Final Report

2006 Update on a Pilot Project to Assess the Effectiveness of an Emission Control System for Gas Compressor Engines in Northeast Texas

Prepared for

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1. INTRODUCTION

In 2004, Northeast Texas Air Care (NETAC) commissioned a pilot project to demonstrate the effectiveness of available technology in reducing nitrogen oxide (NOx) emissions from compressor engines used in gas production operations. This pilot project has succeeded in retrofitting five gas compressor engines with controls that reduced NOx emissions from those engines by greater than 90 percent. The positive conclusion of this project has resulted from the cooperation of local stakeholders, the selection of a highly effective control technology and carefully planned and executed emissions testing procedures. This report documents the design, implementation and results of the compressor retrofit pilot project.

In 2006, NETAC conducted additional longevity testing of previously retrofitted engines, and retrofitted more engines. This report provides an update on two gas compressor engines that were retrofitted in 2005 and includes tests of two additional gas compressor engines that were retrofitted in 2006. Results of the 2006 tests are found in Chapter 5 of this report, and summarized in the Introduction, below.

Background

Significant emission reductions implemented over the past few years through NETAC programs have allowed the NETAC area to be designated by EPA as an ozone attainment area. However, the margin of safety between monitored levels and the standard is small. On December 20, 2002 local governments in Northeast Texas (Gregg, Harrison, Rusk, Smith, and Upshur counties) entered into an Early Action Compact (EAC) with the U.S. Environmental Protection Agency (EPA) and the Texas Commission on Environmental Quality (TCEQ). The purpose of the EAC is to develop and implement a Clean Air Action Plan (CAAP) that will reduce ground level ozone concentrations throughout the five county area to comply with the 8-hour ozone standard by December 31, 2007 and maintain the standard beyond that date. The pilot program to retrofit gas compressor engines has been implemented to support an emission reduction strategy discussed in the CAAP for Northeast Texas.

The 2002 Northeast Texas emissions inventory estimated that 53.9 thousand tons of NOx were emitted annually by sources in the five county area. Non-point gas compressor engines were estimated to contribute approximately 12 thousand tons per year; over 22 percent of the total (NETAC, 2005). Unlike other major NOx emissions sources, such as large industrial facilities and onroad motor vehicles, many compressor engines do not have emissions controls. As a source that is an important NOx emitter and is relatively uncontrolled, compressor engines represent an exceptional opportunity for reducing the total NOx emissions in Northeast Texas. An additional enticement for controlling emissions from this source is the potential for funding those controls via the Texas Emission Reduction Plan (TERP).

In 2001, the Texas Legislature created the TERP fund for the purpose of providing incentive grants for emission reduction projects in the state's 41 nonattainment and near- nonattainment counties. Eligible projects include new purchases, replacements, repowers, retrofit technologies, infrastructure and qualifying fuels. Recently, in an effort to ensure an equitable allocation of the TERP funds, TCEQ designated $9,381,231 for the NETAC area through the first half of FY2007. In order to be eligible for a TERP grant a project must meet a number of requirements.

Several of the key eligibility requirements specified by TCEQ guidelines for an off-road mobile source equipment retrofit project are that the retrofit is certified to emit at least 25 percent less NOx than the baseline engine, that the cost is less than $13,000 per ton of NOx reduced and that the retrofit is not required under state or federal law, rule, regulation or other agreement (TCEQ, 2004). Certification of the emission reduction is described as, "certified or verified by the EPA, the CARB[1], *or otherwise accepted by the TCEQ* [italics and footnote added]" (TCEQ, 2004). The results of this pilot project show that the retrofit of rich-burn compressor engines with a nonselective catalytic reduction system achieves NOx emissions reductions that greatly exceed the cost and emission requirements of the TERP program. Additional information about applying for TERP incentive grants is provided later in this report.

Summary of Results

In the early stages of this project, representatives of NETAC met with representatives of gas compressor engine operators. At that meeting, small (less than 500 horsepower), rich-burn gas compressor engines were identified as the best candidate group for retrofit. The Hanover Company, a compressor engine operator, made five such engines available for retrofit over the course of the project. A non-selective catalytic reduction (NSCR) system was determined to have the greatest potential for reducing NOx emissions from this type of compressor engine.

Baseline emissions testing and post-retrofit emissions tests were performed by third-party specialists qualified to use EPA-defined test methods to demonstrate attainment with emission standards and permitted emission rates. Two emissions tests were performed on each engine. One test determined the engine's baseline NOx emission rate prior to retrofit. The second test, occurring after the engine was retrofit, established the post-retrofit emission rate. For two engines it was possible within the timeframe of this project to conduct additional post-retrofit tests after the engines had been operating more than 4,000 hours. This additional testing was done to establish the longevity of this control strategy. In this test, a comparison was made of the "pre-catalyst" (exhaust gases on the engine side of the catalyst) and "post-catalyst" (exhaust gases on the exit of those gases to the atmosphere) emission rates. The comparison of pre- and post-catalyst emission rates during the longevity testing shows that the catalyst is still functioning with high reduction efficiency after 6 months of continuous operation. A summary of the testing results is provided for each of the engines in Table 1-1.

Table 1-1. Summary of NOx emissions reductions.

Engine Description		Tested Emission Rates		Reduction of NOx Emissions	Longevity Testing	
Engine ID	**Engine Description**	**Baseline (g/hp-hr)**	**Post-retrofit (g/hp-hr)**		**Pre-Catalyst (g/hp-hr)**	**Post-Catalyst (g/hp-hr)**
70640	CAT 342 NA	11.61	0.26	98%	26.81	0.99
74236	CAT 3306 TA	13.01	0.55	96%	20.77	0.85
70024	CAT 342 TA	13.29	0.49	96%		
75558	CAT 3306 TA	12.70	0.36	97%		
72386	CAT 3306 NA	12.43	0.47	96%		

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[1] California Air Resources Board

For all of the engines retrofit in this project, the post-retrofit emissions tests showed NOx emissions rates were decreased by greater than 95 percent after installation of the NSCR system. The average cost effectiveness is better than $185 dollars per ton of NOx reduced.

In August of 2006, further testing established the longevity of this control technology and obtained additional data that demonstrates the reduction efficiency of the catalysts. The 2006 tests evaluated emissions reductions by comparing "pre-catalyst" and "post-catalyst emission rates. In two cases, the additional tests were on engines that had previously been tested in 2005, as shown in Table 1-1, extending longevity testing to as long as 1.5 years (~12,000 hours) of operation. A summary of the 2006 testing results is provided for each of the engines in Table 1-2.

Table 1-2. Summary of NOx emissions reductions from 2006.

Engine Description		2005 Reduction of NOx Emissions	Emissions Testing		2006 Reduction of NOx Emissions
Engine ID	**Engine Description**		**Pre-Catalyst (g/hp-hr)**	**Post-Catalyst (g/hp-hr)**	
74236	CAT 3306 TA	96%	4.68	0.18	96%
75558	CAT 3306 TA	97%	6.41	0.58	91%
74376	CAT 342 NA		7.91	1.19	85%
77764	CAT 3306 NA		10.37	0.05	99%

At the time of the 2006 testing, Engine 75558 had 12,000 hours and Engine 74236 had 8,000 hours of continuous operation with the catalysts installed.

Report Organization

Section 2 describes the planning stage of the retrofit, wherein an industry partner was obtained, the specifics of compressor engine operations were studied and a control technology was selected. Section 3 describes the emission control equipment installation and accompanying emissions testing. Also in Section 3, the emissions reductions achieved by the retrofits and the cost effectiveness of the control strategy are presented. Section 4 describes the steps required to duplicate the retrofits made in this pilot project. This section addresses the requirements for obtaining TERP incentive grants and provides the specific information, such as emissions reductions and cost effectiveness calculations that would be necessary for a TERP-funded compressor retrofit. Section 5 describes additional testing performed in 2006.

2. DESIGN OF RETROFIT AND TESTING PROGRAM

Based on the results of the Northeast Texas emissions inventory, gas compressor engines were identified as significant NOx contributors. However, the gas compression industry operates several distinct categories of engines, each with different operational and emissions characteristics. Before beginning emissions testing and control equipment installations, it was necessary to determine what portion of the industry would yield the greatest emissions reductions with the installation of controls. After refining the scope of the project to a segment of the industry, small unregulated gas compressors, a specific type of emission control method was then identified. Finally, the last step in the planning phase was to design a thorough testing procedure that would mirror the federal emission testing and verification program.

Overview of the Gas Compression Industry

The gas compression industry can be divided into three segments based on the size of the facilities. Large compressor engine stations, such as the one depicted in Figure 2-1, are perhaps the most visible elements of the gas compression industry. These facilities are primarily located along major gas transmission and distribution lines. Large volumes of gas pass through these facilities (upwards of 100 MMSCF per day), and these stations feature very large - often over 1,000 horsepower - lean burn engines. In some cases turbines may be used in place of reciprocating engines. Large gas transmission facilities like these are regulated under the Title V or NSPS programs. Despite their large size, there are relatively few such facilities and the total NOx emissions from this category is comparatively modest. A review of the 2002 National Emission Inventory revealed only seven such facilities in the five county area. The combined annual NOx emission from all equipment at these facilities was less than 500 tons (EPA, 2005).

Figure 2-1. Large compressor station (American Central Gas Compressor Station; Carthage, TX).

A smaller type of gas compression facility is often found at major junctions or along trunk lines in the gas gathering system. Such facilities frequently feature a single large. rich-burn compressor engine. The engine is likely to be greater than 500 horsepower and have a non-selective catalytic reduction control system installed to prevent the facility from being designated as a major source (NETAC, 2004). An example of this type of compressor engine is presented in Figure 2-2.

Figure 2-2. Medium size gas compressor engine installation (Evaporative Systems Inc, 2005).

