-combustion chamber to increase ignition energy and reliability. For rich-burn engines, the most promising strategy remains to use an NSCR catalyst, although these may not be able to achieve extremely low NO_x limits continuously. It is likely that yet more precise controls for existing technology or new development of control technologies will be necessary to reach extremely low NO_x limits. As always, further reductions in NO_x will run the risk of decreasing engine efficiency, producing more CO, and potentially increasing the rate of other pollutants, such as ammonia.

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

Significant regulatory activity is occurring in many oil- and gas-producing states. These pending regulations are driven by draft environmental impact statement (EIS) documents that tend to call for NO_x limits in the range of 1 - 2 g/bhp-hr on all engines, regardless of size and would be finalized in 2007. In the Four Corners area these limits are driven by visibility concerns for nearby national parks and wilderness areas and general concern about ozone (McCarthy, 2006). Such limits have generally not been demonstrated for small engines, and it is questionable whether they are technologically or economically feasible. Currently, size- and use-based thresholds exist for New Mexico, Oklahoma, Colorado, Texas, and Wyoming. The lowest hp engines regulated are 50 bhp, typically for newer engines or in ozone non-attainment areas.

One plausible way to forecast what emissions criteria may soon face oil and gas producers is to examine the rules implemented by precedent-setting states, such as California and New York. In California a document providing guidance was published by the California Air Resource Board (CARB) in 2002 and is still in effect. This document gives local permit-granting authorities guidance on decision-making and operators a point of reference when developing a project plan. The CARB permitting guideline document includes:

- A review of control technologies considered best available control technology (BACT) in California for pollutants including NO_x, CO, VOCs and particulate matter.
- Emission performance for BACT expressed in terms of lbs/MW-hr, as follows:
 - NO_x = 0.5 lb/MW/hr (equivalent to 0.15 g/bhp-hr or 9 ppmvd at 15% O₂).
 - VOC = 0.5 lb/MW/hr (equivalent to 0.15 g/bhp-hr or 25 ppmvd at 15% O₂).
 - CO = 1.9 lb/MW/hr (equivalent to 0.6 g/bhp-hr or 56 ppmvd at 15% O₂).
 - PM = 0.06 lb/MW/hr (equivalent to 0.02 g/bhp-hr).
- Note that the NO_x limit for IC engines is the same as the turbine NO_x limit for units < 3 MW.

- The emission levels in the guidance document require post combustion controls. For NO_x, NSCR is required for rich-burn engines and SCR is required for lean-burn units. CO and VOCs require an oxidation catalyst for lean-burn engines, while NSCR addresses these pollutants for rich-burns.
- CARB suggests that rich-burn engines from 86 to 750 bhp have achieved these emission levels²
- An initial performance test and subsequent periodic testing are identified as reasonable monitoring requirements. For units less than 100 hp, a quarterly portable analyzer test is recommended in lieu of reference method source tests.
- CARB recommends requirements for parameter monitoring (e.g., catalyst temperature) and operator requirements to log and report all maintenance activities for the engine and emissions control equipment.
- CARB notes that existing local district permitting thresholds for IC engines vary, but implies that a 50 bhp threshold, consistent with the lowest threshold from district regulations, is appropriate.

In New York, revisions to the NO_x RACT rule from 2004 focus on reducing emissions from IC engines. The revisions reduce the minimum brake horsepower to which the rules apply, focusing on non-attainment areas, and set the NO_x emissions limit at 1.5 g/bhp-hr for natural-gas fired engines beginning in April of 2005. It allows for alternatives on some engines to reduce the baseline by 90% from the 1990 level or use averaging over all affected equipment. Additionally, the rule allows exemptions when it can be demonstrated that a level is not technologically or economically feasible and exempts emergency power generators. Although testing frequency is not specified by the rule, compliance must be demonstrated using an EPA Reference Method source test.

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, internal combustion engine-driven compressors remain most economically feasible in most situations.

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

² The research team does not agree with this statement – however, it is widely believed by the regulatory agencies that catalysts can consistently and reliably sustain emissions at extremely low levels.

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 accounted for. 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 and 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.

Current technologies exist to meet the needs of a 2 g/bhp-hr lean-burn engine. These consist of the lean-burn emissions control retrofit and are provided by OEMs or third-party aftermarket providers. The OEM solutions tend to be expensive, though costs could be reduced if retrofits occurred during scheduled maintenance-driven overhauls rather than as a response to critical emissions needs. The third-party aftermarket providers can offer less expensive options by reducing the amount of equipment to replace. Whenever a turbocharger needs to be added or replaced to increase airflow, the retrofit price rises significantly. This makes lean-burn retrofits most feasible for large horsepower engines which have higher capital value.

For lower horsepower lean-burn engines and lower emissions limits, like those in California, there remains a small technology gap. Less expensive methods of increasing air flow are needed for smaller engines or engines that cannot be turbocharged, such as the Ajax. Additionally, ignition systems that can light off very lean mixtures need to be further developed so that less NO_x is produced in ignition. For example, a significant fraction of the NO_x produced in a lean-burn engine with a pre-combustion chamber is actually produced in the chamber itself.

The technology to meet a 2 g/bhp-hr NO_x limit that appears to be effective and feasible for large rich-burn engines is NSCR with an air-to-fuel ratio controller. However, this system shows significant drift with ambient conditions (McGivney, 2006) and has not been proven to provide reliable continuous control. Additionally, the air-to-fuel ratio controllers tend to be difficult to program, and additional alarms are probably necessary before an operator could be confident that any out-of control condition could be detected.

