Report 12: Cost-Effective Reciprocating Engine Emissions Control and Monitoring for E&P Field and Gathering Engines

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Abstract

This quarterly report discusses continuing work in the testing phase of the project that evaluates emission control technologies applied to a two-stroke cycle natural gas-fueled engine. In this phase, a one cylinder Ajax DP-115 (a 13.25 in bore × 16 in stroke, 360 rpm engine) is used 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.

This report describes potential emission reduction technologies, some of which have already been tested, and describes progress toward completing remaining tests to evaluate further synergies between some of the more promising technologies. While the end-goal is a closed-loop control system coupled with a low cost NO_X retrofit package, additional work remains.

Technologies including pre-combustion chambers, 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 preparing the test cell for tests using a 180 psig fuel valve. 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.

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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, during Phase 2 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, with the majority of this increase expected from three primary areas: Offshore Gulf of Mexico, Rocky Mountains, and Canadian imports. Mature basins in the Southwest and Mid-Continent areas also will contribute to the total domestic supply, and maximizing their output will be necessary to meet the aggressive 30 Tcf gas demand target. Oil and gas production operations in the United States face a wide variety of environmental regulations that are imposed by multiple, sometimes overlapping, jurisdictions. In particular, onshore production must grapple with existing and emerging regulations that address National Ambient Air Quality Standards for NO_2, ozone, fine particulates, acid deposition and regional haze, while pending air toxics regulations will address formaldehyde emissions from compressor engines. The scope of these regulations includes the wellhead and field gathering reciprocating engine-driven compressor 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 the total pollutant loading. Reciprocating engines have been identified as a meaningful source category. These engines are used to produce electricity for a leasehold, compress and re-inject natural gas for increased oil production, or compress natural gas so that it can be delivered to local gathering systems that feed ultimately into gas transmission pipelines.

At present, the region with the greatest confluence of emissions concerns is the Rocky Mountain and Intermountain West area. In these regions, significant concerns about regional haze control accelerated the implementation of NO_X and fine particulate regulations that are only pending in many other producing areas. However, the 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. 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;

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; and

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; or

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.

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 $\mathbf{NO_X}$ and formaldehyde controls and monitoring on compressor engines, 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 the:

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 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.



Figure 3. The NGML one-cylinder Ajax engine test bed during installation.

Ajax Two-Stroke Cycle Engine

While the overall project includes rich-burn and lean-burn four stroke cycle (4SC) engines, and lean-burn 2SC engines, this report focuses on the lean-burn two-stroke cycle engines used in the E&P industry. This engine classification is comprised almost exclusively of the Ajax engine. The Ajax engine, which is still in production today, is a horizontal reciprocating engine. The integral engine-compressor comes with 1, 2, 3 or 4 power cylinders depending on the power requirements.

Figure 3 shows the one-cylinder Ajax DP-115 engine that is in use for this project and report. The DP-115 has a bore of 13.25 inches and a stroke of 16 inches. Figure 4 shows the inside of the cylinder. Of note is that the cylinder is scavenged by intake and exhaust ports. The 2SC engine must have a forced air flow rate through the engine. In many 2SC engines, this forced air flow is created by crank-case compression, pump scavenging, or turbocharging. The Ajax series of engines uses an air chest that surrounds the lower portion of the cylinder and a set of reed valves in the air intake system.

The Ajax Engine Cycle

As the piston moves toward top dead center during the compression portion of the cycle, air is sucked in through the reed valves. The typical reed valve assembly is shown in Figure 4. The reed valve consists of thin metal plates that are spring loaded to maintain contact with the reed valve seat. As the pressure decreases in the air chest, the reed valve metal plates are pulled down and air flows through the reed valves into the air chest. As the piston begins its power stroke, traveling from top dead center toward bottom dead center, the underside of the piston compresses the air in the air chest. As the air pressure increases, the



Figure 4. Ajax engine reed valve assembly.

reed valve metal plates seal against the reed valve seat to prevent air from escaping through the reed valves. The air pressure in the air chest reaches about 10 psig when the piston uncovers the top portion of the exhaust ports. At this point, exhaust blowdown occurs, and essentially depressurizes the cylinder. As the piston moves further toward bottom dead center, the intake ports become uncovered and the air-chest air, pressurized to 10 psig, flows into the cylinder to loop scavenge the exhaust products and create a fresh air charge for the next engine cycle. As the piston then moves from bottom dead center toward top dead center, the intake and exhaust ports are covered, and the combustion air that remains in the cylinder is compressed. At some point prior to top dead center, the gas injection valve in the center of the head, shown in Figure 5, admits gas into the cylinder. Since the Ajax is designed to operate with fuel pressures less than 30 psig, the gas must be admitted before the cylinder pressure reaches 30 psig. At about 7° before top dead center (BTDC), the two spark plugs fire to ignite the mixture inside the cylinder.

