

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

Technical Progress Report

DOE Award DE-FC26-02NT15464

Work completed: September 15, 2002 – March 31, 2003

Author

Kirby S. Chapman, Ph.D., Kansas State University

Submitted by

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

Significant Assistance Provided by

Coerr Environmental Corporation
400 Silver Cedar Court, Suite 240
Chapel Hill, NC 27514

Collaborative Research Associates, Inc.
1300 Deep Run Road
Naperville, IL 60540

Energy and Environmental Analysis
1655 N Fort Meyer Drive, Suite 60
Arlington, VA 22209

December, 2003

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

During the first reporting period, the project team focused on establishing the industry advisory committee and gathering information and data from the advisory committee. The first meeting was held in Houston, Texas on March 28, 2003. Key items from this meeting clearly showed that the industry feels the easiest path to emissions compliance is to transform the engine fleet into four-stroke cycle rich burn engines with exhaust catalysts. This strategy, however, does not provide the benefit of improving engine performance and makes it extremely difficult to monitor engines for emissions compliance.

The project team concluded that many technologies that have been developed for the natural gas pipeline-sized engines can be retrofitted to the E&P engine fleet. These technologies will have the added benefit of monitoring specific engine parameters that can lead to improved engine performance as well as reduced engine emissions.

Table of Contents

Disclaimer	ii
Abstract	iii
Table of Contents	iv
Introduction	1
Research Progress	1
Task 1: Industry Steering Committee	1
Further Work Planned	4
Task 2: Develop a Database of Existing E&P Engine Inventory	4
Task 3: Assess Control and Monitoring Technologies	4
Task 4: Determine Technology and Market Gaps	5
Task 5: Conduct Controlled Tests to Evaluate Promising Technologies	5
Task 6: Determine on-engine control system and sensor requirements for remote emissions monitoring	5
Conclusions	5
Appendix A: Minutes from the First Industry Steering Committee Meeting	7

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 their 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.

Research Progress

Primary effort during this reporting period was focused on Task 1, which was to create an industry-based steering committee that will ensure that the project ultimately meets the needs of the E&P industry. This task provided the research team with the direction and guidance needed to pursue Tasks 2 and 3, the outcomes of which will be more fully reported in future reporting periods.

Task 1: Industry steering committee

The intent of the industry steering committee is to provide ongoing direct industry feedback on program direction, goals, promising control strategies, practical design and operational considerations in the field, and general coordination with other industry initiatives and recent related experiences.

The project team established the committee from a group 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 Benge, Universal Compression

Jim LaBounta, Western Gas Resources

Jack Kopfman, Williams

Rob Rice, Hanover Compression

Don Duttlinger, PTTC

Terry Twyman, API (Ad Hoc member)

The first advisory committee meeting was convened in Houston, Texas on March 28, 2003 at the Bush Intercontinental Airport Marriott Hotel. In attendance at this meeting were Rob Rice, Preston Batula, and Diane Houston (Hanover), Margaret Walther (Coerr), Robert Akins, Steve Bowlin, Gary Perkins, and Douglas Jordan (El Paso Field Services), James McCarthy (Coerr), Mike Whelan (Collaborative Research), Kirby Chapman (K-State), Greg Beshouri (AETC), and Paul Bautista (EEA).

The purpose of this meeting was to brief the committee members on the specific goal and objectives of the project, and develop a working relationship between the research team and committee members. While the specific minutes from this meeting are in the appendix of this report, the key outcomes from the meeting were:

- The engine database will focus more on engine frequency distribution and less on a full inventory. The distribution may vary based on the age of the field, region, etc. If engine popularity differs by region, consideration of region-specific engine distribution will be important since technology for engines in declining fields will be of less interest than technology for engines in growth areas. Committee members agreed to contact Walther regarding engine lists available for inclusion in the database.
- The user community felt that oftentimes, the engine manufacturers give incredibly low guarantees that are extremely difficult to achieve in normal operation. This may cause problems with rule-writing in the future months/years. Also, the engines need to be loaded 80-100% to even consider meeting these guarantees.
- Some committee members believe that remote monitoring is a necessity. These engines are widely displaced geographically and it is not practical or cost effective to expect manual monitoring of these engines. Hence, some sort of telemetry system needs to be in place. Otherwise, the work force necessary to maintain the engines is too large.
- Hanover estimates that in the U.S., their fleet numbers about 6,000 with an average bhp rating of 400 bhp. The engines are on average about 500 bhp at the well head, and 200 bhp in production. Engines have about a 30 year life time.
- Interestingly, fuel consumption was not always a “visible” loss. This is because the operators oftentimes do not pay for the fuel that is consumed (the engines are a parasite on the gathering line). However, fuel consumption is expected to become more of an issue as supplies tighten and demand increases.