The NSCR control technology has not been proven for smaller engines and appears to fail catastrophically at very low emissions limits, such as those in California (Arney, 2006). This shows that a large technology gap exists. For catalysts to be used successfully at gathering sites and wells, they must be proven to work on small engines. It is likely that the system would have to be adjusted given the lower exhaust temperature for smaller engines. Additionally, for a smaller engine, NSCR becomes less cost-effective. If NSCR-controlled engines will be expected to reach lower emissions limits consistently, significant modeling and development of the entire catalyst/air-to-fuel ratio controller system is necessary so that the appropriate changes can be made. Changes to the air-to-fuel ratio controller control algorithm are likely to be essential.

While systems exist to continuously determine the emissions level of NO_x and CO, continuous emissions monitoring tends to be economically unfeasible in most situations. To close the market gap between the need for continuous monitoring in some cases and its economic burden, virtual sensors could be developed. These sensors would infer emissions levels from engine data. Ion sense is a particularly good candidate for a virtual NO_x sensor. By monitoring the ion current several conditions could be determined: in-cylinder pressure, NO_x levels, and the approach of unfavorable combustion processes, such as detonation, (Beshouri, 2006). Continued development of ion sense includes advanced algorithms to interpret the ion signal and glean reliable emissions numbers. Such development is being pursued by AETC, a California-based company.

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

The control system for lean-burn engines in the field is expected to provide increased air flow and sufficient ignition energy to reach the leanest possible air-to-fuel ratio that is acceptable, given emissions and operational tradeoffs. This may consist of using turbochargers where possible on larger four-stroke cycle engines, and modifying the air flow path on two-stroke cycle engines, such as the Ajax. A fuel control valve may also be used to limit fuel flow and maintain a lean air-to-fuel ratio, although this could limit the engine's operating range. Finally, a system to increase ignition energy will be used. Where possible, this will likely be a screw-in pre-chamber, as this is expected to be the most cost effective. However, this will not be finalized until the controlled laboratory testing of the Ajax is completed. At that point, the control technology package for lean-burn engines may be revised to reflect the package found to be most effective and economically feasible in laboratory studies.

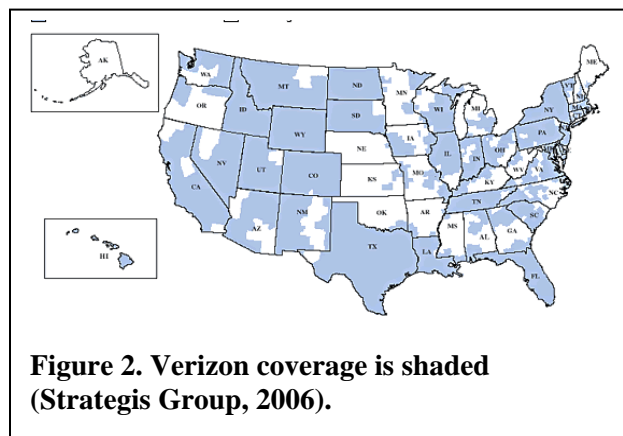
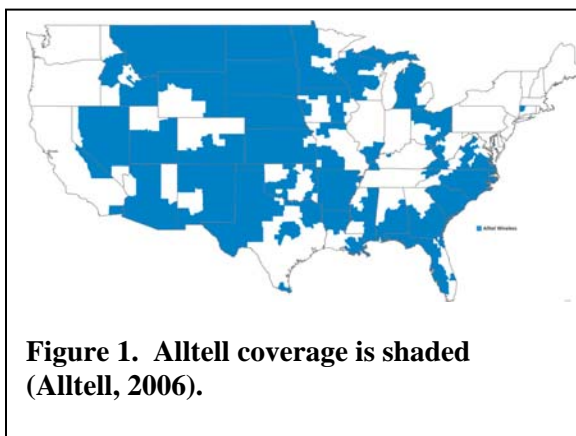
The control system for rich-burn engines will likely be a NSCR system with a full authority air-to-fuel ratio controller, assuming such a system can be shown to work on engines of the size used in the field. The air-to-fuel ratio will be measured with an exhaust gas oxygen sensor (EGO), or lambda sensor, in the exhaust stream. The signal will feed back into a controller, which will control the air-to-fuel ratio to a programmed set-point by determining the opening of the fuel valve. The keys to this strategy include assuring that the controller can achieve the set-point over the engine's entire operating range, which is called full-authority control, and verifying that the lambda sensor stays operational. The lambda sensor signal may be confirmed using ion-sense or virtual sensors. Additionally, parameters such as exhaust temperature change and pressure drop across the catalyst will be monitored and used to trigger alarms to ensure the system is functioning. This system will not be confirmed until extensive testing shows that it will be effective at the critical engine sizes. Confirmation will be provided by cost-share funded developmental field and laboratory testing on small, four-stroke-cycle, rich-burn engines.

The desired remote monitoring could be performed in a variety of ways. For instance, a portable emissions analyzer can be used in a semi-continuous mode. In this case, the probe would be inserted into the stack semi-permanently and programmed to take data for 15 minutes every hour. It would use a purge inlet, which would automatically open at the end of the data collection cycle, to expose the electrochemical cells to the fresh air necessary for long-term function. Data can be logged by the analyzer or converted to an analog signal and recorded with a low-speed data acquisition system. Unfortunately, cells may need to be replaced fairly

frequently if emissions levels surpass the maximum level to which a sensor can be exposed. Another option is to use solid-state sensors to take data. These sensors would be mounted permanently in the exhaust stack and data could be recorded by a low-speed data acquisition system. A final possibility would be the use of ion sense as a virtual sensor. This would require advanced software, but it is likely such software will be available by the time field tests occur. A virtual sensor system would require a high-speed data acquisition system including an on-site computer.