The final category of compressor engines is the group of relatively small, rich-burn compressor engines that are installed near gas producing wells. These compressor engines service gas production from one or several wells, with a total gas throughput between 0.1 and 10 MMSCFD. The size of each individual engine is below 500 horsepower, but there are estimated to be thousands of these engines in the five-county NETAC area. This class of compressor engines does not typically have emissions controls. Without emission controls, the emission rate for these engines is approximately 10 to 12 grams per horsepower hour (g/hp-hr). Depending on the tuning of the engine, the emission rate may approach 20 g/hp-hr. Given that these engines operate nearly constantly (greater than 8,000 hours per year), a single 200 horsepower compressor engine operating at 50 percent load could easily produce over 10 tons NOx per year. Considering the potential emission from each individual engine, in combination with the tremendous number of engines, it is apparent that these individually small engines are in fact responsible for the majority of compressor engine emissions. The fact that the engines are uncontrolled also indicates that they represent an opportunity for the abatement of NOx emissions. Figure 2-3 shows an uncontrolled compressor engine of approximately 250 horsepower.

Figure 2-3. Small, uncontrolled, rich-burn compressor engine (Northeast Texas).

Cooperation of Stakeholders

In December of 2004, representatives of NETAC met with gas compressor engine operators to discuss the pilot project. In that meeting, it was agreed that the group of small, rich-burn engines was the best candidate group for the project. The Hanover Company, a major compression services provider, had previously investigated the possibility of retrofitting their engines with funding from the TERP program. Hanover's research into the available control technologies had identified a control system combining a fuel/air controller and an after-treatment catalyst as very promising. It was suggested that this particular control technology would achieve NOx reductions greater than 90 percent at a cost of approximately $10,000 per engine. Thus a control technology appeared to be available for small, rich-burn engines that had the potential to meet the emissions reduction and cost effectiveness requirements of the TERP program.

With a consensus on the best candidate group of engines and the apparent availability of at least one viable control method, it was decided to move forward with the pilot project by installing emission controls on small, rich-burn compressor engines. The available funding suggested that at least 3 engines could be retrofit. Compressor engine operators were invited to participate in the pilot project on a voluntary basis. Though several operators showed interest in participating, in the end only the Hanover Company elected to make engines available for retrofit. In the first round, Hanover identified 3 engines for retrofits. In the second round, two additional Hanover engines were retrofit.

Selection of Control Technology

The technology for controlling exhaust emissions from natural gas (NG), rich-burn, engines is well understood and documented in technical reports and industry trade journals. The most viable method for reducing NOx emissions from rich-burn engines is to equip them with non-selective catalytic reduction (NSCR) systems. Numerous state, federal and industry sources confirm the effectiveness of this control strategy, as does the industry partner in this pilot project.

According to a 1997 report published by the Manufacturers of Emission Controls Association, the NSCR technology has been used to control NOx emissions from rich-burn engines for over 15 years, and more than 3,000 rich-burn engines had been equipped with NSCR technology in the U.S. (MECA, 1997). In it's comprehensive emission factors document, AP-42, the US EPA (1995) cites NSCR controls as one of the control technologies available for natural gas fired rich-burn engines. Similarly, many state agencies have suggested equipping rich-burn engines with NSCR as an effective way to meet emissions standards. For example, the California ARB (2001) found that this was a common and highly effective control strategy in its determination of the control technology available for spark-ignited internal combustion engines. Several studies are available from the Gas Research Institute[1,2] and the EPA[3] that document the emissions reductions possible when this control strategy is applied to large internal combustion engines. Locally, the Hanover Company has had considerable success implementing this strategy on some of the larger (greater than 500 hp) engines in its fleet (McClurg, 2005).

NSCR reduces NOx, carbon monoxide (CO) and hydrocarbon (HC) emissions simultaneously if an engine is operating at the stoichiometric air/fuel ratio[4]. Because emissions from three pollutants are simultaneously reduced the technology is commonly referred to as a three-way catalyst (TWC). A TWC utilizes HC and CO in the exhaust as a reducing agent for NOx. The excess HC and CO pass over a catalytic converter that contains metals such as platinum, rhodium, and palladium. These catalysts oxidize the excess HC and CO to H_2O and CO_2, while reducing NOx to N_2. The conversion efficiencies can be more than 90% for NOx emissions, about 90% for CO and about 70% for HC emissions.

Applying this technology to gas compressor engines was expected to be the most cost effective NOx emissions reduction strategy available. When selecting this control technology, the cost effectiveness was conservatively (higher cost and lower benefit) estimated at $300 per ton of NOx reduced, as demonstrated in the calculation below. The actual results show an even greater cost effectiveness.

Base Emissions = (Power) x (Load Factor) x (Hours/year) x (Emission Factor)

Where

Power = 220 horsepower

Load Factor =85% (US EPA (2004) NONROAD model)

Hours/year = 6,000 (owner/operators report over 8,000 hours per year)

Emission Factor = 12 g/hp-hr (US EPA (2004) NONROAD model, manufacturers report up to 20.5 g/hp-hr for uncontrolled engines); Controlled emission factors was estimated to be no higher than 2 g/hp-hr

Base Emissions Rate = 14.8 tons of NOx per year per unit

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[1] "Retrofit NOx Control Technologies for Natural Gas Prime Movers." Section 4, Gas Research Institute, March 1994, GRI-94/0329.

[2] "NOx Reduction Technology for Natural Gas Industry Prime Movers." Acurex Corporation for Gas Research Institute, August 1990, GRI-90/0215.

[3] "Stationary Reciprocating Internal Combustion Engines: Updated information on NOx Emissions and Control Techniques." Final Report. US Environmental Protection Agency, Office of Air Quality Planning and Standards. August 2000.

[4] Stoichiometric air/fuel ratio is defined as a condition where there is just enough oxygen for conversion of all the fuel into completely oxidized products, or so called the complete combustion.

Cost Effectiveness = (Cost) x (Capital Recovery Factor) / (Annual emission reduction)

Where

Cost = $10,000 estimated including installation
Capital Recovery Factor = (INT) x (1 + INT)^(LIFE)/[(1+INT)^(LIFE) – 1]
INT = Interest rate = 0.03 (3%)
LIFE = 3 years
Annual Emission Reduction = 80% x Base Emissions Rate

Estimated Cost Effectiveness = $298 per annual ton of NOx reduced

In order for the TWC to achieve high conversion efficiencies for all three pollutants, the air/fuel ratio must be held close to the stoichiometric point. Therefore, an electronic air/fuel ratio controller must be used to regulate the engine and the exhaust entering the TWC. The controller adjusts the air/fuel ratio based on the exhaust oxygen content monitored by an oxygen sensor mounted on the upstream side of the catalytic converter.

Based on discussions with vendors of this technology, the fuel/air controller can be supplied by a different vendor than the catalyst and exhaust system. For instance, the direct parts supplier for the pilot project purchases fuel/air controllers from distinct manufacturers depending upon the size and model of the engine and owner preference. The catalyst is purchased from another manufacturer, and the direct supplier then fabricates the housing and exhaust system for the specific engine application. Therefore, three different firms manufacture the complete retrofit device. The technology is widely available and many vendors offer similar services.

The efficiency and durability of a TWC system is closely related to proper control of the air/fuel ratio. Rich air/fuel ratio settings can damage the catalyst with high temperatures resulting from oxidizing the high HC and CO concentrations in the fuel-rich exhaust gas. To prevent damage to the catalyst it is necessary that the performance of the TWC system be monitored periodically, especially for retrofit applications where the TWC and air/fuel ratio system are not OEM-engineered to the engine.

Design of Testing Program

To be eligible for TERP funding, retrofit systems must be certified or verified by the EPA, the CARB or *otherwise accepted by TCEQ* (2004). Due to time constraints and the high level of involvement that the EPA and CARB programs require of the technology vendor, it was not possible to participate in the EPA or the CARB certification programs. However, the testing plan for the pilot project was designed to mirror that of the EPA program. Thus, the goal of the testing program that accompanied the engine retrofits was to provide verification of the NOx reductions that would be acceptable to TCEQ, and to do so within the time allotted for the project.

There are two types of programs within EPA that verify emission control devices. The Environmental Technology Verification (ETV) program operated out of North Carolina is primarily for stationary source controls. Another verification program for mobile sources is operated out of EPA in Washington D.C. The EPA mobile source verification program has so far focused exclusively on diesel engine particulate emission reduction. CARB also verifies diesel engine particulate and NOx emission reductions through their mobile source verification program, but leaves stationary source controls to local California air quality management districts to enforce through permits. Because the gas compressor engines under consideration have many of the characteristics of stationary sources and use natural gas fuel, the ETV verification program was considered the most applicable.

The ETV program is a large effort encompassing all manner of emission control technologies to address solid, liquid and air pollution. The ETV sets up testing protocols using a number of guidance documents. Based on conversations with EPA's contractor for the ETV (Trenholm, 2005), a typical timeline for a single vendor to complete the minimal verification testing is as follows:

- Submit the testing protocol (1 month development)
- Approval of protocol (2 months to address any concerns and gain final approval)
- Contract with EPA designated verification contractor (1 month)
- Schedule and conduct testing and prepare report (4 months)
- Issue final results and EPA recommendations (1 month)

Overall, verification would have required about 12 months for a single vendor and engine type. In addition to the initial testing, EPA would likely require longer term confirmatory testing to ensure the durability of the catalyst and controls. The long term testing would add time to the verification schedule described above. To participate in the EPA's ETV program would have required time and resources beyond what was allocated for this project. Further, it would have required that an equipment vendor apply to the program, provide field-ready equipment for testing, bear a portion of the test cost and fulfill numerous managerial responsibilities (EPA, 2000). Finding such a partner was unlikely within the time frame of this project. Instead, ENVIRON developed an emission testing procedure that followed EPA guidance as closely as possible. In particular, the NOx testing method specified by EPA was adopted for use in the pilot project. The testing program was designed to determine the effect of the catalyst retrofit on both emissions and fuel economy.

The method designed for NOx emission verification is called Method 7E and is used in combination with Methods 1, 2, and 3 for exhaust flow and other emissions analyses including carbon dioxide (CO2), carbon monoxide (CO), and total hydrocarbon (THC) (US EPA, 2000). These methods detail the specific test procedures for exhaust flow rate and gas composition required to calculate emissions using the equation below.

Emissions (g/hr) = (Gas composition) x (Exhaust flow rate)

The combination of the measured emissions rates with the measured engine load was used to determine the emission rate in terms of grams per horsepower-hour. Comparing the baseline emission rate with the retrofit emission rate then yielded the control efficiency of the retrofit.