- Many of the operating companies have recognized that green house gas (GHG) emissions will become more of an issue in the coming years. Hence, lowering fuel consumption is a direct way to reduce GHG emissions. Some companies believe that lowering the GHG emissions will provide the opportunity to actually create a GHG emissions market for buying and selling credits.
- Some committee members felt four-stroke rich burn engines would begin to proliferate, since that is the only way to achieve 0.15 g/BHP-hr. These engines use a catalyst to achieve this NO_x level. They prefer lean-burn engines due to efficiency but they have not found a way to easily and inexpensively satisfy the lowest emissions limits. However, there are not many regions that require 0.15 NO_x yet. Most regions use 1.0 NO_x as a floor, which may be a viable target for lean burn engines. Packagers are concerned about buying 1.0 NO_x engines, only to find that they cannot lease them in 0.15 NO_x regions. Hence, they are considering buying all 0.15 NO_x engines. This means that fleet engines will become more and more dominated by rich-burn engines to maintain fleet flexibility.
- As the gas field plays out, load drops followed by a drop in speed. Then the four-stroke cycle (4SC) lean burn engines will not generate the air and have problems on older wellheads typically running at 50% load. The rate of decay is low, so NSCR engines tend to stay within the controller's range.
- The point was made that once the 8-hour O₃ standard is implemented, the number of non-attainment areas will sky rocket, with many of the affected counties distant from urban areas typically affected by the 1-hour standard. In addition, regional haze and fine particulate concerns in the western U.S. will result in ongoing issues for NO_x as a particulate precursor (nitrate formation).
- Current technologies that are installed on these engines:
 - Air-to-fuel ratio controllers. For the most part, these are low cost controllers. Altronics supplies the EPC 200, and Waukesha supplies the TCM-2 for their engines. The TCM-2 controls exhaust and air flow from the engine/turbocharger. The TCM-2 costs approximately \$30,000. Gas quality will impact the ability of the controller to control the engine.
 - Rich burn NSCR. There needs to be a substantial cost reduction to make these pervasive within the E&P industry. Lower cost precious metals and substrates and improved resistance to high temperatures are necessary. Monitoring systems must have other benefits, such as performance enhancements. The operators do not want to have to pay to only monitor emissions.
 - Lower cost pre-combustion chamber (PCC) and micro-PCC retrofits and better scavenging efficiency. Looking for cost of three-way catalyst and controller for rich burn. On lean burn need controller and oxidation catalyst. Cost should be in the \$20K-50K.

- Substantial discussion revolved around continuous emissions monitoring systems (CEMS), and parametric emissions monitoring systems (PEMS). CEMS are basically stack monitors, while PEMS look at certain parameters that are relatively easy and inexpensive to measure. These parameters are then related, through engineering fundamentals, to NO_x emissions. The benefit of a PEMS is that it not only provides the emission monitoring feature, but also monitors other parameters in the engine that can be used to diagnose or trouble shoot problems with the engine. The PEMS would dovetail in nicely with a remote monitoring system. **If monitoring technology can improve performance and reduce maintenance cost, then it might be attractive.** Generally accepted the concept that emissions would not be measured directly but rather inferred, i.e. if engine is working correct then emissions will be good.

The key outcome from the meeting was that the E&P industry perceives 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 created by the catalyst.

With this background and direction, the team is prepared to focus on Tasks 2 and 3.

Further Work Planned

During the next quarter, the research team will direct most of its effort on Task 2, which will lay the groundwork for Tasks 3 and 4. Upon completion of Task 2, the research team will shift their effort to the identification of control technologies and market gaps.

Task 2: Develop a database of existing E&P engine inventory

Rather than develop a database of the entire inventory of E&P engines, the suggestion from the advisory committee was to sample the current fleet and then characterize the makes and models that are used in the E&P industry. This information would then be used to prioritize the work in Tasks 3 and 4. Task 2 will be the focus of efforts during the second quarter of the project, which is from April 1, 2003 through June 30, 2003.