The emissions monitoring system selected for each field engine will depend upon availability of various resources at each specific site as well as which system the research team determines will be most successful in a given application. In some cases, combinations of monitoring technologies may be used. In addition to emissions monitoring, some engine parameters, which may include various temperatures, pressures, differential pressures, and flow rates, will also be monitored to determine engine output, fuel economy, and convert raw emissions data into brake-specific mass flow rates. These additional signals could be monitored using high- or low-speed data acquisition systems.

High-speed data acquisition systems typically require a computer with a PCI card, whereas the low-speed system currently used at NGML uses a programmable controller with flash memory. Both data acquisition systems have serial and Ethernet networking capabilities. The data acquisition systems can be connected to a cellular modem or radio transmitter. The cellular modem allows the data to be uploaded to a server through the cellular network or for a remote user to connect to the remote system and download data. As shown in figures 1 and 2, Cellular



network coverage is surprisingly good in oil and gas producing areas, such as Texas, New Mexico, Colorado, and Wyoming. Research team members have verified access in the San Juan Basin of the Four Corners area of New Mexico and Colorado during visits to potential sites. In cases where the cellular network may not be accessible or a control room with available high-speed network access is located within about 20 miles, a radio transmitter can be connected to the data acquisition system. It would then transmit data to the local server, which could be accessed via ftp or the internet. A telemetry system of this type has been designed and is scheduled for test in the Four Corners region in 2007.

Conclusions

The research process has proved very fruitful throughout Phase 1. The first step was to create an industry steering committee to ensure the needs of industry are met over the course of this project. The industry steering committee indicated that industry will be forced to use any economically feasible control strategy that exists. However, the committee would prefer strategies which do not decrease the efficiency of engines. Additionally, the committee would like to avoid performing additional monitoring unless the monitoring can provide tools to improve the operating stability or efficiency of engines.

The second task was to develop a representative database to catalog which engines are most common in the exploration and production industry, thus directing research efforts toward those common models. It was determined that among larger engines, four-stroke-cycle, lean-burn engines are most common, followed by four-stroke, rich-burn engines, and two-stroke, lean-burn engines. Despite the fact that two-stroke, lean-burn engines comprise the smallest inventory segment, they still account for 16% of the E&P engines. Two-stroke-cycle, lean-burn engines in the field are nearly all Ajax engines. Thus, the two-stroke, lean-burn engine tested at the laboratory was chosen to be an Ajax. Among four-stroke-cycle, lean-burn engines, Waukesha models are most common, whereas Waukesha and Caterpillar both comprise large portions of the four-stroke-cycle, rich-burn engine inventory. Although not shown in the inventory, most very low horsepower engines are rich-burn engines. This knowledge will prove valuable when choosing engines for field testing.

The third task was to evaluate monitoring and control technologies and select particularly promising technologies for further testing and application to the field. For lean-burn engines, providing air to create sufficiently lean combustion conditions and utilizing a higher-energy ignition technology that allows the leaner mixture to ignite has been found to be most promising. For rich-burn engines, despite some difficulties for low emissions levels or small engine sizes, an NSCR system with a full-authority air-to-fuel ratio controller remains most promising.

The fourth task was to determine technology and market gaps between options and permitting requirements. Significant technology gaps exist for controls in rich-burn engines. The catalyst and air-to-fuel ratio controller system have not been demonstrated to continuously control NO_x and CO levels to 2 g/bhp-hr or lower on smaller engines. The system fails at lower emissions levels. Lean-burn technology is solid down to levels of 2 g/bhp-hr but may not have the capability to reach the very low NO_x levels already required in California and likely to be implemented across diverse geographical areas in the future. Market gaps exist to achieve continuous monitoring technologies that are economically feasible. Although some inexpensive sensors for continuous monitoring have been developed and tested, they are not easily available on the market or have high maintenance costs. The situation does appear to be improving, however, with greater implementation of ion sense, solid state NO_x sensors, and the possibility of using a portable analyzer in continuous mode.

The fifth task, which was moved to Phase 2b, is to test control technologies in a laboratory setting. Some tests have been performed for the laboratory Ajax engine and on rich-burn NSCR systems. However, this testing will continue, and the results will be used to finalize the control

systems for field test engines. These results will be discussed in coming quarterly reports and the Phase 2 final report.

The final task in Phase 1 was to identify the remote control and monitoring system for field engines. The control systems are tentatively planned to be the most promising technologies found in the third task: achieve the leanest possible air-to-fuel ratio with increased ignition energy for lean-burn engines and an NSCR system with a full-authority air-to-fuel ratio controller for rich-burn engines. Of course, the outcome of the controlled testing will impact the final control package chosen for each engine type. Monitoring technology will consist of a low-speed, stand-alone, programmable data acquisition system with standard off-the-shelf sensors to measure any needed engine parameters and various emissions monitoring technology depending on availability and what is practical at each site. The monitoring technologies that will be considered include a portable electrochemical analyzer used in semi-continuous mode, ion sense-based virtual sensors to predict NO_x output, or solid-state NO_x sensors. Remote connectivity will be achieved through cellular technology or radio transmitters communicating with a local server.