Alternate NOx Measurement Devices

The specified test Method 7E for NOx emissions uses an expensive chemiluminescence meter. Hanover routinely uses an inexpensive portable analyzer for confirmatory testing on engines throughout Texas and Louisiana. Hanover agreed to run their method for side-by-side comparison with the more formal and expensive Method 7E. The purpose of this comparison was to determine if Hanover's portable method provided sufficient accuracy to monitor the long-term viability of the retrofit devices.

3. COMPRESSOR ENGINE RETROFITS-PROCEDURE AND RESULTS

Over the course of the pilot project, the selected retrofit technology was installed on five gas compressor engines in Northeast Texas. For all five engines, the test methods designed and implemented in this project have revealed dramatic NOx reductions after installation of the retrofit. Additional testing performed on a subset of the engines has shown that six months after installation the controls continue to provide greater than 90 percent abatement of NOx emissions. The project began with three compressor engines that were retrofit in February of 2005 and then expanded to retrofit two additional engines in August of 2005. The project timeline is shown below in Table 3-1.

Table 3-1. Project timeline.

Date	Engine Group 1	Engine Group 2
January 2004	3 engines identified	
February 8-10, 2005	Baseline testing	
February 14-8, 2005	Installation of retrofit	
February 21-26, 2005	Post installation testing	
July 2005		2 engines identified
August 16-17, 2005	Longevity testing	Baseline testing
August 18-19, 2005		Installation of retrofit
August 29, 2005		Post installation testing

In this section, the implementation of the retrofit is described, followed by a comparison of the uncontrolled versus controlled emissions testing. Finally, the cost effectiveness of this control strategy is analyzed.

IMPLEMENTATION OF RETROFITS

The procedure followed from the selection of engines through the post-installation testing was nearly identical for all five engines. The Hanover Company was tasked with the selection of engines. The criteria of the project for engine selection was simply that the engine was an uncontrolled, less than 500 horsepower, rich-burn engine operating in the five county NETAC area. Beyond those few requirements, the engine selection was left to the Hanover staff. The basic characteristics of the five engines that were ultimately selected are shown in Table 3-2.

Table 3-2. Characteristics of the engines retrofit by the pilot project.

Engine ID	70640	74236	70024	75558	72386
Site Name	Kilgore	Lawrence #1	Leath	China-Knome	Wertz
Location	near Kilgore	near Kilgore	near Kilgore	near Tyler	near Tyler
Make & Model	CAT 342 NA	CAT 3306 TA	CAT 342 TA	CAT 3306 TA	CAT 3306 NA
Rated Horsepower	225	220	265	220	145

Discussion with Hanover personnel identified additional criteria that were used in the selection of engines. Engines with no recent history of mechanical difficulties and engines that were expected to remain in service in the same location for the near future were preferred. These additional criteria were expedient for the purposes of the pilot project, but they are not necessary for successful use or demonstration of the control technology. One of the benefits of the control system selected is that it can be transferred relatively easily from one engine to another. This is a useful feature considering the dynamic nature of the gas compression industry.

Once engines were selected, the retrofit systems were ordered. The components of the systems were nearly identical for the five engines. The only significant variation was the sizing of the catalysts to match the rated power of the engines. Other properties of the system, such as flange and port sizes varied slightly from one engine to the next, but these would only require minor modifications in order to transfer the equipment from one engine to the next. In contrast, the catalyst must be sized appropriately for the engine in order to achieve a high level of control efficiency. The most important factor to be considered in the sizing of the catalyst is the engine power. Appropriate sizing of the catalyst ensures that the designed control efficiency is attained. This is not to say that a certain catalyst is tied to a certain engine. As shown in Table 3-3, the normally aspirated engines were equipped with the same size catalyst as the turbocharged engines. Though that meant that engines differing in power by approximately 40 horsepower were fitted with the same size catalyst, very high NOx reductions were achieved for both power ratings. Thus, in many cases it will require only minor modifications to transfer the control equipment between similar engines.

Table 3-3. Engine type and catalyst selection.

Engine ID	Make Model	Fuel	Catalytic Converter [1]
70640	CAT 342 NA	Pipeline Quality Natural Gas	MINE-X® Model DC48
74236, 75558	CAT 3306 TA		MINE-X® Model DC47
70024	CAT 342 TA		MINE-X® Model DC48
72386	CAT 3306 NA		MINE-X® Model DC47

[1] There are many manufacturers of catalysts. The use of a specific manufacturer in this project is not intended as an endorsement of that manufacturer or their products.

As described in the discussion of this control technology, it was necessary to equip the engines with air/fuel ratio (AFR) controllers to provide for the proper functioning of the catalyst. A solar power supply was also incorporated into the system to provide power for the AFR controller. All these components would need to be installed on any additional retrofits. The only possible exception is the solar panel and battery pack, which would not be necessary if another source of electric power were available at the site. The cost of the equipment purchased for each engine is shown in Table 3-4. The cost of the catalytic converters varied slightly based on the size required for the engine, but all other equipment costs were static. These equipment costs represent most of the total cost of the retrofit, and as shown in Table 3-4, they range between about $7,500 and $7,900 per engine. Freight charges and the labor costs associated with installation are not included in these costs. These minor costs will be discussed further in the analyses of cost effectiveness.

Table 3-4. Costs of retrofit equipment.

Equipment	Unit 70640	Unit 74236	Unit 70024	Unit 75558	Unit 72386	Average
Catalytic Converter	$2,130	$1,800	$2,130	$1,800	$1,800	$1,932
AFR Controller	$4,290	$4,290	$4,290	$4,290	$4,290	$4,290
Solar Power Supply	$1,450	$1,450	$1,450	$1,450	$1,450	$1,450
Total	$7,870	$7,540	$7,870	$7,540	$7,540	**$7,672**

Before the control equipment was installed on an engine, the engine's emissions were tested to determine the baseline emission rates. This testing was performed in accordance with the previously described testing procedure. A third-party company specializing in emissions testing was contracted to perform both the baseline and post-retrofit tests.

In addition to the EPA methods utilized by the third-party testing contractor, personnel from the Hanover Company used a portable analyzer (ECOM AC+ portable analyzer) to test emissions from three of the engines. The purpose of performing this side-by-side test with the portable analyzer was to determine if testing over the long-term with the portable analyzer would provide sufficient accuracy to confirm that the TWC was operating effectively. Performing the same regular maintenance testing using a third-party contractor and the EPA test methods would add a considerable expense to this type of retrofit. On average, the total cost for performing an emissions test following the EPA methods and using a third-party contractor was approximately $2,000 per engine test. That includes both mobilization and testing costs and in all cases more than one engine was tested per mobilization. Testing a single engine could be considerably more expensive on a per-engine measure due to the high costs associated with mobilization. In contrast, testing using the portable analyzer requires only a small amount of staff time and can be performed by compressor operator personnel during regular maintenance visits.

Table 3-5 shows the baseline test results for the five engines as measured using the EPA methods. With the exception of one engine with a slightly lower emission rate, the engines show NOx emission rates greater than the 12 g/hp-hr that was anticipated. In contrast, load factors are substantially below what was anticipated. The load factors were calculated as the ratio of the operating power at the time of testing to the engine's rated power. Operating power was calculated by Hanover personnel based on the gas flow rate and differential pressure. The accuracy of the calculation was confirmed by checking the result against the power suggested by manifold pressure and throttle (McClurg, 2005). At the time of testing, the engines showed an average loading of only 57 percent, as compared to the 85 percent applied by the US EPA (2004) NONROAD model for gas compressor engines in commercial applications. The lower than expected engine loads encountered during baseline testing suggested that the NOx abatement estimates made during the planning stages of the project may have been too high. However, because other assumptions made in those initial estimates - such as baseline emission rates and annual hours of operation - were determined to be too conservative, the annual baseline NOx emissions ultimately calculated for the five engines were similar to initial estimates.

Table 3-5. Baseline engine emission rates.

Engine	**Unit**	**70640**	**74236**	**70024**	**75558**	**72386**	
	Make/Model	CAT 342 NA	CAT 3306 TA	CAT 342 TA	CAT 3306 TA	CAT 3306 NA	
	Power	225	220	265	220	145	Average
Baseline Testing	Operating Power	116	122	142	125	96	120
	Load Factor	52%	55%	54%	57%	66%	
	NOx (lbs/hr)	2.97	3.50	4.16	3.50	2.63	
	NOx (g/hp-hr)	**11.60**	**13.00**	**13.30**	**12.69**	**12.43**	**12.60**
	CO (lbs/hr)	8.07	1.99	5.64	0.72	0.53	
	THC (lbs/hr)	0.55	0.35	1.86	0.37	1.39	

After the baseline emission rates were established, the control equipment was installed by Hanover. Staff at the Hanover Company estimated that approximately 16 employee-hours were required for the installation of equipment on each engine (McClurg, 2005). The equipment installation included the setup of the solar unit, incorporation of the catalytic converter into the exhaust system, and the setup of the AFR controller which included integration of AFR controller's fuel/air control valve. Figures 3-1 and 3-2 show the entire system as installed on one of the engines.