Task 3: Assess control and monitoring technologies

In addition to developing a database of E&P engine characteristics, the industry committee assisted the research team with: 1) the identification of the control technologies that are installed on these engines; and 2) the determination of important attributes needed for control and monitoring technologies. For example, the importance of remote monitoring was mentioned by a number of committee members. Since these engines are geographically diverse, considerable money could be saved with remote monitoring, which would make for an attractive investment. This insight, in conjunction with the developed database, will provide a good starting point for the identification and assessment of commercial and emerging control and monitoring technologies. Work will continue on this task during the third quarter of 2003.

Task 4: Determine technology and market gaps

This task will use the emissions control approaches identified in Task 3.0 to determine the practical targets for the magnitude of emissions reduction in E&P engines. Once the reduction magnitudes are determined, each will be ranked by how applicable it is to the specific inventory of field engines, its expected cost of implementation, and the overall emissions reduction that can be reasonably anticipated from further development and commercialization of the technology.

The second portion of this task will compare the expected emissions reduction performance to the current and expected emissions permitting requirements facing the E&P industry. Doing so will identify the high-impact control technologies that are expected to be widely utilized by the E&P industry, and which should be targeted either for immediate testing, or require more fundamental component development.

This work will be performed during the third quarter of 2003, in parallel with Task 3, and during the fourth quarter of 2003. It is expected that work will center on three major areas: 1) engine controls; 2) ignition systems; and 3) exhaust gas treatment options.

Task 5: Conduct controlled tests to evaluate promising technologies

The most promising technologies identified in Tasks 3 and 4 will be tested under controlled conditions on an Ajax engine, which is in very wide use in E&P operations. The tests will most undoubtedly be conducted at Ricardo, Inc. in Burr Ridge, IL. Ricardo operates a set of state-of-the-art, fully instrumented test cells that can accommodate engines up to 1,000 HP. Up to 160 hours of test time at Ricardo are planned to conduct preliminary performance testing of the array of promising technologies identified in Task 3.

Assuming that an engine can be located, the tests will be conducted during the first quarter of 2004.

Task 6: Determine on-engine control system and sensor requirements for remote emissions monitoring

This task will identify the necessary sensors, software, and hardware to provide remote engine emissions and performance monitoring. The results from Task 3.1 will be used to determine the scope and content of a monitoring system. The project team has expertise in this area, and has actually developed and implemented remote sensing technologies for pipeline engines for what is arguably the most stringent real-time emissions monitoring program in the world (California's RECLAIM program).

Conclusions

The primary conclusion drawn from the work that was completed during the first quarter are:

- The engines that make up the E&P industry vary widely in make and model. The most dominant four-stroke cycle engines are from Caterpillar and Waukesha while the most dominant two-stroke cycle engine is the Cooper Ajax.
- Without intervention or the development of other options, the industry is poised to transform the horsepower into four-stroke rich-burn engines, and then use catalysts to

control emissions. This option, however, does not provide additional ability to monitor and control the engine, and in fact is a scenario that has not been embraced in the natural gas pipeline industry.

The information gathered from the industry participants clearly shows the necessity of this project. For the most part, the industry perception is that the easiest path (and possibly the only path) to emissions compliance is to transform the fleet into four-stroke rich burn engines with exhaust catalysts. However, this deteriorates engine performance and is extremely, if not impossible, to monitor the emissions from these engines.

Appendix A: Minutes from the First Industry Steering Committee Meeting

Steering Committee Meeting

Houston, Texas IAH Marriott, March 28, 2003

Attendees: Rob Rice, Preston Batula, and Diane Houston (Hanover), Margaret Walther (Coerr), Robert Akins, Steve Bowlin, Gary Perkins, and Douglas Jordan (El Paso field Services), James McCarthy (Coerr), Mike Whelan (Collaborative Research), Kirby Chapman (K-State), Greg Beshouri (AETC), Paul Bautista (EEA).

Chapman and Whelan provided background information on the DOE E&P project, specifically covering the scope and objectives of the project. Whelan provided the steering committee members with the tasks and scope of what was expected of the steering committee. The material presented by Chapman and Whelan will be available on the NGML web site so that the committee members can download the information. Mike emphasized that we were looking predominately at retrofit technologies.