Phase 2 Outlook

Phase 2 will encompass the remaining controlled testing and the final field tests. Controlled testing for lean-burn engines will continue to be performed at the National Gas Machinery Lab at Kansas State University. Further controlled testing for rich-burn engines will be conducted as part of an NSCR characterization project funded as cost-share by gas producers in the Four Corners region of Colorado and New Mexico. The final field tests, which will use results from controlled testing to confirm that the appropriate control strategies are being applied, has been rescheduled to begin in the first half of 2008.

Acknowledgements

The authors sincerely appreciate the technical assistance from: Mr. Gene McClendon and Mr. Bruce Chrisman of Cameron Ajax; Mr. Pat Maloney and Mr. Kriss McDonald of Ariel; Advanced Engine Technologies Corporation; Altronic, Inc.; Cameron Energy Services; Diesel Supply Company; Dynalco; Exline Inc.; Progressive Equipment Company; TSI; Emerson Process Management; Innovative Environmental Solutions; and Hoerbiger. Each of these people and companies contributed expertise, equipment, sensors, and transportation services to this project. Additional gratitude is necessary toward Allen Adriani, Paul Bautista, Greg Beshouri, Jim McCarthy, and Mike Whelan, who contributed to the research throughout this phase and the writing of the quarterly reports from which the results for this final report were drawn. Without these individuals and companies, this phase of the project would not have been possible.

References

Alltell Wireless. *Alltell Coverage*. <http://www.alltel.com/corporate/media/coverage.html>, accessed on December 20, 2006.

Arney, Gregg. *Field Comparison of Air/Fuel Ratio Controllers for Detection of Excess Emissions from Rich-burn Engines Equipped with Non-Selective Catalytic Reduction Systems*. Southern California Gas Company, 2006.

Beshouri, Greg. "Combustion Pressure Based Emissions Monitoring and Control for Large Bore IC Engines: An Alternative Parametric Emissions Models (PEMS) Methodology." *ICE* vol 30-1, *ASME Spring Technical Conference*, 1998.

Beshouri, Greg, Mike Duffy, Bo Nilson, Jan Nytomt, and Mark Richter. "Understanding and Applying Ion Sense: A Short Course," *Proceedings of the Gas Machinery Conference*, 2006.

Borman, G., and K. Ragland. *Combustion Engineering*. McGraw-Hill Inc., 1998.

Chapman, Kirby. *Report 1: Cost-Effective Reciprocating Engine Emissions Control and Monitoring for E&P Field and Gathering Engines*. Kansas State University, 2003.

Chapman, Kirby. *Report 2: Cost-Effective Reciprocating Engine Emissions Control and Monitoring for E&P Field and Gathering Engines*. Kansas State University, 2003.

Chapman, Kirby. *Report 3: Cost-Effective Reciprocating Engine Emissions Control and Monitoring for E&P Field and Gathering Engines*. Kansas State University, 2003.

Chapman, Kirby. *Report 4: Cost-Effective Reciprocating Engine Emissions Control and Monitoring for E&P Field and Gathering Engines*. Kansas State University, 2004.

Chapman, Kirby and Allen Adriani. *Report 5: Cost-Effective Reciprocating Engine Emissions Control and Monitoring for E&P Field and Gathering Engines*. Kansas State University, 2004.

Chapman, Kirby and Allen Adriani. *Report 6: Cost-Effective Reciprocating Engine Emissions Control and Monitoring for E&P Field and Gathering Engines*. Kansas State University, 2004.

Chapman, Kirby and Allen Adriani. *Report 7: Cost-Effective Reciprocating Engine Emissions Control and Monitoring for E&P Field and Gathering Engines*. Kansas State University, 2004.

Chapman, Kirby and Allen Adriani. *Report 8: Cost-Effective Reciprocating Engine Emissions Control and Monitoring for E&P Field and Gathering Engines*. Kansas State University, 2005.

Chapman, Kirby and Allen Adriani. *Report 9: Cost-Effective Reciprocating Engine Emissions Control and Monitoring for E&P Field and Gathering Engines*. Kansas State University, 2005.

Chapman, Kirby and Allen Adriani. *Report 10: Cost-Effective Reciprocating Engine Emissions Control and Monitoring for E&P Field and Gathering Engines*. Kansas State University, 2005.

Chapman, Kirby. *Report 11: Cost-Effective Reciprocating Engine Emissions Control and Monitoring for E&P Field and Gathering Engines*. Kansas State University, 2005.

Chapman, Kirby and Sarah Nuss-Warren. *Report 12: Cost-Effective Reciprocating Engine Emissions Control and Monitoring for E&P Field and Gathering Engines*. Kansas State University, 2005.

Chapman, Kirby, Greg Beshouri, Jim McCarthy, Sarah Nuss-Warren, and Mike Whelan. *Report 13: Cost-Effective Reciprocating Engine Emissions Control and Monitoring for E&P Field and Gathering Engines*, Kansas State University. 2006.

Chapman, Kirby and Sarah Nuss-Warren. *Report 14: Cost-Effective Reciprocating Engine Emissions Control and Monitoring for E&P Field and Gathering Engines*. Kansas State University, 2006.

Chapman, Kirby and Sarah Nuss-Warren. *Report 15: Cost-Effective Reciprocating Engine Emissions Control and Monitoring for E&P Field and Gathering Engines*. Kansas State University, 2006.

Energy Nexus Group. *Technology Characterization: Reciprocating Engines*. Environmental Protection Agency Climate Protection Partnership Division, 2002.