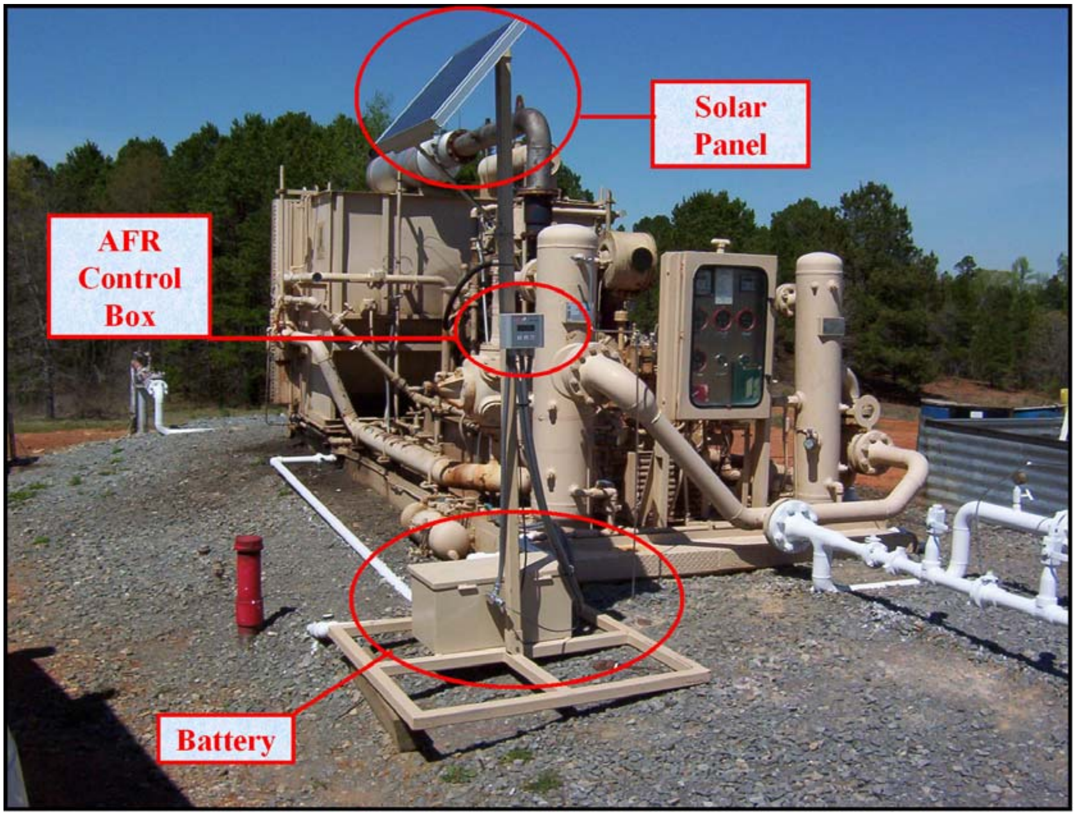

Figure 3-1. Retrofit system - showing solar panel, battery pack and AFR control box.

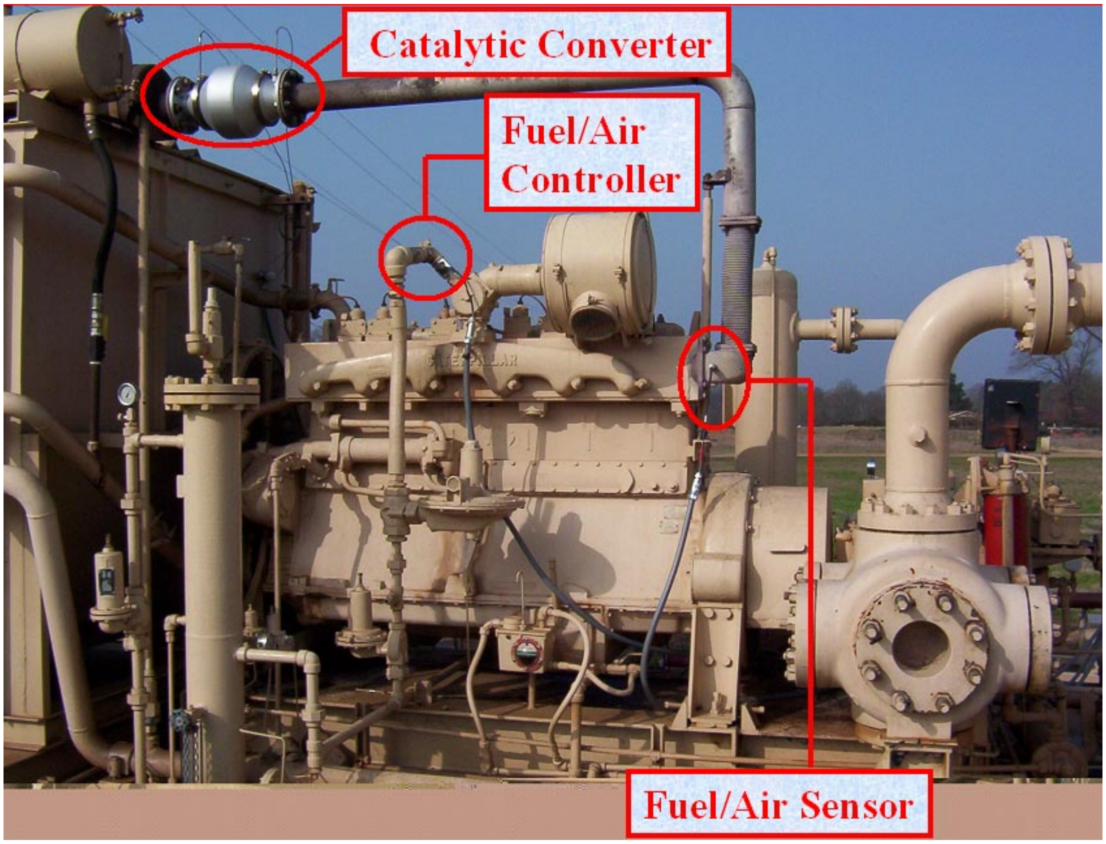

Figure 3-2. Retrofit system - showing catalytic converter, fuel/air controller and fuel/air sensor.

EMISSIONS REDUCTIONS ACHIEVED

After installation of the control equipment, the engines were allowed to run for a minimum of 100 hours before testing the emissions. Emissions from the engines were then tested using the exact procedure that had previously been used to determine the baseline emissions. The results of this post-retrofit testing demonstrated reductions in the NOx emissions that were above 95 percent for all of the engines. CO emissions reductions were also considerable. Table 3-6 summarizes the results of the post-retrofit emissions for each of the five engines. Table 3-7 then presents a comparison of the baseline and post-retrofit emissions.

Table 3-6. Post-retrofit emissions.

Engine	**Unit**	**70640**	**74236**	**70024**	**75558**	**72386**	Average
	Make/Model	CAT 342 NA	CAT 3306 TA	CAT 342 TA	CAT 3306 TA	CAT 3306 NA	
	Power	225	220	265	220	145	
Post-retrofit Testing	Operating Power	137	58	130	125	96	109
	Load Factor	61%	26%	49%	57%	66%	
	NOx (lbs/hr)	0.08	0.07	0.14	0.10	0.10	
	NOx (g/hp-hr)	**0.26**	**0.55**	**0.49**	**0.36**	**0.47**	**0.43**
	CO (lbs/hr)	0.05	0.03	0.13	0.12	0.09	
	THC (lbs/hr)	0.40	0.31	1.03	0.18	0.96	

Table 3-7. Comparison of baseline and post-retrofit engine emissions.

Engine	**Unit**	**70640**	**74236**	**70024**	**75558**	**72386**	Average
	Make/Model	CAT 342 NA	CAT 3306 TA	CAT 342 TA	CAT 3306 TA	CAT 3306 NA	
Baseline Testing	Operating Power	116	122	142	125	96	120
	NOx (g/hp-hr)	**11.61**	**13.01**	**13.29**	**12.70**	**12.43**	**12.61**
	CO (g/hp-hr)	31.56	7.40	18.02	2.61	2.50	12.42
	Estimated Baseline NOx Emission (tons/yr)[1]	12.96	10.33	15.94	14.00	10.52	12.75
Post-retrofit Testing	Operating Power	137	58	130	125	96	109
	NOx (g/hp-hr)	**0.26**	**0.55**	**0.49**	**0.36**	**0.47**	**0.43**
	CO (g/hp-hr)	0.16	0.27	0.45	0.44	0.43	0.35
	Estimated Controlled NOx Emission (tons/yr)[1]	0.30	0.43	0.59	0.40	0.40	0.42
Control Efficiency Demonstrated	**Percent NOx Reduction**	**98%**	**96%**	**96%**	**97%**	**96%**	**97%**
	Percent CO Reduction	99%	96%	97%	83%	83%	92%
	Estimated Annual NOx Abatement (tons)	**12.66**	**9.89**	**15.35**	**13.60**	**10.12**	**12.33**

[1] Annual emissions estimate based on 8,000 hours operation per year and the average operational power of the engine during testing

For all five engines controlled emissions rates of less than 1 gram NOx per horsepower-hour were achieved. The lowest NOx emission rate was 0.26 g/hp-hr and the highest was only 0.55 g/hp-hr. This represents a tremendous improvement over the baseline emission rates, which ranged from 11.61 to 13.29 grams NOx per horsepower-hour. Figure 3-4 shows a graphical representation of the pre- and post-retrofit emission rates for the five engines. The average annual NOx abatement is estimated to be greater than 12 tons per engine. This estimate is based on a comparison of the baseline and post-retrofit annual NOx emissions estimated for each engine. The equation and assumptions used to derive the baseline and post-retrofit annual NOx emissions estimates are shown in Figure 3-3.

Annual Emissions = (Power) x (Hours/year) x (Emission Factor)
Where
Power = the average engine power recorded during testing
Hours/year = 8,000 (owner/operators report over 8,000 hours per year)
Emission Factor = The factor derived from emissions testing results

Figure 3-3. Calculation of annual NOx emissions.

