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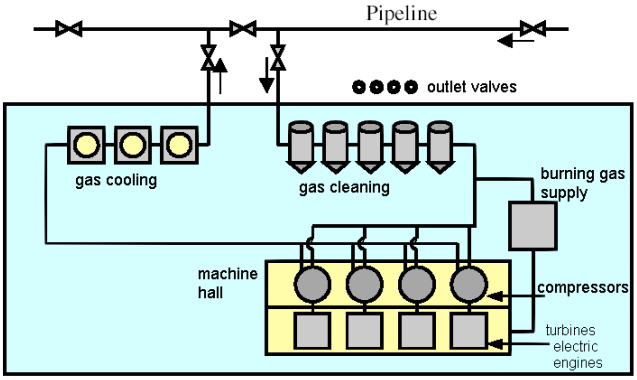
Strategic Emission Reduction Plan (SERP) for Stationary Oil and Gas Sources in the Four Corners Region



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Strategic Emission Reduction Plan (SERP) for Stationary Sources in the Four Corners Region

Introduction

Goal

The overall goal of this strategic plan is to improve air quality and visibility across the Four Corners Region. This improvement is intended to be achieved primarily with use of voluntary measures aimed at controlling emissions from "dirty" turbine, compressor and other engines within the San Juan Basin. It along with other cumulative mitigation measures will also provide sanction for continued operations of existing clean oil and gas engines and through use of cleaner engine technologies will provide opportunities for expansion of oil and gas exploration and production within the San Juan Basin.

Objective

The objective of this strategic plan is to provide a framework for implementing a voluntary NO_x/SO_x, $PM_{10}/PM_{2.5}$, VOC, and CO emission reduction program using incentive based options (e.g., emissions market-based trading systems) combined with company specific caps and/or state or regional cumulative emission ceilings. The proposed SERP framework is intended to complement other policies and programs aimed at reducing criteria air pollutant emissions.

Scope of the Plan

The scope of this plan is limited to current and future operations within the Four Corners Task Force on Air Quality and Visibility (FCTF-AQV) "study area," essentially the San Juan Basin (MOU 2005). Depending on the outcome of evaluation of future plan implementation effectiveness and/or feasibility, proposed strategic emissions reduction plan (SERP) can be expanded to cover other source categories and to the wider FCTF-AQV's "impact area" or cumulative "study area" (MOU 2005).

Initially the plan will cover natural and coalbed methane (CBM) gas (NCBMG) exploration/production engines and associated facilities. Through review and analyses of data for existing engine inventories, innovative source-specific emission reduction options will be formulated using energy efficiency incentive cost-based emission reduction credit formulas. The SERP can be expanded based on the success in implementing the proposed Program, as measured in the success in building industry-government partnerships and the degree of reasonably achievable potential for emission reduction. The decision to expand and include other stationary and mobile sources in the Four Corners Region would of course be at the discretion of the FCTF-AQV's Policy

Oversight Group (POG).

Particular attention will be given to controlling sources contributing to release of primary aerosols (direct source $PM_{2.5}/PM_{10}$ emissions) and direct source emissions linked to formation of secondary aerosols (< 2.5 microns in mass median aerodynamic diameter) that contribute to visibility impairment. Visibility and other regional air issues (e.g., ozone regional haze, rural ozone, wet/dry deposition to sensitive lakes) and local air issues (e.g., criteria air pollutant exceedances, air toxics) will also need to be addressed through use of existing or future SIPs, through other initiatives, such as, the Early Action Compact for Ozone (being developed) and if needed through possible future expansion and/or enhancement of the SERP.

Strategy

The initial strategy focus will cover compressor engines and natural gas-fired and diesel-fired engines associated with production operations (e.g., CBM dewatering pump engines, other pump jack engines) and engines associated with exploration (e.g., drill rig engines). Compressors within the Basin are used for the production and pipeline transport of natural gas produced by the wells. Small wellhead engines are primarily used for water disposal as well as other uses. The compressors and small engines emit NO_x, CO, volatile organic compounds (VOC) and hazardous air pollutants (HAP). To characterize these emissions and to identify the most appropriate and cost-effective controls, engine inventory data are being collected from the oil and gas industry (OGI) producers. The inventory does not cover small natural gas-fired heaters used in conjunction with separation and dehydration units. These heaters would emit smaller and relatively minor quantities of NO_x and CO.

This SERP provides recommendations that combine the use of incentive-based voluntary mitigation measures along with the use of existing state and federal regulatory limits on NOx emissions for OGI exploration and production operations. Through a coordinated partnership between state, local and federal environmental authorities, OGI industry representatives and engine/control technology manufacturer representatives it should be possible to set and achieve a company or operator “fleet” average emission level goal of 2 g NOx/hp-hr for small engines (< 200 hp) and 1 g/hp-hr for large engines (≥ 200 hp). The SERP should achieve these results using economic based incentives along with consideration of cost-effective engine inventory specific pre-combustion control measures for existing small “dirty” engines and use available or soon to be available advanced technologies to accommodate new source growth.