Heywood, J.B. *Internal Combustion Engines*. McGraw-Hill Inc., 1988.

Jahnke, James A. *Continuous Emission Monitoring*, John Wiley and Sons, 2000 (pp. 1-12, 81-82).

Kuo, K. *Principles of Combustion*. Second Edition, John Wiley and Sons, 2005.

McCarthy, Jim “Air Regulations Impacting the Natural Gas Industry: 2006 Air Quality Regulatory Report.” *Proceedings of Gas Machinery Conference*: Oklahoma City, Oklahoma, October 4, 2006.

McGivney, Daniel. “Evaluation of Potential Monitoring Frequency for Internal Combustion Engines Using Portable Electrochemical Cell Analyzers, vol. 1.” Eastern Municipal Water District, 2006.

Orban, John E., Steven J Naber, Christopher A. Sharp, Magdi K. Khair, and Ralph N. McGill. “Long Term Aging of NO_x Sensors in Heavy-Duty Engine Exhaust.” *SAE Technical Papers*, 2005-01-3793, 2005.

Strategis Group Inc. *Verizon Wireless Coverage Map*. <http://www.rentcell.com/coverage-map-airtouch.htm>, accessed on December 20, 2006.

Appendix I

Table 1. Gathering Engines in the DOE Project Database Sorted by Frequency

Manufacturer	<u>Model</u>	Air Fuel Ratio	Cycle	Horsepower	Total	% of Total
Waukesha	H 24 GL	Lean-burn	4-stroke	530	937	19.8%
Caterpillar	G 3408 TA	Rich-burn	4-stroke	400	536	11.3%
Waukesha	F 18	Lean-burn	4-stroke	400	327	6.9%
Caterpillar	G 3516 TALE	Lean-burn	4-stroke	1340	323	6.8%
Ajax	DPC 280	Lean-burn	2-stroke	280	295	6.2%
Waukesha	L 7044 GSI	Rich-burn	4-stroke	1680	270	5.7%
Ajax	DPC 2802 LE	Lean-burn	2-stroke	316	221	4.7%
Waukesha	3524 GSI	Rich-burn	4-stroke	840	197	4.2%
Waukesha	L 5790 GL	Lean-burn	4-stroke	1215	169	3.6%
Caterpillar	G 3412 LE	Lean-burn	4-stroke	585	142	3.0%
Waukesha	VRG 330	Rich-burn	4-stroke	50	104	2.2%
Caterpillar	G 3412 TALE	Lean-burn	4-stroke	585	99	2.1%
Waukesha	L 7042 GSI	Rich-burn	4-stroke	1000-1478	86	1.8%
Caterpillar	G 3304	Rich-burn	4-stroke	80	72	1.5%
Caterpillar	G 3516 LE	Lean-burn	4-stroke	1340	60	1.3%
Caterpillar	G 3516	Lean-burn	4-stroke	1200	38	0.8%
Superior	825	Rich-burn	4-stroke	500-800	35	0.7%
Waukesha	L 7042	Lean-burn	4-stroke	1400	35	0.7%
Ajax	DPC 360	Lean-burn	2-stroke	360	32	0.7%

Table 1. Gathering Engines in the DOE Project Database Sorted by Frequency

Manufacturer	<i>Model</i>	Air Fuel Ratio	Cycle	Horsepower	Total	% of Total
Ajax	DPC 2803 LE	Lean-burn	2-stroke	600	30	0.6%
Waukesha	L 7042 GL	Lean-burn	4-stroke	1000	30	0.6%
Ajax	DPC 60	Lean-burn	2-stroke	60	28	0.6%
Caterpillar	G 399 TA	Rich-burn	4-stroke	700-900	25	0.5%
Ford	LSG 875	Rich-burn	4-stroke	60	25	0.5%
Ajax	DPC 140	Lean-burn	2-stroke	140	24	0.5%
Caterpillar	G 3512 TALE	Lean-burn	4-stroke	585	24	0.5%
Caterpillar	G 3306	Rich-burn	4-stroke	165	22	0.5%
Caterpillar	G 342	Rich-burn	4-stroke	185	22	0.5%
Ajax	DPC 300	Lean-burn	2-stroke	300	21	0.4%
Caterpillar	G 3608 TALE	Lean-burn	4-stroke	2222	20	0.4%
Caterpillar	G 398	Rich-burn	4-stroke	550	20	0.4%
Caterpillar	G 398 TA	Rich-burn	4-stroke	450-700	20	0.4%
Ajax	DPC 115	Lean-burn	2-stroke	115	18	0.4%
Ajax	DPC 180	Lean-burn	2-stroke	180	17	0.4%
Ajax	DPC 600 LE	Lean-burn	2-stroke	600	17	0.4%
Caterpillar	G 3512	Lean-burn	4-stroke	850	16	0.3%
Waukesha	L 7042	Rich-burn	4-stroke	750	15	0.3%
Caterpillar	G 3306 TA	Rich-burn	4-stroke	165	14	0.3%
Caterpillar	G 3606 TALE	Lean-burn	4-stroke	1803	13	0.3%
Clark	RA	Lean-burn	2-stroke	300-500	13	0.3%