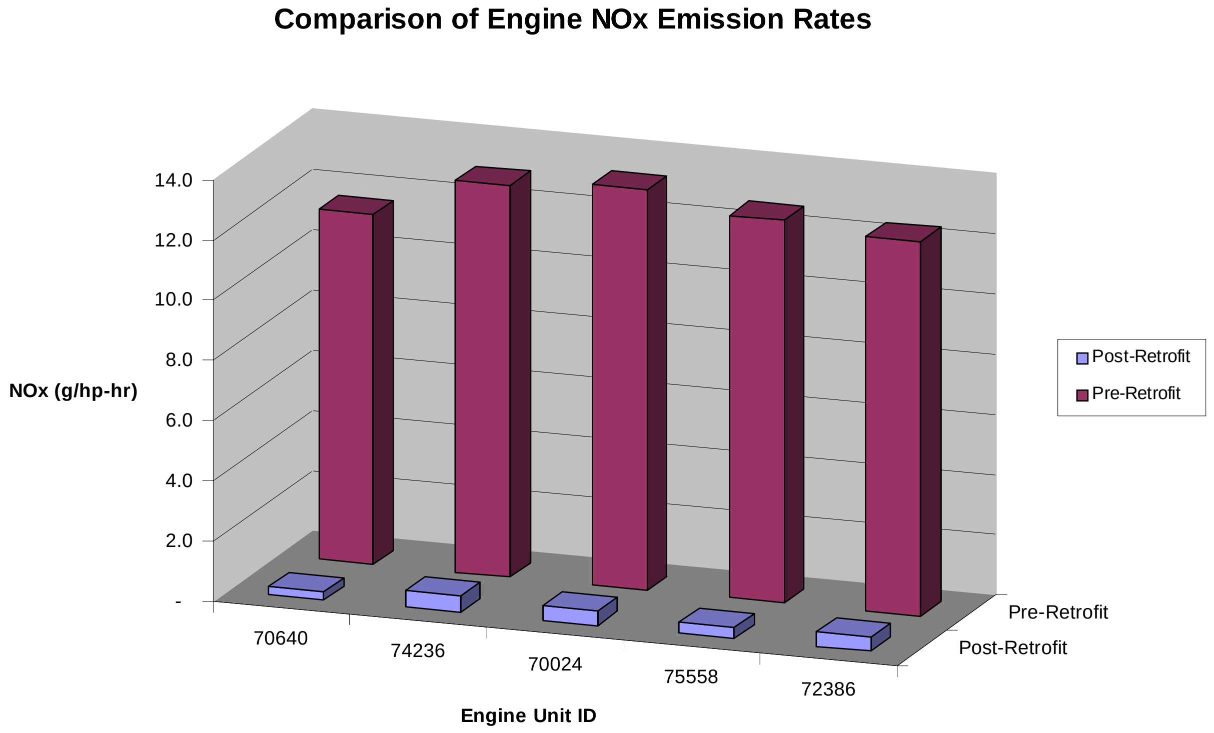

Figure 3-4. Comparison of baseline and post-retrofit engine emission rates.

Evaluation of Portable Analyzer Utility

In addition to the emissions reductions, another significant finding resulted from the emissions tests. A comparison of the emission concentrations yielded by EPA methods as implemented by the third-party contractors and those obtained using a portable analyzer shows that the portable analyzer will be an adequate tool for monitoring performance of the emission controls. For the three engines tested using both the third-party contractor and Hanover's portable analyzer, test results for the baseline gas concentration comparison are shown in Table 3-8. The direct comparison of Hanover's method with the official EPA method performed by the third-party contractor was favorable. Hanover's method was biased low compared with the EPA method. The emissions reported by Hanover's method were 71 – 78% of those reported by the EPA method (less than a 20 ppm difference) after installation and 88 – 99% of those shown by the EPA method (less than a 400 ppm difference) before installation. The bias may result from a well-known detection interference with water in the exhaust. However, the purpose of the method that Hanover uses would be to confirm that the unit is operational, and the pre and post catalyst measurements would be biased similarly because the water and other interferences would be identical as the exhaust composition would be similar pre and post catalyst for emissions other than NOx and CO. Also, the control efficiency is so high that the bias is insignificant in demonstrating the level of the control. Because baseline testing is available to compare with future analysis, the bias is irrelevant for demonstrating compliance.

Table 3-8. Emissions test results obtained with a portable analyzer.

Test Result - Data Source	Engine	Engine	Engine
Unit Number	74236	70640	70024
Rated Power (hp) – Hanover	220	225	265
Before Installation			
NOx (ppmv) – third-party	3159	2089	2509
NOx (ppmv) – Hanover	2793	2072	2331
CO (ppmv) – third-party	2956	9341	5589
CO (ppmv) – Hanover	5249	14000	8382
CO2 (%) – third-party	11.9	10.8	10.9
CO2 (%) – Hanover	10.8	10.6	10.5
THC (ppmv, wet) – third-party	267	331	975
THC (ppmv, wet) – Hanover	---	---	---

Longevity Testing

Though the testing performed soon after the control equipment was installed showed exceptional NOx abatement, there was concern among some stakeholders that the performance of the catalyst may quickly deteriorate. Additional testing has shown that this is not at all the case. After six months of operation, the engines that were retested still showed high levels of NOx control. Hanover staff reported that during the six months of operation the engines operated nearly continuously, shutting down only briefly for regularly scheduled engine maintenance. Engine down-time was estimated to have been less than one percent of the total, implying that after six months the engines had operated for well over 4,000 hours (McClurg, 2005). Table 3-9 shows the results of the testing performed on two engines, six months after the engines were retrofit.

Table 3-9. Results obtained from emissions testing after six months of operation.

Engine	**Unit**	**70640**	**74236**	Average
	Make/Model	CAT 342 NA	CAT 3306 TA	
	Power	225	220	
Longevity Test Conditions	Time Since Retrofit	6 months	6 months	
	Operating Power	87	59	73
	Load Factor	39%	27%	
Pre-Catalyst Testing	NOx (lbs/hr)	5.14	2.70	
	NOx (g/hp-hr)	**26.81**	**20.77**	23.79
	CO (lbs/hr)	5.11	2.44	
	THC (lbs/hr)	2.03	0.56	
Post-Catalyst Testing	NOx (lbs/hr)	0.19	0.11	
	NOx (g/hp-hr)	**0.99**	**0.85**	0.92
	CO (lbs/hr)	0.15	0.23	
	THC (lbs/hr)	1.06	2.15	
Control Efficiency Demonstrated	**NOx Abatement by Catalyst[1]**	**96%**	**96%**	96%
	NOx Control Efficiency[2]	**91%**	**93%**	92%

[1] Comparison of the NOx produced by the engine versus the NOx emitted to the atmosphere

[2] Comparison of the NOx emitted to the atmosphere in this test versus the NOx emitted during baseline testing

The longevity testing used the same EPA methods and third-party contractor as the previous tests. The only difference between these and other tests was that in the longevity testing emissions were testing in two places on each engine. Emissions were tested at the exit to the atmosphere, and in addition, emissions were tested in the exhaust system between the engine and the catalyst. The additional test conducted in the exhaust system was possible due to the installation of a small testing port that was installed during the retrofit of the engines. Testing the exhaust gases before entrance to the catalyst made possible a comparison of the emissions concentrations across the catalyst. Thus, in Table 3-9, two distinct measures of the effectiveness of the controls are presented. The first, termed “NOx abatement by catalyst”, is a comparison of the emission rate before entrance of exhaust gases to the catalyst versus after the catalyst. The second, termed “NOx control efficiency”, is the comparison of the measured rate of emissions to the atmosphere during this test and the measured emission rate during baseline testing.

The NOx abatement by catalyst that was determined in the longevity testing offers a useful measure of the effectiveness of the control strategy because it is relatively independent of the operating conditions at the time of testing. For example, the control efficiency calculated during the longevity testing averaged 92 percent for the two engines. This is a high level of control, but not as high as the average of 97 percent demonstrated in previous testing. However, a cursory examination of the longevity testing results provides a possible explanation for the perceived decline in abatement. On the day of the longevity testing the emission rate for the pre-catalyst exhaust gases averaged 23.79 g/hp-hr. For whatever reason – perhaps because the engines were operating at relatively low loads – the engines were producing NOx at a much higher rate, in terms of g/hp-hr, than during the baseline testing. Thus even though the control system was highly effective, the final emission rates were higher than recorded in the initial post-retrofit tests. The measurement of NOx abatement by the catalyst removes the level of uncertainty that is created by the engine operating conditions at the time of testing. This metric shows that after six months the catalysts were reducing NOx emissions from the engines by 96 percent.

While the effectiveness of a catalyst can decline with time, periodic washing of the catalyst can provide extended life without incurring the cost of replacing the catalyst. It is estimated that this maintenance procedure will be required approximately every two years (DCL, 2002). This longevity testing demonstrated that after six months the control system is still effectively reducing NOx emissions by well over 90 percent. Continued periodic testing of the pre- and post-catalyst emissions concentrations using a portable analyzer should clearly indicate when the effectiveness of the catalyst has declined to such a level that maintenance should be performed.

COST EFFECTIVENESS OF THE COMPRESSOR ENGINE RETROFITS

The results of baseline and retrofit emissions testing on the five gas compressor engines in East Texas have made it possible to calculate the cost effectiveness for this control option. What follows is a presentation of the results and a discussion of the methods and assumptions of this cost effectiveness estimate.

To estimate the cost per ton of NOx abatement it was necessary to derive annual NOx emissions reduction based on the measured emission rates. The calculation of annual emissions reductions required an assumption of the operational schedule of gas compressor engines. The nature of gas production and information provided by gas compressor operators suggests that gas compressor engines operate nearly year-round. The exception to this is periods when the engines are shut down for repairs or maintenance. For the purposes of this cost effectiveness calculation it has been assumed that the engines will operate 8,000 of 8,760 hours per year. The loading of the compressor engines has been estimated based on the average loading at the time of emissions testing. The average load before and after installation of the catalyst was between 41 and 66 percent for the five engines. Using these assumptions and the emission factors determined from emissions testing, annual emissions reductions were estimated for each of the engines as shown in Figure 3-3. The estimated NOx emission reductions are presented in Table 3-10. The average annual emissions reduction for the five engines is 12.3 tons NOx per year.

Table 3-10. Calculation of annual NOx emission reductions due to catalyst installation.

Engine Unit ID	70640	74236	70024	75558	72386	Average
Rated Power (hp)	225	220	265	220	145	
Average Load	56%	41%	51%	57%	66%	
Hours per year (hr)	8000	8000	8000	8000	8000	
Before Installation						
NOx emission factor (g/hp-hr)	11.6	13.0	13.3	12.7	12.4	12.6
Estimated Annual NOx Emission (ton)	13.0	10.3	15.9	14.0	10.5	12.7
After Installation						
NOx emission factor (g/hp-hr)	0.3	0.5	0.5	0.4	0.5	0.4
Estimated Annual NOx Emission (ton)	0.3	0.4	0.6	0.4	0.4	0.4
Reduction in NOx Emissions Achieved						
Reduction (tons)	-12.7	-9.9	-15.4	-13.6	-10.1	-12.3
Reduction (percent)	-98%	-96%	-96%	-97%	-96%	-97%

Cost of the Compressor Engine Retrofits

The total annual cost of the compressor engine retrofits is the sum of three components. The first and most substantial of these costs is that of purchasing the control equipment. Also included in this cost estimate are the approximate costs of the labor required to install the equipment and the anticipated cost for maintenance of the control system. To determine the total annual cost of these components, a project life of five years is assumed. This is a conservative estimate based on the life of the catalyst which manufacturer’s information suggests will be between five and ten years. The TERP-specified annual discount rate of 3 percent has been used to annualize the up-front costs of installation parts and labor.