Description of Proposed Strategic Emission Reduction Plan

The proposed emission reduction strategy involves providing a variety of voluntary measures using economic based incentives (e.g., NO_x markets, energy efficiencies, alternative fuels or energy technologies) along with use of already in place mandatory measures within existing federal rulemaking and/or state regulatory permitting authority. A variety of cooperative and/or collaborative opportunities exist for establishing incentives that could lead to air quality improvements in the region. Some of these are listed and briefly discussed below. Use of a combination cooperative incentives along with in-place regulatory requirements (existing SIP rules and existing federal rules on engine manufacturers) to achieve voluntary strategic mitigation can be used to: 1) initially reduce the annual rate of increase in air emissions, 2) stabilize the annual emission levels at an agreed upon predetermined Four Corners regional emissions cap- or ceiling-level(s) and 3) achieve an overall reduction in emissions now contributing to air quality and visibility degradation and to further impacts on air quality related values.

This SERP includes four major elements or sets of cooperative and collaborative opportunities for implementing primarily voluntary incentive-based control measures. The first opportunity serves as a foundation for carrying-out emission reductions or credits derived from other opportunities in the SERP. It involves cooperation between the producers and the designated state and/or federal agency to setup and implement a market oriented emissions trading system. The details for implementing such a system in the Four Corners Region would need to be worked out. The second opportunity involves promoting collaborative partnerships between oil and gas producers and engine manufacturers to field test new cleaner engine designs and to replace existing old dirty engines. A third opportunity exists between producers and the USEPA to establish and implement best management practices aimed at more efficient and cleaner operations. Finally, an opportunity may exist for oil and gas and environmental stakeholders to collaborate to lobby state legislators on sponsorship of legislation providing accelerated depreciation tax credits that have connected environmental-based benefits. Further elaboration on each or these opportunities or SERP elements are described below.

A. Opportunities involving cooperation and collaboration between producers and multi-state (NM and CO) environmental agencies

San Juan Basin Emission Trading System (ETS) – A commodity market-based system for allocating and trading emissions credits could in combination with other voluntary measures provide opportunities for significant air emission reductions in the Four Corners Region. Such a system could be incorporated in or referenced to existing state regulations covering emissions trading or a new system could be developed and tailored to specific needs and conditions within the Four Corners

Region. There is currently no ETS in effect for the State's of CO or NM[1].

Simple stated in an ETS, a producer who has low-emission engines could sell emissions credits to a producer who has high-emission engines. Typically, 0.8 units of credit could be sold for each unit of reduction below the standard or reference level. The result is a ratcheting down of overall emissions.

An emissions trading commodity market system is an administrative approach used to reduce the cost of pollution control by providing economic incentives for achieving reductions in the emissions of pollutants. In such a plan, a central authority, such as an air pollution control district or a government agency, whether on a federal or state level, sets limits or "caps" on each pollutant, recognizing that clean air is a common-pool resource. Groups that intend to exceed the limits may buy *emissions credits* from entities that are able to stay below their designated limits. This transfer is normally referred to as a trade.

Many different forms of emissions trading have evolved over the past 10 to 20 years. However, the underlying theme is to provide participants with the flexibility to determine the most economic means to reduce emissions. The diversity of trading markets that have evolved is primarily a consequence of the "commodities" (e.g., air pollutant allowances) traded and the scope of the market.

There are three basic types of emission trading programs (ETP). These include emission reduction and/or trading programs that are: 1) bubble-based; 2) allowance, offsets and credits-based emission reduction trading (AOCERT); and 3) caps and trades-based (CapT). Most successful programs, like the USEPA's Acid Rain Program, usually combine elements from the later two, AOCERT and CapT, in combination with baseline and rate-based trading concepts. Each of these ETPs and the two mentioned trading concepts are briefly described below.