Table 1. Gathering Engines in the DOE Project Database Sorted by Frequency

Manufacturer	<i>Model</i>	Air Fuel Ratio	Cycle	Horsepower	Total	% of Total
Ajax	DPC 230	Lean-burn	2-stroke	230	12	0.3%
Caterpillar	G 3612	Lean-burn	4-stroke	3335	12	0.3%
Waukesha	VRG 310	Rich-burn	4-stroke	50	12	0.3%
Caterpillar	G 3306 NA	Rich-burn	4-stroke	145	11	0.2%
Caterpillar	G 3304 NA	Rich-burn	4-stroke	95	10	0.2%
Caterpillar	G 3412 C LE	Lean-burn	4-stroke	627	10	0.2%
Ajax	DPC 30	Lean-burn	2-stroke	30	9	0.2%
Caterpillar	G 379	Rich-burn	4-stroke	400	9	0.2%
Ajax	DPC 360 LE	Lean-burn	2-stroke	360	8	0.2%
Caterpillar	G 333	Rich-burn	4-stroke	127	8	0.2%
Caterpillar	G 3406 TA	Rich-burn	4-stroke	325	8	0.2%
Caterpillar	G 3412		4-stroke	550	8	0.2%
Caterpillar	G 3412 CLE	Lean-burn	4-stroke	585	8	0.2%
Clark	HLA8	Lean-burn	2-stroke	1885	6	0.1%
Ingersoll-Rand	412 KVS	Lean-burn	4-stroke	1910	6	0.1%
Waukesha	F 1197	Rich-burn	4-stroke	100-300	6	0.1%
Caterpillar	G 342 NA	Rich-burn	4-stroke	165	5	0.1%
Caterpillar	G 3512 LE	Lean-burn	4-stroke	920	5	0.1%
Caterpillar	G 398 NA	Rich-burn	4-stroke	450	5	0.1%
Waukesha	F 18 GL	Lean-burn	4-stroke	400	5	0.1%
Waukesha	L 5790	Lean-burn	4-stroke	700-1200	5	0.1%

Table 1. Gathering Engines in the DOE Project Database Sorted by Frequency

Manufacturer	<i>Model</i>	Air Fuel Ratio	Cycle	Horsepower	Total	% of Total
Waukesha	L 7042 GU	Rich-burn	4-stroke	800	5	0.1%
Waukesha	LRZB	Rich-burn	4-stroke	330	5	0.1%
Ajax	DPC 280 LE	Lean-burn	2-stroke	280	4	0.1%
Ajax	DPC 42	Lean-burn	2-stroke	42	4	0.1%
Ajax	DPC 600	Lean-burn	2-stroke	600	4	0.1%
Caterpillar	G 3408 TA	Rich-burn	4-stroke	400	4	0.1%
Caterpillar	G 3408 NA	Rich-burn	4-stroke	255	4	0.1%
Caterpillar	G 342 TA	Rich-burn	4-stroke	200	4	0.1%
Caterpillar	G 3606	Lean-burn	4-stroke	1665	4	0.1%
Caterpillar	G 3608	Lean-burn	4-stroke	2222	4	0.1%
Caterpillar	G 379 TA	Rich-burn	4-stroke	300-400	4	0.1%
Cooper	GMVH-10	Lean-burn	4-stroke	2250	4	0.1%
Waukesha	145	Rich-burn	4-stroke	216	4	0.1%
Ajax	DPC 140 LE	Lean-burn	2-stroke	140	3	0.1%
Ajax	DPC 160	Lean-burn	2-stroke	160	3	0.1%
Ajax	DPC 2804 LE	Lean-burn	2-stroke	700	3	0.1%
Ajax	DPC 80	Lean-burn	2-stroke	80	3	0.1%
Ajax	DPC 800	Lean-burn	2-stroke	720	3	0.1%
Caterpillar	G 3412 TAHCR	Rich-burn	4-stroke	465	3	0.1%
Caterpillar	G 399	Rich-burn	4-stroke	665	3	0.1%
Ford	CSG	Rich-burn	4-stroke	60	3	0.1%

Table 1. Gathering Engines in the DOE Project Database Sorted by Frequency

Manufacturer	<i>Model</i>	Air Fuel Ratio	Cycle	Horsepower	Total	% of Total
Ingersoll-Rand	LVG	Rich-burn	4-stroke	485	3	0.1%
Ajax	DPC 800 LE	Lean-burn	2-stroke	650	2	0.0%
Caterpillar	G 3406	Rich-burn	4-stroke	280	2	0.0%
Caterpillar	G 3406 NA	Rich-burn	4-stroke	215	2	0.0%
Caterpillar	G 3408	Rich-burn	4-stroke	350	2	0.0%
Caterpillar	G 3408 LE	Lean-burn	4-stroke	425	2	0.0%
Caterpillar	G 3508		4-stroke	500	2	0.0%
Caterpillar	G 3508 LE	Lean-burn	4-stroke	515	2	0.0%
Caterpillar	G 3512 C LE	Lean-burn	4-stroke	945	2	0.0%
Caterpillar	G 3516 TA	Rich-burn	4-stroke	1085	2	0.0%
Caterpillar	G 3616 LE	Lean-burn	4-stroke	1340	2	0.0%
Caterpillar	G 379 NA	Rich-burn	4-stroke	400	2	0.0%
Caterpillar	G 399 TALCR	Rich-burn	4-stroke	930	2	0.0%
Generac	133 GTA	Rich-burn	4-stroke	297	2	0.0%
Ingersoll-Rand	KVG	Rich-burn	4-stroke	625	2	0.0%
Superior	2408	Lean-burn	4-stroke	1600	2	0.0%
Waukesha	F 135	Rich-burn	4-stroke	35	2	0.0%
Waukesha	F 2895	Rich-burn	4-stroke	600-700	2	0.0%
Waukesha	F 817	Rich-burn	4-stroke	100-350	2	0.0%
Waukesha	L 36 GL	Lean-burn	4-stroke	785	2	0.0%
Waukesha	L 5794 GSI	Rich-burn	4-stroke	1385	2	0.0%