The One-Cylinder Engine Test Bed

The Ajax engine essentially represents a one-cylinder engine test bed that is similar in many ways to all 2SC engines used in the E&P industry. The rated speed of the test engine is 360 rpm and the rated torque is 1,605 lb-ft. The key difference is that the air flow rate through the Ajax engine cannot be easily increased because the cylinder uses a pressurized plenum to scavenge the cylinder. Since the accepted methodology to reduce NO_X emissions in a 2SC engine is to further lean the in-cylinder trapped charge, one way to accomplish this on the Ajax is to decrease the fuel flow rate into the engine. By keeping the air flow rate the same, the equivalence ratio necessarily decreases with decreasing fuel flow rate. A second way is to increase the engine speed.

The test engine was chosen because it represents a large percentage of the type of Ajax engines currently used in the E&P industry. This particular engine was manufactured in 1966 and did not contain the low emission combustion technologies that Cooper-Ajax includes on new engines. The primary differences are:

The test engine contained an oil-bath air filter and current production engines ship with a paper air filter;

Low emissions Ajax engines ship with a pre-combustion chamber head, while the test engine contains an open-chamber head.; and

The test engine is fitted with a mechanical governor and the new engine ships with an electronic governor.

The series of tests for this portion of the project were designed to assess the emission reduction potential of each upgrade, as well as assess any improvement in fuel consumption.

Engine Test Matrix

The test matrix was created during a research team meeting. Prior to this meeting, several emission reduction technologies were reviewed and ranked in order of emission reduction cost-effectiveness. The final test matrix is shown in Table 1. The left column in the table lists four variables that can be modified with a particular upgrade technology. The row along the top of the table lists the as-found condition, oil bath, along with four engine modifications that can

Table 1. Ajax engine test matrix (test results from shaded boxes were previously reported).

Variables	Builds				
	Vary Air Filter		With Paper Air Filter		
	Oil Bath	Paper Filter	Screw in PCC	Scavenge Port	Fuel Valve 180 psig
Ignition Timing	No	Yes	Yes	Yes	Yes
Ignition Energy	No	Yes	Yes	Yes	Yes
Air-to-Fuel Ratio (load)	Yes	Yes	Yes	Yes	Yes
Exhaust Gas Recirculation	No	Yes	Yes	Yes	Yes

potentially lead to low-cost emissions reduction. The column to the right of the oil bath is the build that replaces the oil bath air filter with the paper air filter. Reading down this column, the series of tests vary the ignition timing, the ignition energy, air-to-fuel ratio, and the amount of exhaust gas recirculation that is pushed into the trapped charge. As stated above, the air-to-fuel ratio is varied by varying the fuel that is admitted to the trapped charge. The three columns to the right of the paper filter column are additional engine modifications to be tested in conjunction with the paper air filter (i.e., the paper filter is not removed for these tests).

The shaded tests have been completed, with results reported previously. The remaining tests are ongoing and will be completed in the next few months.

Research Progress

Much of the progress in this quarter has been focused on upgrading the test cell for the next set of tests, which will use a 180 psig fuel valve. As a preliminary measure, a valve has been installed, and the engine operated. Testing the valve and engine before measuring emissions data, will enable technical problems to be solved before actual tests are run. This will ensure the most accurate data possible. As is necessary for the new fuel valve, a filter has been installed in the fuel line.

In order to effectively measure fuel flow to the engine at the higher pressure, a flow meter that is more sophisticated than that used for previous tests will be necessary. After careful consideration, the Micro Motion ELITE sensor, a Coriolis-style, mass flow meter has been selected. Micro Motion, a division of Emerson Process Management, donated this sensor, and the installation process is underway.

A compressor to bring fuel at the standard municipal pipeline pressure of around 30 psig to the required 180 psig is also being acquired. In the meantime, the system has been tested using compressed natural gas at 3,000 psig, which is then regulated down to 180 psig. When the gas decompresses, it becomes very cold, and does not accurately simulate typical E&P conditions. To address this situation, a fuel-line heating system has been devised and installed, as shown in Figure 5. The surface temperature of the fuel line is measured with a type-J thermocouple a few feet in front of the fuel-valve. Power proportional to the difference in desired temperature and the measured temperature is delivered to a heating tape in contact with the fuel line before the temperature sensor. Using this system, the fuel line surface temperature at the measurement point is maintained between 50°F and 60°F.



Figure 5. High-pressure fuel line with heating system and insulation removed.

Conclusions and Future Work

Much progress has been made toward running the remaining tests. The tests using the 180 psig fuel valve are expected to begin early in the upcoming quarter. Tests comparing different orifices for the pre-combustion chamber are also expected to occur soon. The orifice, along with a mechanical check valve, regulates the flow of fuel into the chamber. Two additional orifices can be inserted into the screw-in pre-combustion chamber for comparison to the original. Tests comparing different scavenging port designs, ignition energy, and exhaust gas recirculation remain priorities, as well.

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