ETP 1: Bubble Programs allow an entity with multiple emissions sources to combine their total emissions targets from these multiple sources under one accounting entity. This creates flexibility to apply pollution control technologies to whichever source under the bubble has the most cost effective pollution control options, while ensuring the total amount of emissions under the bubble meets the

[1] In Colorado a generic ETS called Regulation No. 5 "Generic Emissions Trading and Banking" was drafted in the mid-1990s but never adopted (King, Kirsten 2006). The original intent was to incorporate it to the CO SIP. Colorado, in its Regulation No. 18 "Control of Emissions of Acid Deposition Precursors," also refers to EPA emission trading system under the national Acid Rain Program and the allowance for the development of a nitrogen oxides trading program to be implemented through State Implementation Plan (SIP) revision. However, Regulation 18 states that the Air "Division does not intend to implement this trading option at this time." Finally CO is drafting a regional haze SIP that may incorporate an ETS. A draft of the RH SIP is expected to be available for public comment in the summer of 2007. The In New Mexico, the state's regional haze state implementation plan (SIP) under Section 309 of the Regional Haze Rule, was approved by the New Mexico Environmental Improvement Board in November 2003. Although the Haze Rule uses and makes reference to an evaluation for the need for NO_x and PM emission control strategies based upon the analysis in the WRAP Western Backstop (WEB) Emissions and Allowance Tracking System (WRAP 2003), the haze rule does not incorporate a state specific ETS.

overall environmental restrictions.

ETP 2: Allowances, Offsets and Credits-based Emission Reduction Trading (AOCERT) Programs represent the next iteration of emissions trading. These systems are new source project-based, often incorporating non-capped emission sources or source owner/operators. The system will allow producers that wish to increase their emissions to obtain offsetting reductions from entities that are not required to reduce their emissions. The market-based ETP used by the USEPA in its Acid Rain Program is largely based on the use of an allowance based system but it also includes the use of emission caps as described below under ETP 3. This program is already being viewed around the world as a prototype for tackling emerging environmental issues

An allowance authorizes a unit within an owner company source to emit one ton of a regulated pollutant. Allowances may be used during a given year or any year thereafter. At the end of each year, the unit must hold an amount of allowances at least equal to its annual emissions, i.e., a unit that emits 5,000 tons of NO_x must hold at least 5,000 allowances that are usable in that year. Allowances are allocated for each year beginning in the base year. The designated regulatory authority allocates allowances at an emission limit rule based or an agreed upon targeted emission rate (e.g., 3 g of NO_x/hp-hr), multiplied by the unit's baseline horsepower rating (the average load or natural gas consumed over an agreed upon historical operating period prior to the established base year for trading program). The total number of allowance issued per year can be capped ensures that the mandated emissions reductions are maintained over time (see further discussion below under ETP 3, cap and trade programs). Units that began operating in or later than the base year are not allocated allowances. Instead, they have to purchase allowances from the market or from auctions and direct sales to cover their pollutant emissions.[2]

Allowances may be bought, sold, and traded by any individual, corporation, or governing body, including brokers, municipalities, environmental groups, and private citizens. The primary participants in allowance trading are officials designated and authorized to represent the owners and operators of oil and gas production facilities that emit traded pollutant. One way track and trade allowances is to model the ETS adopted for the San Juan Basin based upon the USEPS Acid Rain Program (USEPA, 2006 ATS). The Illinois EPA's Emission Reduction Market System and the Indiana Department of Environmental Management's credit

[2] In addition to annual allocations, allowances can also be made available upon application to the regulatory authority's reserves. Three types of reserves can be established. First, source units can apply for and receive additional allowances by installing a qualifying technology (pre- or aftertreatment controls that can be demonstrated to remove at least xx% of the unit's NOx emissions) or by reassigning their reduction requirements among other units employing such technology (see Appendix __ for applicable engine control technologies). A second reserve can be setup to provide allowances as incentives for units achieving NOx emissions reductions through customer-oriented conservation measures or renewable energy generation. Finally, a third reserve can be used to contain allowances set aside for auctions, which are sponsored yearly by the designated regulatory authority.

registry trading system also have web sites to track allowances and to trade (buy/sell) credits (IEPA, 2006 ERMS and IDEM, 2006 ECR). In addition, a roadmap for establishing an emission trading and allocations trading system has been prepared by WRAP (as authorized in Sec 309 of the Regional Haze Rule) to do so, if it become necessary. The proposed system is called the Western Backstop (WEB) Emissions and Allowance Tracking System (EATS)[3].

An emission credit represents surplus reduction in air pollutant emissions equal to one ton of pollutant per year (1 tpy) that exceeds the amount of reduction required under state or federal law, regulation, order (i.e., consent decrees, agreed orders, etc.), or other enforceable mechanism. Emission credits must be permanent and quantifiable. Emission reductions that have previously been used to avoid New Source Review through a netting demonstration are not considered surplus. New sources, for example, undergoing NSR permitting requirements must offset the increase in emissions from the proposed new facility (e.g., compressor) to provide a net air quality benefit. The purpose of offsetting these emissions is to allow for improvement in air quality in the region while still allowing for growth in oil and gas production. Offsets are created when an emitting company makes voluntary, permanent emission reductions that are legally recognized by a regulator as Emission Reduction Credits or Offsets. Those Offsets are sold to new or expanding emission sources to 'offset' the new emissions. Regulators approve each trade; however, regulators usually require a percentage of the Offsets be retired as a dividend to the environment. A mass NO_x or HC or PM emission reduction is not an emissions offset or credit. An official offset or credit requires formal recognition (accreditation) by the designated or empowered regulatory authorities (e.g., NM Environmental Department, CO Department of Public Health and Environment, USEPA Region VIII).