From a definition perspective, E&P was targeted to include wellhead, gathering, processing, and up to the interstate transmission system.

Walther and McCarthy covered the progress and needs to develop the engine database. McCarthy pointed out that this really was not a database, but instead was a frequency spectrum. The purpose of the database is to determine which engines are in high use so that the research project tasks can be focused accordingly. The key items that need to be in the database are:

- Make and model
- Cycle
- Rated load and speed
- NA/T/TA
- Rich/lean
- Application

Database will focus more on engine frequency distribution and less on a full inventory. The distribution may vary based on age of field, region, etc. If engine popularity differs by region, consideration of region-specific engine distribution will be important since technology for engines in declining fields will be of less interest than technology for engines in growth areas. Committee members will contact Walther regarding engine lists available for inclusion in the database.

Chapman announced that he had a conversation with Reid Smith of BP prior to the meeting. Smith plans to participate in the project, but was not able to attend this particular meeting. Reid pointed out that they have a lot of engines that operate at part load, averaging maybe

50% load. This is because the reservoirs continue to lose capacity, and hence the compression power is less due to lower gas flow. Smith also pointed out that there are some engines that are “rebuilt” of automotive engines where some of the cylinders are used for power and the remaining cylinders used for compression. He had found that these retrofit engines were not very clean, though.

The three primary geographic locations that need attention are Wyoming, East Texas, and New Mexico (California notwithstanding).

There is a pending EPA rule that actually certifies certain equipment. This certification is for non-stationary engines, but may be important for engines in E&P that are portable / frequently moved.

Oftentimes, the manufacturers give incredibly low guarantees that are extremely difficult to achieve in normal operation. This may cause problems with rule-writing in the future months/years. Also, the engines need to be loaded 80-100% to even consider meeting these guarantees.

Some committee members believe that remote monitoring is a necessity. These engines are spread out all over the place, so some sort of telemetry system needs to be in place. Otherwise, the work force necessary to maintain the engines is too large.

Hanover estimates that in the U.S., their fleet numbers about 6,000 with an average hp rating of 400 hp. The engines are on average about 500 bhp at the well head, and 200 bhp in production. Engines have about a 30 year life time.

Fuel consumption is not always a “visible” loss. This is because the operators oftentimes do not pay for the fuel that is consumed (the engines are a parasite on the gathering line). However, fuel consumption is expected to become more of an issue.

Many of the operating companies have recognized that green house gas (GHG) emissions will become more of an issue in the coming years. Hence, lowering fuel consumption is a direct way to reduce GHG emissions.

We discussed different categories of engines that should be targeted for this project. These are:

1. Engine Category (i.e. gross A/F, mixing type, cycle)
 - a. Rich Burn carbureted 4SC (NA, T, and TA)
 - b. Lean Burn carbureted 4SC (NA, T, and TA)
 - c. Smaller Lean burn direct injection 2SC (i.e. Ajax)
 - d. Lean Burn port injected 4SC (NA, T, and TA of Superior G series)
2. Remediation Technology
 - a. Lean out/PCC
 - b. Enhanced mixing

- c. NSCR
 - d. HCCI or micro-pilot
3. Emissions Target
- a. Severe Non attainment (0.15 g/BHP-HR NO_x)
 - b. Non attainment (1-2 g/BHP-HR NO_x)
 - c. Attaining (???)

Some committee members felt four-stroke rich burn engines would begin to proliferate, since that is the only way to achieve 0.15 g/BHP-hr. These engines use a catalyst to achieve this NO_x level. They would really like lean engines due to efficiency but can not easily satisfy the lowest emissions limits. However, there are not many regions that require 0.15 NO_x yet. Most regions use 1.0 NO_x as a floor, which may be a viable target for lean burn engines.

With regard to monitoring, California requires CAM down to 100 hp, 500-2000 hp requires fuel monitoring, and above >2000 hp daily CEMS/PEMS.

Caterpillar is doing significant research that should be reviewed and summarized.

Maybe the best way to illustrate this is with a set of matrices (one for each engine type). An illustrative example is (suggested by Paul Bautista): *Four-Cycle Carbureted Rich Burn*

Control Technology	OEM new engine guarantee	Retrofit permit limit
Retard ignition timing	n.a	2-10 g
A/F controller + NSCR	0.15 g	0.15 g
Etc.		

