Report 14: Cost-Effective Reciprocating Engine Emissions Control and Monitoring for E&P Field and Gathering Engines

Technical Progress Report

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Abstract

Continuing work in controlled testing uses a one cylinder Ajax DP-115 (a 13.25 in bore × 16 in stroke, 360 rpm engine) to assess a sequential analysis and evaluation of a series of engine upgrades. As with most of the engines used in the natural gas industry, the Ajax engine is a mature engine with widespread usage throughout the gas gathering industry. The end point is an assessment of these technologies that assigns a cost per unit reduction in NO_X emissions.

Technologies including one pre-combustion chamber, in-cylinder sensors, the means to adjust the air-to-fuel ratio, and modification of the air filter housing have been evaluated in previous reports. Current work focuses on final preparations for testing pre-combustion chambers with different characteristics and using mid-to-high-pressure fuel valves and initial runs of these tests. By using the Ajax DP-115 these tests are completed in a low-cost and efficient manner. The various technologies can be quickly exchanged with different hardware, and it is inexpensive to run the engine.

Progress in moving toward field testing is discussed, and changes to the first planned field test are presented. Although changes have been made to the previous plan, it is expected that several new sites will be selected soon. Field tests will begin in the next quarter.

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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 will take 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 will be reviewed, and priority technologies will be identified for further development. The identified promising technologies will be 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 NO_2, regulations regarding acid deposition and regional haze, and pending air toxics regulations, all of which 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 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 will propose regulations in 2006 for final adoption in 2007 that will address 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. The proposed project will significantly improve the cost-effectiveness of implementing NO_X and formaldehyde controls and monitoring on compressor engines, while characterizing emissions tradeoffs – thus ensuring 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 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:

- Obtain an industry consensus for

  - specific engine types and models on which to focus development efforts,
  - installed cost targets,
  - 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 will sum 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.

Controlled Tests

Controlled tests are conducted on the Ajax DP-115 at Kansas State University to address a series of upgrades intended to improve emissions. The DP-115 is a mature two-stroke cycle lean burn (2SCLB) engine, typical of those found at gathering sites. While many technologies have already been tested, more remain. Progress in controlled testing during this quarter included further preliminary testing on higher-pressure fuel valves and testing further pre-combustion chamber designs.

Much work was focused on finishing preparation for testing higher-pressure fuel valves. Before any testing could be done, it was necessary to provide a steady supply of high pressure (180 psig and 500 psig) natural gas at the NGML. This supply is provided by an Ariel JG/2 compressor. Figure 1 illustrates this compressor package that was installed at the NGML during April. The compressor, which had been part of a natural gas vehicle fueling station, is owned by the city of Manhattan, and was non-functional when it was leased to the NGML for no annual fee. The NGML did substantial work to repair the compressor and upgrade it for use with the Ajax and

Figure 1 Ariel compressor as removed from City site.

higher-pressure fuel valves. Ariel Corporation contributed all parts and service personnel for during the repair process. This work included overhauling the compressor, having the compressor valves rebuilt for different pressures (work provided by Hoerbiger Corporation), changing the internal piping in the compressor to run the gas through the appropriate stages, adding another cooler, and adding automated controls for safety and ease of use.

The installed reconfigured compressor skid packaged is shown in Figure 2. The compressor now provides a 60 psig and 525 psig natural gas stream. The 525 psig gas stream is regulated to 500 psig or 180 psig for use with the higher pressure valves.

When the system was ready in mid-May, the prototype 180 psig valve was tested for functionality and stability for twelve hours. The 500 psig valve was tested for functionality and stability for six hours. Due to the prototype nature of these valves, they were shipped back to the owners after initial testing. However, because it was demonstrated that both valves work well with the test engine and fuel supply provided, similar valves working at 180 psig and 500 psig will be used in a more complete battery of tests that will include emissions data at points in the range 75% of full load to full load, giving

Figure 2. Ariel JG/2 compressor as installed at NGML.

various air-to-fuel ratios, and three ignition timings.