Cap and Trade (CapT) Programs are more evolved forms of emissions trading. A regulatory authority establishes an aggregate cap on the emissions of a pollutant that is a firm and permanent limit for a group of emitters. The allowed cap has historically been a fraction of the historic emissions from those sources. For example, the U.S. Acid Rain Program instituted a 50% reduction from 1980 levels of SO_2 emissions from utilities, and the Ozone Transport Commission NO_x Program imposed a 65% reduction from 1990 levels and is scheduled to achieve an 85% reduction after the next phase. Trading occurs when an entity with excess allowances, liberated through actions or improvements made, sells them to an entity requiring allowances.

There are also two additional trading concepts involved with emissions trading that

[3] Section 309(d)(h)(4)(v) of the Regional Haze rule requires that "the Implementation Plan must provide for submitting data to a centralized system for the tracking of allowances and emissions." Although the DC Court of Appeals has vacated EPA's original Regional Haze Rule, its new final rule is expected to be published within the next 40 to 60 days. Five western states have already submitted their RH SIPs and are expected to resubmit their SIPs once the new EPA RH rule is promulgated (Patrick Cummins, 2006).

can be combined with the above systems:

Baseline Emission Reduction Trading Concepts (BERTC) are also new source project-based, often incorporating non-capped industries and entities. This type of system allows an entity to voluntarily reduce emissions below an agreed baseline under business as usual. The accreditation system is based upon the delta between two emission forecasts: with and without the proposed project. One way to establish baseline emission levels (as used in ETS 2 above) is to set it to the average emissions by producers for last 2 to 3 years of operations. The baseline emissions should not be more than federal and state emission cap (see below). There should be the target reduction in the emissions over an agreed upon time period, say a 5 years. The reduced yearly allowances over this period will provide for incremental emission reductions through the incrementally reduced total allowance available to producers. This emission trading concept is sometimes referred to as a Clean Development Mechanism (CDM).

Rate-based (or relative) emissions trading focuses on the emission per unit of output rather than absolute emissions. This system is intended to promote increased efficiency without limiting growth of the underlying business. Within such a system entities that improve their efficiency beyond the target levels can trade the excess improvement with other companies. For example, Corporate Average Fleet Efficiency (or CAFE) standards in the US allow auto manufactures to make changes within their own fleet of vehicles to ensure an overall average improvement in gas mileage per vehicle sold.

B. Opportunities involving cooperation/collaboration partnerships between oil and gas producers and engine manufactures and the FCTF-AQV

Collaborative voluntary opportunities, between producers and engine manufactures, exist to investigate cost effective emission reductions through use of selective engine replacements and engine retrofits and use of emission credit incentives and energy efficiencies to introduce advanced engine technologies and alternative technologies. These decisions would need to be based on review and analysis of engine specific data and by performing and evaluating field and laboratory test results on existing engines. Producers would provide key engine data parameters from their existing engine inventories and would identify which engines in their fleets would be best candidates for replacements. They would also identify candidate engines for retrofits and laboratory testing. Engine manufacturers would provide new heavy-duty state-of-the-art engines for field tests.

The producer specific engine inventories collected through company specific surveys would collect the data parameters on existing engines currently operating within the San Juan Basin. This data would include, for example, engine 1) manufacture/contact, 2) model number, 3) age, 4) load cycle, 5) size (e.g., bhp), 6)

power load, 7) estimated maintenance cost, and 8) emission controls (e.g., turbocharged, electronic fuel injection, TC/after-cooled, air/fuel ratio controlled combustion, NO_x absorbers, nonselective/ selective catalytic reduction).

Identifying which engines would be good swap-out candidates will require review of data on engine age, condition and performance. Data on engine age and maintenance cost can be used to look for correlation between age and emissions and to quantify maintenance cost of existing engines compared to replacement and Maintenance costs of new engines. Replacing new engines in a phased manner could provide significant cost-benefits to producers in the long run and would provide incremental reduction in overall emission levels. Old or badly worn engines may be good candidates for replacement with newer ones that have lower emissions using available engineered exhaust aftertreatments.

Four voluntary emission reductions initiatives can be pursued in this partnership area. These areas would include 1) voluntary replacements of old and dirty engines in respective company inventories, 2) identify the best engine candidates for cost-effective voluntary retrofits, 3) run a laboratory test-bed to evaluate advanced engine controls for possible adaptation to new engine designs and/or introduction into current production operations, and 4) voluntary introduction of available next generation engine technologies and alternative fuel or power technologies. Each of are initiative areas are discussed further below.