For the five engines, the average cost of the control equipment and engine modifications including air/fuel ratio controllers and the solar power units to power those controllers was $7,672. Hanover personnel estimated that the total personnel-hours required to install the control equipment was 16 hours per engine; two technicians working eight hours on each engine (McClurg, 2005). Assuming a rate of $80/hr the cost of the labor required to install the equipment on the five engines was $6,400, an average of $1,280 per engine. The average upfront cost of the retrofit was thus $8,952 per engine.

This control technology was selected in part because it is known to be reliable. Hanover staff reported having had no maintenance problems with any of the components of the system (catalyst, AFR controller, solar panel and battery) during this pilot project. Further, the Hanover Company has installed similar NSCR control systems on more than 160 of its larger compressor engines to comply with permit requirements and has experienced very few problems. Of the few problems that Hanover has encountered, the majority were caused by the combustion of excessively contaminated fuel and a smaller number by the overloading of an engine (McClurg, 2005). The tolerance of a catalyst to contaminants will depend upon the specific model of catalyst. Table 3-11 shows the manufacturer's recommended maximum contaminant concentrations for one of the catalysts installed by this project.

Table 3-11. The manufacturer's recommended maximum contaminant concentrations for one model of catalyst (DCL, 2002).

Contaminant	Location	Maximum
Zinc	Lube oil	900 ppm
Phosphorus	Lube oil	400 ppm
Chlorinated compounds	Fuel	10 ppm
Sulfur	Fuel	200 ppm
Silicon compounds	Fuel	Nil
Heavy and base metals such as lead, mercury, arsenic, antimony, zinc, copper, tin, iron, barium, nickel and chromium, and phosphorus and sulfur.	Exhaust gas	30 ppm (collectively at inlet)
	Catalyst substrate	0.5 grams per cubic foot of catalyst substrate

So long as an engine is not overloaded and the fuel supply is not excessively contaminated, the maintenance costs of this control system are limited to those of several regularly occurring tasks. These maintenance tasks include biannual cleaning of the catalyst, quarterly replacement of the oxygen sensor and replacement of the solar power unit's battery every four years. The expected costs of the regular maintenance option and the installation of the retrofit are summarized in Table 3-12.

Table 3-12. Installation and maintenance costs for all five engine retrofits.

Installation Costs			
Parts			
Item	No. Units	Cost per unit	Total Cost
DC47-6 Catalytic Converter	3	$ 1,800	$ 5,400
DC48-6 Catalytic Converter	1	$ 2,130	$ 2,130
DC48-4 Catalytic Converter	1	$ 2,130	$ 2,130
AFR Controller Kit (single) 0.75"NPT	3	$ 4,290	$ 12,870
AFR Controller Kit (single) 1.25"NPT	2	$ 4,290	$ 8,580
Thermocouple & 40' wire	5	$ -	$ -
Solar unit (incl. batteries)	5	$ 1,450	$ 7,250
		Total Parts Cost for 5 Engines	$ 38,360
Labor			
Description	Employee-Hours	Approx. Hourly Rate	Total Cost
Installation	48	$ 80	$ 6,400
		Total Labor Cost for 5 Engines	$ 6,400
		Total Cost of Parts and Labor	$ 44,760
		Average Cost per Unit	$ 8,952
Operation and Maintenance Costs (per unit)			
Description	Frequency (Occur./year)	Cost	Annual Cost
Clean Catalyst	0.5	$ 300	$ 150
Oxygen Sensor Replacement	4	$ 50	$ 200
Replace Battery	0.25	$ 200	$ 50

When the costs presented in Table 3-12 are annualized over the five-year life of the project at a discount rate of 3 percent, the total annual cost of this retrofit is $2,250 per engine. Annual costs would be lower for an assumed project life longer than five years.

Cost Effectiveness

The average emissions reduction of the compressor engine retrofit has been derived from the results of carefully planned emissions testing. The annual cost of the retrofit has been estimated based on actual installation costs and anticipated maintenance costs. From these figures it is a simple matter to estimate the cost effectiveness. The average annualized cost of installation and maintenance of $2,250, divided by the average annual emission reduction, 12.3 tons NOx, gives a cost of $183 per one-ton reduction of NOx emissions. In contrast, the average annual cost effectiveness of previously approved TERP projects is $8,160/ton (TCEQ, 2005b). Thus, the cost effectiveness demonstrated by this pilot project shows that the installation of catalysts on gas compressor engines is an exceptionally cost effective strategy for achieving NOx emission reductions.

Additional Cost Considerations

One possible cost of the compressor engine retrofit that was not included in the calculation of cost effectiveness is a decrease in fuel efficiency. Though the compressor engines in question are classified as rich burn engines, many of the engines are tuned to run slightly lean. Running lean can result in higher fuel efficiency and is thus implemented as a cost saving measure. There are two important implications of this fuel efficient engine tuning. The first is that engines operating in lean burn conditions tend to produce more NOx. The elevated NOx emission rates are one of the reasons that compressor engines are such a large source of NOx emissions. The second implication is that when the engines are equipped with fuel/air controllers and set to operate very near to stoichiometric, the engine's fuel efficiency may suffer. In fact, the results of emissions testing on two of the engines retrofit by the pilot project shows that fuel economy did decrease.

Table 3-13 shows the baseline and post-retrofit emission rates measured for carbon species at two of the engines. Using these emission rates and the assumption that the fuel burned by the engines is 90 percent methane and 10 percent ethane, is was possible to estimate the engines' fuel consumption. Given that the engine load for these two engines was the same during baseline and post-retrofit testing, a direct comparison of the baseline and post-retrofit fuel consumption shows the change in engine fuel economy. Fuel consumption increased by 11 and 17 percent. The most likely explanation for this increase is the adjustment of the fuel/air mix from slightly lean to stoichiometric. If this is indeed the cause, then the actual impact of the retrofit on fuel economy will vary from engine to engine, depending upon the baseline operating conditions. For some engines, a decline in fuel economy may be an important cost to weight against the emissions benefits.

Table 3-13. Change in compressor engine fuel consumption.

Engine ID		**75558**	**72386**
Site Name		**China-Knome**	**Wertz**
Baseline Testing	Load	57%	66%
	CO2 (lb/hr)	102.01	123.62
	CO (lb/hr)	0.72	0.53
	THC (lb/hr)	0.37	1.39
	Estimated Fuel Consumption (lb/hr)	37.64	46.36
Post-Retrofit Testing	Load	57%	66%
	CO2 (lb/hr)	121.21	140.22
	CO (lb/hr)	0.12	0.09
	THC (lb/hr)	0.18	0.96
	Estimated Fuel Consumption (lb/hr)	44.05	51.68
Increase in Fuel Consumption		17%	11%

4. POSSIBLE APPLICATIONS OF COMPRESSOR ENGINE RETROFITS IN NORTHEAST TEXAS

The results of this pilot project demonstrate that retrofitting gas compressor engines with NSCR control systems is a highly cost effective strategy for reducing NOx emissions. This control strategy offers high potential benefits for Northeast Texas, where a large number of small uncontrolled gas compressor engines are operated in an ozone near-nonattainment area. A voluntary program that included incentive grants for purchasing the retrofit technology could achieve a significant reduction in the total NOx emissions in the five county NETAC area. The incentive grants offered through the TERP program are a promising source of funding for such a program. The requirements of the TERP program and the information necessary to apply for a grant are presented in this section. Also presented is a brief analysis of how the widespread adoption of this control strategy might impact NOx emissions in Northeast Texas.

TERP INCENTIVE GRANTS

Uncontrolled gas compressor engines operated in the NETAC area satisfy all the technical requirements for TERP incentive grants. Before this pilot project, the fact that the use of NSCR controls on compressor engines was not an EPA or CARB verified control measure was a possible impediment to accessing these grants. However, the results of this pilot project leave no question as to the effectiveness of this control measure. According to TERP guidance documents, the control technology must result in NOx emissions that are at least 25 percent less than the engine’s emissions prior to the retrofit (TCEQ, 2004). This pilot project has demonstrated that the NOx emission reduction achieved by a well-designed NSCR system installed on a gas compressor engine is over 90 percent. A complete list of the TERP requirements that are applicable to this type of engine retrofit is shown below.

Relevant TERP Nonroad Engine Retrofit Project Requirements

- Retrofit verified to emit at least 25 percent less NOx than the engine prior to the retrofit.
- The cost effectiveness of a project must not exceed $13,000 per ton of NOx emissions.
- Retrofits are not eligible if required under state or federal rules or any other legally binding document.
- The activity life must be at least 5 years.
- Not less than 75 percent of the annual usage of the equipment for the activity life must be projected to take place in one of the eligible counties.
- Grant-funded equipment must be monitored and its performance reported to TCEQ for the life of the activity.
- Applicants must agree to notify TCEQ of any changes in use of the equipment over the life of the activity. (TCEQ, 2004)

The type of compressor engine retrofits demonstrated by this project satisfy the technical requirements listed above. In this discussion it is assumed that the compressor engine is categorized as a nonroad mobile source engine, meaning that the engine moves location at least once per year. Depending on how long the engine is operated on one site, it may be categorized as a stationary engine. The eligibility requirements for stationary engines are very similar to the requirements for nonroad engines. Whether the engine is classified as nonroad or stationary should not present an obstacle to accessing TERP funding.

One of the requirements for TERP incentive grants that may at first appear onerous for a compressor engine retrofit is that at least 75 percent of the equipment use must occur in an eligible county. This seems to conflict with the fact that compressor engines must have a certain degree of mobility so that they can follow the compression requirements of gas production. There are two reasons why this should not present a serious obstacle to implementation of these retrofits in the NETAC area. The first is that the compressor engine could be moved to any location in the five county area without conflicting with the requirement. The second is that it may be possible to swap the NSCR system from an engine that was moving out of the eligible counties to an uncontrolled engine in the eligible counties. To transfer the control equipment in such a way would most likely require prior approval from the TERP program. Either of these responses to the need to discontinue the operation of a retrofit compressor engine in the eligible counties would ensure that the emissions reduction benefits stayed in the eligible counties (Table 4-1).