Table 1. Gathering Engines in the DOE Project Database Sorted by Frequency

Manufacturer	<i>Model</i>	Air Fuel Ratio	Cycle	Horsepower	Total	% of Total
Ajax	DPC 105	Lean-burn	2-stroke	105	1	0.0%
Ajax	SB 330	Lean-burn	2-stroke	330	1	0.0%
Caterpillar	G 3412 TA	Rich-burn	4-stroke	400	1	0.0%
Caterpillar	G 342 HAHCR	Rich-burn	4-stroke	225	1	0.0%
Caterpillar	G 342 TALCR	Rich-burn	4-stroke	265	1	0.0%
Caterpillar	G 3512 GSI	Rich-burn	4-stroke	520	1	0.0%
Caterpillar	G 3516 LETA	Lean-burn	4-stroke	1170	1	0.0%
Caterpillar	G 3516 SITA	Rich-burn	4-stroke	1085	1	0.0%
Caterpillar	G 3516 TALEHS	Lean-burn	4-stroke	1265	1	0.0%
Caterpillar	G 3518 LE	Lean-burn	4-stroke	630	1	0.0%
Caterpillar	G 3606 LE	Lean-burn	4-stroke	1665	1	0.0%
Caterpillar	G 3606 TA	Rich-burn	4-stroke	1615	1	0.0%
Caterpillar	G 3616	Lean-burn	4-stroke	1200	1	0.0%
Caterpillar	G 3616 TALE	Lean-burn	4-stroke	4705	1	0.0%
Caterpillar	G 379 TA LCR	Rich-burn	4-stroke	415	1	0.0%
Caterpillar	G 398 HCTA	Rich-burn	4-stroke	700	1	0.0%
Clark	HRA8	Lean-burn	2-stroke	800	1	0.0%
Cummins	GTA50G2				1	0.0%
Waukesha	12V-AT27GL	Rich-burn	4-stroke	3065	1	0.0%
Waukesha	F 11 GSI	Rich-burn	4-stroke	60	1	0.0%
Waukesha	L 5108	Lean-burn	4-stroke	1072	1	0.0%

Table 1. Gathering Engines in the DOE Project Database Sorted by Frequency

Manufacturer	<i>Model</i>	Air Fuel Ratio	Cycle	Horsepower	Total	% of Total
Waukesha	L 5108 GL	Lean-burn	4-stroke	1122	1	0.0%
Waukesha	L 5108 GU	Rich-burn	4-stroke	600	1	0.0%
Waukesha	L 5790 GU	Rich-burn	4-stroke	877	1	0.0%
Waukesha	L 5794	Lean-burn	4-stroke	1250	1	0.0%
Waukesha	L 5794 LT	Lean-burn	4-stroke	1354	1	0.0%
Waukesha	L 7042 GNA	Rich-burn	4-stroke	896	1	0.0%
Waukesha	VRG 220	Rich-burn	4-stroke	42	1	0.0%
TOTAL					4729	100.0%

Appendix II

Table 1. 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	~\$5K including necessary data acquisition modules, plus cost to replace sensor if damaged	newly commercial	requires port in exhaust stack	all for monitoring, reliability has not yet been established
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	commercial	installation of sensors and software	used extensively with post-combustion controls
Ion Sense	give information about combustion quality, in-cylinder equivalence ratio, NOX 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

Table 2. Comparison of control technologies.

Control Technology	NOX Impact	Other Impacts	Combustion Impacts	Cost	Availability	Implementation	Technology Compatibility
<p>Pre-combustion Chamber (integral)</p> <p>1 g/bhp-hr range</p> <p>none known</p> <p>improve combustion stability</p> <p>part of retrofit cost</p> <p>commercial by OEM</p> <p>requires new cylinder head, secondary fuel system</p> <p>typically added during low emissions retrofit to very lean engine to maintain superior combustion, A/F ratio controller possible, SCR or oxidation catalyst could be applied (probably not cost-effective)</p>	<p>up to 10% reduction</p> <p>decreased fuel economy, possible CO tradeoff</p>	<p>increased fuel economy, possible CO tradeoff</p>	<p>can only be adjusted a few degrees</p>	<p>very low</p>	<p>commercial</p>	<p>minor adjustment</p>	<p>all</p>
<p>High Energy Ignition System</p> <p>2.5 - 3 g/bhp-hr range</p> <p>none known</p> <p>improve combustion stability</p> <p>part of retrofit cost</p> <p>commercial</p> <p>requires new ignition system, spark plugs</p> <p>typically added during low emissions retrofit to lean engine to maintain superior combustion, A/F ratio controller possible, SCR or oxidation catalyst could be applied (probably not cost-effective)</p>	<p>up to 90% reduction</p>	<p>increased fuel economy, possible CO tradeoff</p>	<p>higher output power, higher efficiency, restricted operation range, risk of unstable combustion</p>	<p>\$500K to \$2 million</p>	<p>commercial</p>	<p>requires significant changes to old equipment and installations of new equipment</p>	<p>requires higher air boost (turbochargers), higher ignition energy (PCC or HEIS), A/F ratio controller possible, SCR or oxidation catalyst could be applied (probably not cost effective)</p>
<p>Lean-burn Combustion with Low-Emissions Retrofit</p>	<p>up to 10% reduction</p>	<p>increased fuel economy, possible CO tradeoff</p>	<p>can only be adjusted a few degrees</p>	<p>very low</p>	<p>commercial</p>	<p>minor adjustment</p>	<p>all</p>
<p>Retard Ignition Timing</p>	<p>up to 10% reduction</p>	<p>increased fuel economy, possible CO tradeoff</p>	<p>can only be adjusted a few degrees</p>	<p>very low</p>	<p>commercial</p>	<p>minor adjustment</p>	<p>all</p>