Upon completion of initial tests using the higher pressure valves, the system was prepared for tests using pre-combustion chambers with varying designs. Theoretically, pre-combustion chambers provide sufficient energy to ignite air-fuel mixtures that are too lean to be ignited by typical spark plugs. The pre-combustion chambers tested included a simple ball-and-spring check valve to prevent exhaust from entering the pre-combustion chamber fuel supply and various fuel orifice sizes. Orifices of 0.020" and 0.040" for the Cameron Eco-Jet pre-combustion chamber were tested with this check valve.

The first orifice was 0.020" in diameter. This small diameter orifice greatly limited the engine's range of operation. When fired only with the spark plug in the pre-combustion chamber, the engine was able to run only up to 25% of full load. At a constant pre-combustion chamber fuel-supply pressure, the differential pressure across the orifice stayed relatively constant. This is shown in Figure 3. For a constant upstream pressure, $q = F_{FM}\sqrt{\Delta p}$, where q represents mass flow, F_{FM} is the flow meter coefficient, and Δp is the differential pressure across the orifice plate. Thus, the quantity $\frac{q}{F_{FM}}$, plotted in Figure 3, is proportional to flow. The errors come from uncertainty in the differential pressure, and are propagated according to Bevington [1].

Using the 0.040" orifice, the engine operated throughout its entire range. However, the larger orifice did not function exactly as expected. Figure 4 clearly shows that the pressure in the pre-combustion chamber fuel supply line was greater than that in the line supplying it. This was true regardless of engine speed. As the engine operated at a higher load, the discrepancy became

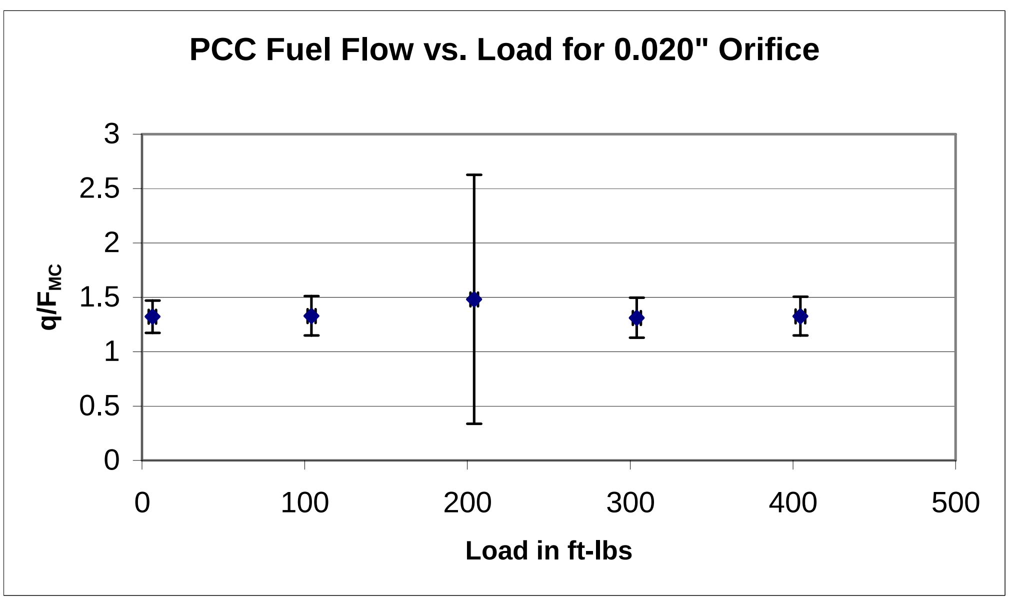

Figure 3. A quantity proportional to flow, $\frac{q}{F_{FM}}$, remains constant as load increases.