1. **Voluntary Replacements of "Dirty" Engines: Old with New Swap-outs and Establishing Field Test-beds** - This voluntary measure can be arranged through a negotiated agreement between producers and engine manufacturers to provide opportunities for both by swapping-out small (< 300 hp) old dirty engines with new small cleaner by-design engines. Old or badly worn engines may be candidates for replacement with newer ones that have lower emissions and have engineered exhaust aftertreatments available. The newer engines are more reliable and need less maintenance. The agreement should include establishing field test-beds to monitor emissions from new engines under real operating and environmental conditions. The field measurements would improve the quality of emissions data in the data base and verify decreased emissions from improved engine technology. This data can also be used establishing validated emission reduction credits for use in any emission trading program that may be adopted and implemented in the San Juan Basin. In addition to the market-based incentive provided by engine swap-outs, the added newer cleaner engines would provide incentive benefits through lower maintenance and operation costs. The incentive for engine manufacture participation in this swap-out/in test-bed program would be the potential for it to lead to large new small oil and gas engine markets.

2. **Identify the Best Engine Candidates for Cost-Effective Retrofits** - Each producer will have a different mix of engines and emissions reduction technologies. The basic approach is the same and follows the following steps:

   a.) First, construct a data base of the producer's engines with particular

emphasis on the installed power, the engine technology (rich-burn, lean-burn, or diesel), the type of emission-control technology (no aftertreatment, NSCR, SCR, or oxidation catalyst), and the emissions from each engine. It may be necessary to use portable emission measurement systems (PEMS) to determine the actual emissions from the engines.

b.) Look for a group of engines that have emissions that are out of proportion to their installed power. These are likely to be engines with no exhaust aftertreatment. Retrofit those engines with exhaust aftertreatment or replace old engines with new engines having exhaust aftertreatments. The recommended aftertreatments are: NSCR for rich-burn engines, oxidation catalysts for lean-burn engines, and SCR for diesel engines (see Appendix B for further details on these post-combustion technologies).

c.) Look for a group of engines that account for a large percentage of the overall NO_x emission, even if this emission is not out of proportion to the overall total. Either add an appropriate exhaust aftertreatment or upgrade an existing aftertreatment. It is likely that many engines in this group will be the same make and model. A common solution will exist for them, and there can be an economy of scale for multiple identical units.

A limited engine inventory survey was conducted to collect and analyze the some of the key parameters just mentioned. Two producers have participated and have provided their respective engine inventory data. Review of this data is given in Appendix A.

In addition to the identified engines that are the most appropriate candidates for post-combustion retrofits (most likely the large or moderate sized engines), cost-effective pre-combustion controls on smaller engines should also be evaluated and some possibly unique aftertreatment controls should be considered. Best candidates would likely be engines with relatively short logged service or operation times (e.g. < 5 yrs). An example cost-effective pre-combustion control measure for uncontrolled small stationary engines would be to add automatic air-fuel ratio controllers. This measure my also be cost-effective for large engines. An example cost-effective post-combustion control measure would be to try using motor vehicle styled tail-pipe controls (catalytic converters) on small engines. These controls may be able to be retrofitted cost-effectively on a large number of small engines operating in the San Juan Basin. Motor vehicle style catalytic converters are cheap and very reliable.

A wide variety of engine control technologies are available for use in engine retrofits. These technologies are listed and reviewed in Appendix B.

3. **Laboratory Test-bed for Advanced Engine Controls** - Establish laboratory test-bed to evaluate advanced pretreatment technologies on a representative set of existing uncontrolled or poorly controlled operational engines. These tests would be designed to find optimal energy efficient measures aimed at reducing overall emissions in inventories from participating producers. Some examples of advanced technologies that could be tested, evaluated and

improved/refined, as necessary, include:

a. Laser ignition system that could allow lean-burn engines to operate at leaner conditions than are now possible and would reduce engine maintenance costs by eliminating the need to replace spark-plugs.

b. Nitrogen-enriched air using air-separation membranes as an alternative to exhaust-gas recirculation (EGR). The technology could improve engine life by eliminating the abrasive particulate matter and other combustion products from the engine intake. This option is primarily intended for diesel engines, which have a considerable amount of particulate matter in their exhaust.

c. Catalytic methods of producing hydrogen from the fuel. Small quantities of this hydrogen could improve the flame speed and ignitability of the fuel in lean-burn engines. This would allow the engine to be tuned for lower emissions.

d. Develop improved catalysts for aftertreatment of exhaust emissions.