<p>Geneous Impression</p>	<p>Exhaust Gas Recirculation</p>	<p>Advanced In-cylinder Mixing</p>	<p>Pre-stratified Charge</p>	<p>Pre-combustion Chamber (screw-in)</p>	<p>Control Technology</p>	<p>Pre-combustion Chamber</p>
<p>expected to on lean-burn combustion</p>	<p>expected to be similar to or improve upon lean-burn combustion</p>	<p>30 - 70 % reduction</p>	<p>2 g/bhp-hr range</p>	<p>1 g/bhp-hr range</p>	<p>NOX Impact</p>	<p>2 - 4 g/bhp-hr range</p>
<p>CO tradeoff</p>	<p>possible CO tradeoff</p>	<p>increased fuel economy, possible CO tradeoff</p>	<p>possible CO tradeoff</p>	<p>none known</p>	<p>Other Impacts</p>	<p>none known</p>
<p>expected to on lean-burn combustion</p>	<p>expected to be similar to or improve upon lean-burn combustion</p>	<p>improve combustion stability</p>	<p>power derated by 20%</p>	<p>improve combustion stability</p>	<p>Combustion Impacts</p>	<p>improve combustion stability</p>
<p>development</p>	<p>includes development</p>	<p>less than major changes to air system required for very lean engine operation</p>	<p>cost of changes to air delivery system</p>	<p>part of retrofit cost, lower than integral PCC</p>	<p>Cost</p>	<p>than integral PCC, increased replacement commercially</p>
<p>firm R&D</p>	<p>developing</p>	<p>nearly commercial (retrofits available)</p>	<p>commercial</p>	<p>commercial by OEM and 3rd party</p>	<p>Availability</p>	<p>requires secondary fuel system</p>
<p>significant equipment, difficult to development</p>	<p>requires significant changes to air intake and exhaust</p>	<p>replace fuel delivery system, requires high pressure fuel</p>	<p>requires changes to fresh charge delivery system</p>	<p>requires secondary fuel system, secondary cooling system</p>	<p>Implementation</p>	<p>requires secondary fuel system</p>
<p>on system, ally requires compatible with stion controls (ost-effective)</p>	<p>requires lean-burn engine, PCC or HEIS, not compatible with post-combustion controls due to exhaust temperature requirements</p>	<p>higher air boost to lean engine, SCR, NSCR could be applied (probably not cost-effective)</p>	<p>applicable only to 4-stroke, rich-burn, carbureted engines, compatible with EGR, NSCR could be applied (probably not cost-effective)</p>	<p>typically added during low emissions retrofit to lean engine to maintain superior combustion, A/F ratio controller possible, SCR or oxidation catalyst could be applied (probably not cost effective)</p>	<p>Technology Compatibility</p>	<p>maintain superior combustion, A/F ratio controller possible, SCR or oxidation</p>

Catalysts	Oxydation catalyst	Selective catalytic reduction	Air-to-Fuel Ratio Controller	Control Technology	Control Technology
<p>duction</p>	<p>none</p>	<p>1 mole of NOX is reduced 80-90% by .9 to 1 mole NH3</p>	<p>that of the combustion or post-combustion controls it is used with</p>	<p>NOX Impact</p>	<p>NOX Impact</p>
<p>on-methane, decreases by up to 3%</p>	<p>reduces CO and non-methane HC by 98 - 99%, methane by 60 - 70%</p>	<p>requires storage of NH3, unreacted NH3 can be released</p>	<p>that of the combustion or post-combustion controls it is used with</p>	<p>Other Impacts</p>	<p>Other Impacts</p>
<p>in engine</p>	<p>backpressure on engine</p>	<p>backpressure on engine</p>	<p>that of the combustion or post-combustion controls it is used with</p>	<p>Combustion Impacts</p>	<p>Combustion Impacts</p>
<p>cost of catalyst, increase (including special catalysts)</p>	<p>cost of catalyst, catalyst replacement</p>	<p>cost of catalyst, catalyst replacement, increase operating costs (including reagent supply)</p>	<p>~\$30K range</p>	<p>Cost</p>	<p>Cost</p>
<p>commercial</p>	<p>commercial</p>	<p>commercial</p>	<p>commercial</p>	<p>Availability</p>	<p>Availability</p>
<p>of catalyst, into exhaust</p>	<p>requires addition of catalyst</p>	<p>requires addition of catalyst and ammonia injection to exhaust, storage for ammonia</p>	<p>requires changes to air delivery system</p>	<p>Implementation</p>	<p>Implementation</p>
<p>line, requires compatible combustion</p>	<p>requires excess O2, compatible with lean-burn combustion controls</p>	<p>compatible with combustion controls</p>	<p>could be used to control lean-burn with low emissions retrofit or with catalysts, not affective alone</p>	<p>Technology Compatibility</p>	<p>Technology Compatibility</p>