Table 4-1. Counties eligible for TERP grants.

Bastrop	Guadalupe	Orange
Bexar	Hardin	Parker
Brazoria	Harris	Rockwall
Caldwell	Harrison	Rusk
Chambers	Hays	San Patricio
Collin	Henderson	Smith
Comal	Hood	Tarrant
Dallas	Hunt	Travis
Denton	Jefferson	Upshur
Ellis	Johnson	Victoria
El Paso	Kaufman	Waller
Fort Bend	Liberty	Williamson
Galveston	Montgomery	Wilson
Gregg	Nueces	

In the TERP guidance documents, the procedures to be used for calculating emissions reductions and cost effectiveness are stipulated. Those procedures do not result in significantly different emission reduction estimates or cost effectiveness figures than those presented in this report. However, the emissions reductions and cost effectiveness are recalculated below with strict adherence to the TERP-stipulated procedure. These calculations could be duplicated in an application for a TERP incentive grant.

For the calculation of the emissions reduction, the use of federal NOx emissions standards is advised (TCEQ, 2005). The technical supplement to the TERP guidance lists these emission standards for diesel engines, but does not provide an emission factor applicable to gas compressor engines. Before 2004, there was no federal emission standard for gas compressor engines of this type. The NOx emission standard implemented in 2004 is 3 g/hp-hr and in 2007 it will be lowered to 2 g/hp-hr. The US EPA's (2004) NONROAD model does provide an estimate of the NOx emission rate for this class of engines prior to model year 2004. That emission rate is 12 grams NOx per horsepower-hour. Unless the TERP program stipulates that a different baseline emission rate should be used, the use of 12.0 g/hp-hr for pre-2004 engines is most appropriate. With this baseline emission rate and the emission reduction percentage demonstrated by this project, a reduced NOx emission factor can be determined as shown below. In this calculation we have interpreted the results of the pilot project conservatively and use a NOx emission reduction percentage of 90 percent. Though all engines showed NOx reductions of greater than 95 percent, 90 percent has been used to account for potential decline in catalyst performance as it approaches the need for washing. Once the reduced NOx emission factor has been determined, the NOx emission reduction is estimated as shown in Table 4-2.

Calculation of Reduced NOx Emission Factor

Reduced NOx Emission Factor = (Baseline Emission Factor) x (1 - Percent Reduction/100)
Where
Baseline Emission Factor = 12 g/hp-hr (EPA's NONROAD model)
Percentage Reduction = 90
Reduced NOx Emission Factor = 1.2 g NOx/bhp-hr

Table 4-2. TERP method of calculating annual NOx emission reduction.

Baseline		Reduced Emissions	
NOx emission factor (g/hp-hr)	12	NOx emission factor (g/hp-hr)	1.2
x load factor[1]	0.54	x load factor[1]	0.54
= corrected NOx emission factor (g/hp-hr)	6.5	= corrected NOx emission factor (g/hp-hr)	0.65
x horsepower[2]	215	x horsepower	215
= grams per hour (g/hr)	1390	= grams per hour (g/hr)	139
Baseline g/hr - reduced emission g/hr =			1250
x annual hours of operation[3]			8,000
x percent within affected counties			100%
= grams per year reduced (g/year)			10,031,000
		divided by 907,200 grams per ton	
= estimated annual NOx emissions reduction (tons/yr)			11
x activity life (years)[4]			5
= estimated activity life NOx emissions reduction (tons)			55

[1] Average of engine load factors during baseline and post-retrofit tests.
[2] Average horsepower of engines in the pilot project.
[3] Operators estimated that engine activity exceeds 8,000 hours per year.
[4] Catalyst manufacturer estimates catalyst's useful life will be 5-10 years.

The NOx emission reduction of 55 tons calculated in Table 4-2 is based on the average characteristics of the engines in the pilot project. Some elements of this calculation will vary depending upon the engine that is proposed to be retrofit. The engine horsepower will certainly be dependent upon the engine proposed to be retrofit. Other characteristics such as the load factor and annual hours of operation may change if data from the site in question indicates that the values determined by this study are not appropriate.

Using the annual NOx emissions reduction of 11 tons and the project costs, the cost effectiveness can be calculated using the TERP-specified method. TERP incentive grants can only be used to offset certain costs. Specifically exempted from TERP grants are expenses for in-house labor and travel. The list of expenses that can be offset by a TERP grant is shown below.

Costs that TERP may reimburse

- Invoice cost of the retrofit, including sales tax and delivery
- Supplies directly related to the installation of the devices
- Installation costs
- Re-engineering costs, if the equipment must be modified for the retrofit
- Other costs directly related to the project, subject to approval by TCEQ

(TCEQ, 2004)

In the cost effectiveness calculation included in the previous section, the labor of Hanover personnel was included in the project cost. Under the TERP program this in-house labor could not be included in the grant. No specific mention is made in the TERP guidance about the inclusion of maintenance costs, such as the periodic washing of the catalyst. These maintenance costs are directly related to the functioning of the retrofit so it is assumed that they would be approved for inclusion under a TERP grant. The total cost of the retrofit project that would be offset by a TERP incentive grant is thus the total cost previously calculated, \$10,622 (includes net present value of maintenance costs), less the in-house labor cost, \$1,280. The resulting project cost, \$9,342, is used in the cost effectiveness calculation shown in Table 4-3.

Table 4-3. TERP cost effectiveness method.

Step 1. Determine the Capital Recovery Factor (CRF)	
$CRF = [(1 + i)^n(i)] / [(1 + i)^n - 1]$ i = discount rate (0.03) n = activity life (5)	
Capital Recovery Factor =	0.2184
Step 2. Determine the annualized cost	
(Incentive amount) x CRF = Annualized Cost	
(\$9,342) x 0.2184 = \$2,040	
Annualized cost (\$/year) =	\$2,040
Step 3. Determine cost effectiveness	
Annualized cost (\$/year) / Annual NOx emissions reduction (tons/year) = Cost effectiveness (\$/ton)	
Cost effectiveness (\$/ton) =	**\$185**

The cost effectiveness determined using the TERP method is only slightly different from the cost effectiveness determined in the previous section. Regardless of the method of calculation, the cost effectiveness of this control strategy is far better than what is required under the TERP program. In fact, the cost effectiveness of retrofitting compressor engines with NSCR systems appears to be unmatched by any project funded by TERP-funded from 2002 through 2004 (TCEQ, 2005b).

POTENTIAL BENEFIT TO NORTHEAST TEXAS AIR QUALITY

Each compressor engine that is retrofit with the NSCR system represents a small contribution towards improved air quality. The value of this retrofit on the level of a single engine has been clearly established by this pilot project. Further, looking beyond the individual engine retrofit, the potential NOx reductions that could be achieved by the widespread adoption of this control strategy are remarkable. This fact is apparent in Northeast Texas where there are estimated to be thousands of this type of engine.

The 2002 emission inventory for the Northeast Texas EAC Area estimated that a total of 53.9 thousand tons of NOx are emitted annually in Gregg, Harrison, Rusk, Smith and Upshur counties combined. In this pilot project, the average NOx abatement resulting from an engine retrofit was approximately 12 tons per year. If, for example, the entire sum of TERP funds that has been allocated to the Northeast Texas EAC Area, $9,381,231, were dedicated to compressor engine retrofits, the costs demonstrated by this pilot project show that over 1,000 engines similar to those in this project could be retrofit. Thus, the total NOx reduction that could be achieved is greater than 10 thousand tons, or almost 20 percent of the total NOx emissions.

The actual emissions reductions that are achieved will depend not only on the number of engines that are retrofit, but on the characteristics of those engines. In this pilot project, the engines that were retrofit had similar baseline operating characteristics. All engines were Caterpillar engines that baseline testing established to be operated in the range of 96 to 142 horsepower. Baseline emission rates for the engines were clustered in a relatively narrow distribution about 12.6 g/hp-hr. Though these baseline characteristics are expected to be common to many of the small, rich burn compressors in Northeast Texas, there is undoubtedly a range of compressor sizes and operating conditions. Nonetheless, given the high level of NOx abatement and low cost demonstrated by this project, this emissions control strategy is expected to be highly cost effective for most if not all small, rich burn compressor engines in Northeast Texas.

5. ADDITIONAL TESTING IN 2006

This chapter presents results of additional testing that was conducted in 2006 to update the Northeast Texas Air Care (NETAC) pilot project to demonstrate the effectiveness of available technology in reducing nitrogen oxide (NOx) emissions from compressor engines used in gas production operations. The 2006 testing provides an update on two gas compressor engines that were retrofitted in 2005 and includes tests of two additional gas compressor engines that were retrofitted in 2006. In this chapter, the implementation of the retrofit is described, followed by a comparison of the uncontrolled versus controlled emissions, followed by a comparison of the 2006 tests with earlier tests.

A total of five engines were tested, however, results for four engines are presented in this Chapter. A fifth engine operated by BP was selected and tested, however there were difficulties with the air/fuel ratio (AFR) controller maintaining proper engine operating conditions during emissions testing and the results are not considered reliable. BP plans to modify the AFR controller and retest the engine and these results will be reported later.

SUMMARY OF RESULTS

In August of 2006, further testing was done to establish the longevity of the catalyst control technology and to obtain additional data to demonstrate the reduction efficiency of the catalysts. The additional tests were a comparison of the “pre-catalyst” and “post-catalyst emission rates. The basic characteristics of the four engines that were tested are shown in Table 5-1

Table 5-1. Characteristics of the engines tested in 2006.

Engine ID	74236	75558	74376	77764
Site Name	Lawrence #1	China-Knome	Lockridge	Oak Hill #2
Location	near Kilgore	near Tyler	near Kilgore	Near Kilgore
Make & Model	CAT 3306 TA	CAT 3306 TA	CAT 342 NA	CAT 3306 NA
Turbocharged	Yes	Yes	No	No
Rated Horsepower	220	220	225	120

A comparison of the tests with those previously conducted are shown in Table 5-2.