The goal of both the new engine and cleaner existing engine programs, with field and laboratory test-bed components would be to produce cleaner inventories with emission benchmarks meeting or exceeding USEPA's recently promulgated emission standards for new stationary nonroad engines (40 CFR Part 1048, 68347, November 8, 2002). These rules include currently effective Tier 1 steady-state emission standards and Tier 2 duty cycle transient emission standards, which become effective for new engines in 2007. The Tier 2 standards (see Table 1) establish a NO_x+HC cap at 2 g/hp-hr and a CO cap at 15.4 g/hp-hr. The NO_x+HC levels are duty cycle averages. By using the transient Tier 2 standards it is possible to provide some flexibility for producers in establishing their banked emissions (depending on existing control levels this can include either a positive or negative balance). Once banked emission levels are established for each producer, the required emission reduction levels can be determined and emission trading/controls can than be initiated.

Heavy-duty natural gas fired engines that meet EPA 2007 emission levels (1.2 g/bhp-hr NO_x and 0.01 g/bhp-hr PM) are now commercially available. Heavy-duty engines are in the final stages of R&D for EPA 2010 emission levels set at 0.2 g/bhp-hr NO_x and 0.01 g/bhp-hr PM (Clark 2006).

Table 1: Emission Standards for Large spark-ignition (SI) Engines* (25 hp)
(40CFR, PART 1048 - Non-road stationary engine standards)

Tier 1 Steady-State Emission Standards (Simple Rated Load Laboratory Measurement)					
Tier	Year	$HC+NO_x$	CO	$HC+NO_x$	CO
		g/kW-hr		g/hp/hr	
1	2004	4	50	3	37.3

Tier 2 Duty Cycle (Transient) Emission Standards (Transient Laboratory Testing)					
Tier	Year	$HC+NO_x$	CO	$HC+NO_x$	CO
		g/kW-hr		g/hp/hr	
2	2007	2.7	4.4	2	3.3
		2.2	4.4	1.6	3.3
		1.7	5.6	1.3	4.2
		1.3	7.9	1	5.9
		1	11.1	0.7	8.3
		0.8	20.6	0.6	15.4

4. Advanced Developing Engine Technologies and Alternative Technologies - In selecting engines for use in new or expanded production fields, strong consideration should be given to very clean next generation engines that are or are near commercial availability or to alternative pumping power technologies.

a.) Next Generation Natural Gas and Diesel Engines - Commercially Available Engines or Near Commercial In-Development Engines

High-Pressure Direct-Injected, Ultra Low- NO_x Natural Gas Engine: Cummins-Westport - The Cummins ISX engine using the High Pressure Direct Injection (HPDI™) developed by Westport Innovations, Inc. is a natural gas fuel system with exhaust gas recirculation (EGR) that met the following required specifications during demonstration testing:

- Peak torque of 1,650 ft-lb (2,236 N-m)
- Rated power of 450 hp (335 kW)
- Peak thermal efficiency of 40% with typical diesel part-load efficiency
- NO_x emissions of 0.5 g/bhp-hr
- PM emissions of 0.1 g/bhp-hr
- Substitution of diesel with natural gas greater than 90% over the certification cycle

Steady state engine calibration was developed using design of experiment test techniques. Testing over the European Stationary Cycle (ESC) 13-mode cycle resulted in weighted NO_x emissions of 0.37 g/bhp-hr, NMHC emissions of 0.2 g/bhp-hr, methane (CH_4) emissions of 2.08 g/bhp-hr, PM emissions of 0.04 g/bhp-hr, and a weighted thermal efficiency of 36.1% (Duggal 2004).

In its final hardware configuration in 2004, the engine was shipped to the Cummins Engine test facility for transient testing and calibration refinement. The results from these tests are reported in Duggal 2004.

b.) Alternative Technologies

1 *Fossil Powered Electric Driven Motors* - Look for special situations, for example, in using electricity driven motors to replace fossil fuel fired

engines. This could be in situations where close proximity to electric power lines would easily facilitate replacement with electric motors. Although most of the engines used in the oil and gas industry are widely dispersed and far from power lines, there may be some that are close enough to a power line to make replacing an engine with an electric motor practical.

In areas that are not near electrical power lines, there may be clusters of small engines with high emissions. In these areas it may be possible to replace the small high-emission engines with a larger low-emission engine and an electric generator. Relatively short dedicated power lines would deliver the power to electric motors that replace the small high-emission engines.