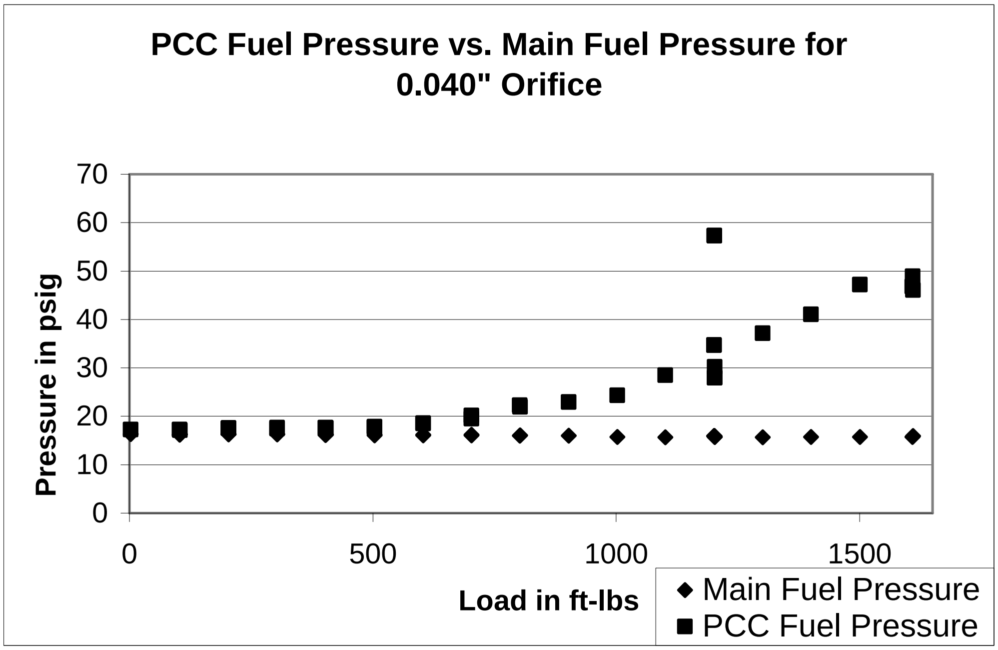

Figure 4. For the 0.040" orifice, the pressure in the PCC fuel line is higher than the pressure of the line supplying it.

larger. For a given load, the pressure actually rose in the pre-combustion chamber fuel line as the needle valve to its supply was closed. This indicates that exhaust gases entered the fuel line of the pre-combustion chamber. The presence of exhaust gases in pre-combustion chamber fuel line implies that the check valve in the pre-combustion chamber was not functioning correctly.

A new, low-lift check valve assembly, shown in Figure 5 and expected to be more effective, will be used with the Cameron Eco-Jet during further tests. Additionally, five orifices in sizes ranging from 0.020" to 0.040" will be tested with the Eco-Jet. Finally, two further pre-combustion chambers by Diesel Supply Company will be tested. While the basic design is the same as the first pre-combustion chamber tested, the orifice sizes are different. The smaller orifice is

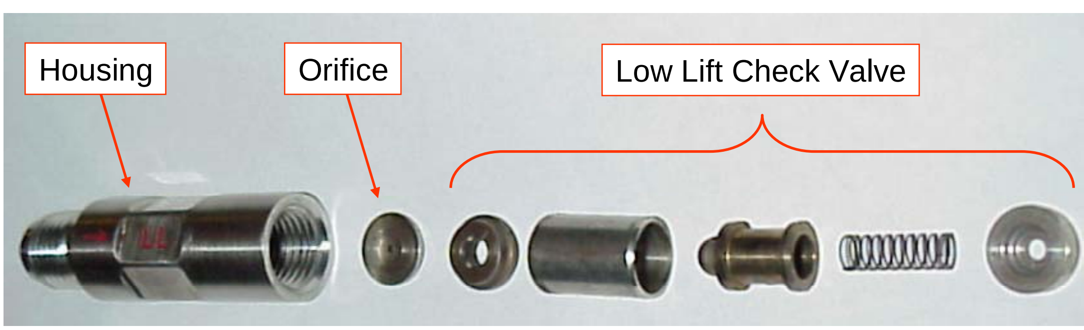

Figure 5. The low-lift check valve for Eco-Jet will be used in further testing. It is expected to be more effective than the simpler ball-and-spring style check valve.

expected to give a very lean equivalence ratio in the pre-combustion chamber, and the larger orifice is expected to create a stoichiometric equivalence ratio in the pre-combustion chamber.