Table 5-2. Longevity testing results for engines tested in 2005 and 2006.

Engine Description		**2005 Reduction of NOx Emissions**	**Longevity Testing (after one year of operations)**		**2006 Reduction of NOx Emissions**
Engine ID	**Engine Description**		**Pre-Catalyst (g/hp-hr)**	**Post-Catalyst (g/hp-hr)**	
74236	CAT 3306 TA	96%	4.68	0.18	96%
75558	CAT 3306 TA	97%	6.41	0.58	91%

A summary of the testing results of the additional two engines is provided Table 5-3.

Table 5-3. Summary of NOx emissions reductions for 2 engines retrofitted in 2006.

Engine Description		Test Conditions		NOx Emissions Testing		Reduction of NOx Emissions
Engine ID	**Engine Description**	**Operating Power**	**Load Factor**	**Pre-Catalyst (g/hp-hr)**	**Post-Catalyst (g/hp-hr)**	
74376	CAT 342 NA	142	0.63	7.91	1.19	85%
77764	CAT 3306 NA	124	1.0	10.37	0.05	99%

COMPRESSOR ENGINE RETROFITS-PROCEDURE AND RESULTS

As summarized above, additional testing was conducted on four engines in August 2006. The test methods were identical to those used previously in 2005. The first group of tests (on August 10, 2006) were longevity tests conducted on two installations that were tested in 2005. The remaining tests (on August 23, 2006) were conducted on two engines that had not been previously tested. Catalysts were installed on these engines on August 10, 2006. Due to time constraints, we were not able to conduct baseline tests prior to installation of the catalysts. Pre-catalyst and post-catalyst tests were conducted on both engine groups. The project timeline for the 2006 testing is shown in Table 5-4.

Table 5-4. Timeline for 2006 retrofits and testing.

Date	Engine Group 1	Engine Group 2
July 24, 2006	2 Engines identified	
August 6, 2006		2 Engines identified
August 10, 2006	Longevity testing	
August 10, 2006		Installation of retrofit
August 23, 2006		Post Installation Testing

As with previous tests, the procedure followed from the selection of engines through the post-installation testing was nearly identical for all four engines. The Hanover Company was tasked with the selection of engines that had previously been tested to evaluate the longevity of the control equipment previously tested. In discussions with the Hanover Company, only two engines previously tested were available to retest because the other two engines had been transferred out of the NETAC area. However, control equipment had been removed from those two engines and was available to install on two additional engines.

The criteria for selecting two additional engines were that the engine be an uncontrolled, less than 500 horsepower, rich-burn engine operating in the five county NETAC area. Discussion with Hanover personnel identified additional considerations to use in the selection of engines. Engines with no recent history of mechanical difficulties and engines that were expected to remain in service in the same location for the near future were preferred. These additional considerations were expedient for the purposes of the pilot project, but they are not necessary for successful use or demonstration of the control technology. One of the benefits of the control system selected is that it can be transferred relatively easily from one engine to another. This is a useful feature considering the dynamic nature of the gas compression industry. In fact, the control technology from two engines previously tested that were no longer in service had been removed by Hanover staff and was reinstalled on the second group of engines.

Once engines were selected, the retrofit systems were installed and testing was scheduled. The components of the systems were nearly identical for all engines. The only significant variation was the sizing of the catalysts to match the rated power of the engines. Other properties of the system, such as flange and port sizes varied slightly from one engine to the next, but these would only require minor modifications in order to transfer the equipment from one engine to the next. The most important factor to be considered in the sizing of the catalyst is the engine power and catalyst vendors can provide advice on engine/catalyst compatibility. Appropriate sizing of the catalyst ensures that the designed control efficiency is attained. This is not to say that a certain catalyst is tied to a certain engine. As shown in Table 5-5, the normally aspirated engines were equipped with the same size catalyst as the turbocharged engines. Though that meant that engines differing in power by approximately 40 horsepower were fitted with the same size catalyst, very high NOx reductions were achieved for both power ratings. This demonstrated that only minor modifications were necessary to transfer the control equipment between similar engines.

Table 5-5. Catalyst type and for engines tested in 2006.

Engine ID	Make Model	Fuel	Catalytic Converter [1]
74376	CAT 342 NA	Pipeline Quality Natural Gas	MINE-X® Model DC48
74236, 75558	CAT 3306 TA		MINE-X® Model DC47
77764	CAT 3306 NA		MINE-X® Model DC47

[1] There are many manufacturers of catalysts. The use of a specific manufacturer in this project is not intended as an endorsement of that manufacturer or their products.

As described in the discussion of this control technology, it was necessary to equip the engines with electronic air/fuel ratio (AFR) controllers to provide for the proper functioning of the catalyst. A solar power supply was also incorporated into the system to provide power for the AFR controller. All these components would need to be installed with any additional retrofits. The complete cost of the catalytic converter and AFR package ranged between about $7,500 and $7,900 per engine. A complete cost effectiveness analysis was presented in Section 3 of this report.

There was insufficient time to conduct baseline testing for engines not previously equipped with a catalyst. Therefore, the only baseline tests conducted prior to installation of the control equipment was the tests previously conducted on the two Group 1 engines. All testing was performed in accordance with the previously described testing procedures. A third-party company specializing in emissions testing was contracted to perform both the post-retrofit tests.

On average, the total cost for performing an emissions test following the EPA methods and using a third-party contractor was approximately $2,800 per engine test. That includes both mobilization and testing costs.

Staff at the Hanover Company estimated that approximately 13 employee-hours were required for the reinstallation of equipment on each of the Group 2 engines (personal communication from Keith McClurg, 2006). Labor was estimated to be $975 per engine. The equipment installation included the setup of the solar unit, incorporation of the catalytic converter into the exhaust system, and the setup of the AFR controller which included integration of AFR controller’s fuel/air control valve. Figure 5-1 shows the compressor engine located at the Oak Hill Compressor Station with the catalyst placed in the exhaust system.

Figure 5-1. Retrofit system showing catalyst installation in compressor exhaust line.

LONGEVITY TESTING

After nearly one year of continuous operation, additional testing of the two engines previously tested in 2005 found highly efficient NOx control. It should be noted that the only engine retested which had previously been tested prior to installing the catalyst (baseline test) was the unit at China-Knome (#75558). Hanover staff reported that during the past year the two engines operated nearly continuously, shutting down only briefly for regularly scheduled engine maintenance. Engine down-time was estimated to have been less than two percent of the total, implying that after one year, engine had 74236 operated for well over 8,000 hours and after 1 year and 6 months, engine 75558 had operated for over 12,000 hours (McClurg, 2006). Table 5-6 shows the results of the testing performed on two engines, one to one and a half years after the engines were retrofitted.

Table 5-6. Emissions test results for engines with one year or more of operation.

Engine	Unit	75558	74236	Average
	Make/Model	**CAT 342 NA**	**CAT 3306 TA**	
	Power	**225**	**220**	
Longevity Test Conditions	Time Since Retrofit	1.5 year	1 years	
	Operating Power	121	84	102.5
	Load Factor	0.54	0.38	
Pre-Catalyst Testing	NOx (lbs/hr)	3.11	2.27	
	NOx (g/hp-hr)	**6.41**	**4.68**	5.55
	CO (lbs/hr)	2.37	2.43	
	THC (lbs/hr)	0.32	2.43	
Post-Catalyst Testing	NOx (lbs/hr)	0.28	0.09	
	NOx (g/hp-hr)	**0.58**	**0.18**	0.38
	CO (lbs/hr)	0.24	0.11	
	THC (lbs/hr)	0.18	0.34	
Control Efficiency Demonstrated	**NOx Abatement by Catalyst[1]**	**91%**	**96%**	94%

[1] Comparison of the NOx produced by the engine versus the NOx emitted to the atmosphere.

The longevity testing used the same EPA methods and third-party contractor as the previous tests. Testing the exhaust gases before entrance to the catalyst made possible a comparison of the emissions reduction across the catalyst, termed the "NOx abatement by catalyst." The NOx abatement by the catalyst offers a useful measure of the effectiveness of the control strategy because it is relatively independent of the operating conditions at the time of testing. The measurement of NOx abatement by the catalyst shows that after one to one and a half years the catalysts were reducing NOx emissions from the engines by an average of 94 percent.

While the effectiveness of a catalyst can decline with time, periodic washing of the catalyst can provide extended life without incurring the cost of replacing the catalyst. The catalyst supplier estimated that this maintenance procedure will be required approximately every two years (DCL, 2002). This longevity testing demonstrated that after one year or more, the control system is still effectively reducing NOx emissions by an average of well over 90 percent. Continued periodic testing of the pre- and post-catalyst emissions concentrations using a portable analyzer should detect when the effectiveness of the catalyst has declined to such a level that maintenance should be performed.

Testing Reinstalled Catalysts

Two Hanover engines were retrofitted in August 2006 with equipment that had been removed from engines that were transferred out of the NETAC area. The emissions test results for these engines are shown in Table 5-7. These tests may be considered as longevity tests on the catalysts, since the catalysts were purchased in 2005, but the number hours each catalyst had been in service is not known. Also, the catalysts might have been contaminated during removal and storage. One catalyst demonstrated excellent NOx abatement performance (99% reduction) but the other catalyst achieved only 85% NOx reduction indicating that it may need to be cleaned.

Table 5-7. Emissions test results for engines retrofitted in 2006.

Engine	**Unit**	**74376**	**77764**
	Make/Model	**CAT 342 NA**	**CAT 3306 TA**
	Power	**225**	**120**
Test Conditions	Operating Power	142	124
	Load Factor	0.64	1.0
Pre-Catalyst Testing	NOx (lbs/hr)	3.22	2.81
	NOx (g/hp-hr)	**7.91**	**10.37**
	CO (lbs/hr)	15.13	4.60
	THC (lbs/hr)	1.19	0.69
Post-Catalyst Testing	NOx (lbs/hr)	0.51	0.01
	NOx (g/hp-hr)	**1.19**	**0.05**
	CO (lbs/hr)	0.37	0.21
	THC (lbs/hr)	0.64	0.25
Control Efficiency Demonstrated	**NOx Abatement by Catalyst[1]**	**85%**	**99%**

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