- Meets attainment levels
- Meets moderate non-attainment levels
- Meets serious non-attainment levels
- Meets severe non-attainment levels
- Meets extreme non-attainment levels

This is just a suggestion to easily identify those technologies that have most widespread applicability on the basis of engine type and emissions reduction capability. Once those are identified they can be characterized with regard to providers, cost, performance, experience, etc. At a minimum, such a matrix will qualitatively identify the known or expected impact of the NO_x control technology on other pollutants such as CO, formaldehyde, and VOCs.

Hanover is concerned about buying 1.0 NO_x engines, only to find that they cannot lease them in 0.15 NO_x regions. Hence, they are considering buying all 0.15 NO_x engines. Fleet engines will tend to be rich burn to maintain fleet flexibility. There are 264 non attainment counties, not serious or extreme. Expect controls on smaller and smaller engines. No conversion of lean

to rich, and not much current interest in 0.15 g/Bhp-hr for a lean burn engine. As the gas field plays out, load drops are followed by a drop in speed. Then the 4SC lean burn will not generate the air and have problems on older wellheads typically running at 50% load. The rate of decay is low, so NSCR engines tend to stay within the controller's range.

If an engine is moved to a new site, or an engine is replaced at a current site, this can trigger NSR and then BACT.

Point was made that once the 8-hour O₃ standard is implemented, the number of non-attainment areas will sky rocket, with many of the affected counties distant from urban areas typically affected by the 1-hour standard. In addition, regional haze and fine particulate concerns in the western U.S. will result in ongoing issues for NO_x as a particulate precursor (nitrate formation).

The typical targets are:

0.15 NO _x	0.6 CO	Severe non-attainment
1.0 NO _x	-- CO	Wyoming
2.0 NO _x	3 CO	Other places

EEA maintains a database with links to state requirements for DG emissions that may help in clearing up the state by state requirements.

Operating application determines extent of cycling, variable speed and part load operation. This is an extra dimension that may be good to have but not necessary for the project.

Ajax has modified their engines (probably new engines) so that the NO_x emissions are less than 1. Supposedly these are substantially less than 1. Paul Bautista will investigate this.

Current technologies that are installed on these engines:

- Air-to-fuel ratio controllers. For the most part, these are low cost controllers. Altronics supplies the EPC 200, and Waukesha supplies the TCM-2 for their engines. The TCM-2 controls exhaust and air flow from the engine/turbocharger. The TCM-2 runs in the \$30,000 range. Paul will investigate these technologies. Gas quality will impact the ability of the controller to control the engine.
- Rich burn NSCR. work on monitoring. Cost reduction. Lower cost precious metals and substrates. Better resistance to high temps. Want to collect data to calculate performance. Any monitoring must have other benefits. Do not want to measure emissions only.

- Lower cost PCC and micro-PCC retrofits and better scavenging efficiency. Looking for cost of three-way catalyst and controller for rich burn. On lean burn need controller and oxidation catalyst. Talking ~\$20k-50k.
- For 2SC lean burn, maybe ~100 psi injection. For larger engines, more like 400 or 500 psi. In general little engines will be lower.

Substantial discussion revolved around continuous emissions monitoring systems (CEMS), and parametric emissions monitoring systems (PEMS). CEMS are basically stack monitors, while PEMS look at certain parameters that are relatively easy and inexpensive to measure. These parameters are then related, through engineering fundamentals, to NO_x emissions. The benefit of a PEMS is that it not only provides the emission monitoring feature, but also monitors other parameters in the engine that can be used to diagnose or trouble shoot problems with the engine. The PEMS would dovetail in nicely with a remote monitoring system. **If monitoring technology can improve performance and reduce maintenance cost, then it might be attractive.** Generally accepted the concept that emissions would not be measured directly but rather inferred (i.e., if engine is correctly working then emissions will be good).

From Paul Bautista: Technologies we have identified to date include:

- Retard ignition timing
- High energy ignition
- Pre-combustion chambers
 - Micro pre-combustion chamber
 - Screw-In pre-combustion chamber
 - Jet Cells
- Pre-stratified charge
- Enhanced missing
 - High pressure injection
 - Supersonic fuel injection
- NSCR
- Oxidation catalysts