Remote Monitoring and Control

Progress toward field testing using remote monitoring and control continues. It has been determined that the site previously selected for the first field tests on four-stroke cycle rich-burn (4SCRB) engines is not suitable. The process for selecting a new site, as well as additional sites will begin in July with a presentation to various interested parties, namely BP. Once sites have been selected, remaining field tests will be conducted as final control solutions are selected for each type of engine and the engine becomes available.

The CAT 342 (150-200 bhp) in southern California was deemed unsuitable due to the very challenging emissions profile. Although previous testing by AETC had appeared promising, the solution presented in the last quarterly report and reviewed below does not appear sufficient to achieve NO_X emissions below 1 g/bhp-hr. While this solution seems to remain viable down to about 3 g NO_X/bhp-hr, at the lower setpoint of 0.15 g NO_X/bhp-hr the NO_X levels swing to an out-of-control condition with ambient temperature or humidity changes. In an out-of-control condition, emissions can be much higher than they are for good control at the higher setpoint. It may be possible to adjust the controller algorithms and oxygen sensor placement to improve the limits to which good control is possible. However, this is not feasible at the southern California site. The owner and operator of the new first test site for the 4SCRB engine technologies, as well as the state regulatory agencies, will be amenable to developing a control scheme that may undergo changes during the beginning of the testing.

The goals for four-stroke cycle rich-burn (4SCRB) engines remain basically the same: to monitor the alarm status of the air-to-fuel ratio controllers and use full-authority fuel control. As previously described, 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 an Altronic controller, which will control the air-to-fuel ratio to a programmed setpoint by determining the opening of fuel valves. It remains essential that the controller can achieve the NO_X setpoint over the engine's entire operating range and that the lambda sensor stays in compliance. To ensure full-authority control, the controller and valve will be examined to ensure that the needed air-to-fuel ratios can be achieved under all likely conditions. The data acquisition system used to run the controller will be connected to a network to provide remote monitoring.

Ensuring control of air-to-fuel ratios under all conditions could be more challenging than initially expected. To attain such control, more sophisticated algorithms for the controller will need to be developed. In current incarnations, signals from lambda sensors before and after the NSCR catalyst may give conflicting signals. These conflicting signals cause the control algorithm to go out of range. <u>Significant effort may be necessary to determine the exact cause and develop a improved control strategy</u>. These difficulties make it even more critical to use an ion sense signal to monitor combustion performance and complement the oxygen sensor.

The ion sense signal is an electrical current created by the electrodynamic response of the chemical ions in the combustion chamber to the bias voltage across the spark plug gap. The signal has three distinct phases. In the ignition phase, the current is a result of creating a spark at the spark plug, so it has an oscillatory, decaying nature and reversed polarity. In the flame-front phase, ions are produced by the chemical reaction at the flame front. While this signal has not yet been correlated to species data, it potentially holds valuable information. Finally, during the post-flame phase, ions are created through thermal ionization. Thus, more ions exist for higher temperatures. Many of the ions come from NO_X formation, so the signal can be correlated directly with in-cylinder NO_X concentration and cylinder pressure. This means an ion current gives information which allows the operator or controller to detect misfire, detonation, instability, and relative cylinder balance [2]. Additionally, the signal level is related to the air-to-fuel ratio in the combustion chamber, so it will provide a reliable check for the lambda sensor.

Conclusions and Future Work

Although much remains to be done, considerable progress has been made in the last quarter. Controlled tests are continuing, and the next tests to be pursued will be conducted soon. Plans for beginning the first field tests to assess solutions for remote monitoring and control have been adapted as necessary, and a number of engine sites will be selected in the next quarter. Some field tests are expected to begin within the next quarter.

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