2. *Renewable Energy Powered Electric Driven Engines* - Replace natural gas engines with solar or wind power driven electric engines. Development of wind farms to supply power is a mitigation option currently being considered by the FCTF-AQV. Although such a system would have to be gradually phased in, it could eventually supply more power than is required to drive an electric compressor, CBM pump, and drill rig engine system within the San Juan Basin. Any excess power could be brokered with utilities and sold and distributed back onto the electric power grid. This option could be an attractive revenue generating incentive to the oil and gas industry. If fully realized it could completely eliminate or significantly reduce engine emissions (e.g., 85% reduction of NO_x emissions) to a degree potentially larger than any another control option covered in this strategy paper. If turns out that wind farms produce smaller gains (e.g., 50% reduction in NO_x emissions), the gains realized could be used as credits in any emission trading system that is established for the Four Corners Region. Emission credits from wind farms could serve as another attractive incentive to producers. This option would require further regional terrain specific feasibility study (e.g., can the wind farm be located within the basin) and possible company specific economic feasibility study (e.g., an oil and gas industry wind farm partnership might be the way to go).

3. *Hybrid Systems: Blend Solar/Wind/Diesel/NG* Engines- Solar and wind energy is not always available when it is needed. A hybrid system having solar or wind power coupled to an engine could reduce overall engine emissions while providing power when solar or wind energy are not fully available.

C. Opportunities involving producer/refiner GasSTAR type voluntary partnerships with USEPA

Finding opportunities for proactive adoption of best management practices that cuts energy use, stops energy loss and reduces air emissions makes good economic sense for energy producers and reduces air emissions, including greenhouse gases. One program, Natural Gas STAR Program, has been very successful in reducing greenhouse gas emissions, specifically methane. It may be possible to adopt or adapt and extend this program in the Four Corners Region. The Natural Gas STAR Program is an EPA-sponsored, voluntary market-based

program that encourages natural gas companies to adopt cost effective methods for reducing methane emissions for greenhouse gas credits. Natural Gas STAR Partners agree to implement cost-effective Best Management Practices (BMP), which will save participants money and improve environmental quality. Some examples of some BMPs that have been very successful in reducing methane emissions or losses to the environment from production, transmission/distribution, and processing are listed in Appendix C.

Other BMPs that could in addition to having methane reduction benefits could also produce significant reductions NO_x, VOCs, CO, and HAPs. These BMPs are being pursued or considered by some partners in the Natural Gas STAR Program. A few promising BMPs (the quoted text below are excerpts from EPA PRO Fact Sheets produced for the Natural Gas STAR Program) that should be considered by producers are highlighted below. Some of these have already been covered in Section B Opportunities that were covered above. The economic benefits that can be realized through adoption of these BMPs are not provide below but can be found in the referenced fact sheets.

a.) Improve Engine Maintenance - Poorly maintained engines will have higher emissions than well maintained ones. Proper maintenance will save costs, such as from reduction of or elimination of unplanned outages and from increase engine efficiency performance in the long run as well.

b.) Automated Air/Fuel Ratio Controls – Automated air/fuel ratio controls with closed-loop feedback can decrease emissions while improving fuel economy. They can achieve this because of precise control of the air/fuel ratio. One operator has achieved a fuel savings of 18 to 24 percent and reduced emissions by installing an automated control called REMVue. The system also has alarm triggers that can be set to shut the engine down before a catastrophic failure occurs. It is also reported that equipment life and maintenance are improved, but these items are difficult to quantify. (EPA 2004a).

The PRP Fact Sheet noted that the greatest system and efficiency improvements opportunities are for large (1,000 hp to 3,000 hp) rich burn turbocharged engines. Potential methane, CO_2, CO, VOCs and NO_x emissions reductions for 51 engines in the using the REMVue were estimated using AP-42. Although they acknowledged reductions in CO2 and NO_x would be an added benefit of the REMVue system, post audits on the test engines operating with and without controls showed no change in NO_x emissions. This may have been due to desire to operate at air-fuel ratios that were more to optimize low unburned methane and low CO emissions.

c.) Replace Natural Gas Starters with Compressed-Air, Compressed-Nitrogen, or Electric Starters – In the natural-gas industry, engines are often started using gas expansion starter motors powered by high-pressure natural gas. The gas used to start the engines is vented to the atmosphere.

All compressor stations employing natural gas pneumatic starter motors, including those that use the compressor, itself, can benefit from implementing this BMP. One Partner reported saving 500 Mcf/yr resulting from multiple pneumatic applications. Another reported saving 5 to 15 Mcf at two

compressor stations with multiple starts. Although reducing methane emissions is the primary benefit of this BMP, VOC and HAP emission reductions could also be significant but were not reported (EPA 2004b, c, d, and e).

The air starter typically requires a compressed air tank and an engine-driven compressor while the electric starter requires a battery and an engine-driven generator. However, other options are possible. The only facility change required of the compressed nitrogen system is installation of high-pressure nitrogen fill connection. Periodic deliveries of nitrogen are required.

d.) Reduce Frequency of Natural Gas Engine Starts – Before and during starting, a compressor engine, the compressor is unloaded by venting the gas in its discharge manifold to the atmosphere. The discharge wastes natural gas and is an undesirable discharge of methane and possibly other pollutants into the atmosphere. (EPA 2004f)

Reducing methane emissions is the primary benefit of this BMP. The technology is applicable to all sectors of the oil and gas industry. Methane emission reductions are the primary justification for this BMP, but significant reductions in other air pollutants may possible.

e.) Replace Old Ignition to Reduce False Starts – Each engine false start will not only result in excessive methane but also NO_x and CO emissions. (EPA 1004f)

The associated benefit of replacing old ignition systems with a newer system designs can save up to 1,150 scf of methane loss per start. The replacements can also significantly reduce operating costs. Although the benefit in reduction of NO_x and other air pollutants were not quantified, depending on the new replacement ignition system design that is choose, significant reductions may also be achievable. These emission reductions would not only come from the reduction in false starts but also during normal engine duty operations. One ignition system, the Advanced Laser Ignition System, promises to produce to provide higher engine efficiencies, lower maintenance costs and lower NO_x emissions. Such systems are being tested at Argonne's engine facility.

f.) Install Electric Compressors (Eliminate NG-Fired Compressor Engines) – Replacing natural gas fired compressor engines with electric motors eliminates NO_x, CO, and VOC emissions as well as eliminating most of the methane emissions associated with starting the engines. Although there is an increase in emissions at the power plant, emissions from power plants are typically lower than those of natural gas fired engines. In addition, maintenance costs can be reduced since electric motors are inherently more reliable than engines. (EPA 2004g)

This BMP is most applicable to facilities with easy access to electric power lines and with high compressor maintenance costs. Replacing natural gas or diesel compressor engines can provide significant air pollution and methane emission reductions. Reduction in methane losses have been estimated to range from 40 Mcf/yr to 1,500 mcf/yr.

This BMP is also identified as an alternative technology option in Section B.4 in

this draft emission reduction plan.

D. Opportunities involving cooperation between DOI (Federal Land Managers), TRES-IRS, and oil and gas producers

1. **Tax incentives** - The government could make replacement of high-emission engines with low-emission engines or retrofitting emission controls attractive by offering accelerated depreciation. Opportunities may exist for oil and gas and environmental stakeholders to collaborate with FCTF-AQV stakeholders to lobby state legislators on sponsorship of legislation that provides accelerated depreciation tax credits that have connected environmental-based benefits.
2. Lease incentives – Considering established DOI leasing practices and policies it would not be practically feasible to offer oil and gas lease incentives at this time.

References

Clark, W., 2006, personal communications on March 10, National Renewable Energy Laboratory, DOE

Cummins, Patrick 2006, WRAP Co-Director, Air Quality Program Manager, Western Governors' Association, private conversation with M. Lazaro, March 20

MOU 2005, Memorandum of Understanding – For the Interagency Policy Oversight Group of the Four Corners Task Force on Air Quality and Visibility, Nov/Dec

V.K. Duggal, E.J. Lyford-Pike, J.F. Wright, M. Dunn, D. Goudie, and S. Munshi, 2004, Development of the High-Pressure Direct-Injected, Ultra Low- NO_x Natural Gas Engine, Final Report, National Renewable Energy Laboratory (NREL), NREL/SR-540-35911, May

IEPA, 2006, Emission Reduction Market System (ERMS), http://oaserms.admop.epa.state.il.us:7000/public/iceman.www_aperm001.show, accessed in March

IDEM, 2006, Indiana Emission Credit Registry (IECR), http://www.in.gov/idem/air/emissioncreditregistry/index.html, accessed in March

King, Kirsten 2006, Colorado Department of Public Health and Environment, private conversation with M. Lazaro, March 20

USEPA, 2006, Allowance Data Tracking (ADT) System, http://www.epa.gov/airmarkets/tracking/index.html, accessed in March

USEPA, 2004a, Automated Air/Fuel Ratio Controls, PRO Fact Sheet No. 111, Dec.

USEPA, 2004b, Replace Gas Starters with Air, PRO Fact Sheet No. 103, Sept.

USEPA, 2004c, Replace Gas Starters with Nitrogen, PRO Fact Sheet No. 101, Sept.

USEPA, 2004d, Install Electric Starters, PRO Fact Sheet No. 108, Sept.

USEPA, 2004e, Reduce the frequency of Engine Starts with Gas, PRO Fact Sheet No. 102, Sept.

USEPA, 2004f, Replace Ignition – Reduce False Starts, PRO Fact Sheet No. 104, Sept.

USEPA, 2004g, Install Electric Compressors, PRO Fact Sheet No. 105, Sept.

WRAP, 2003, Western Backstop SO_2 Trading Program - Model Rule, August 13, (Final Draft)

Nomenclature

Agencies

DOE	US Department of Energy
DOI	US Department of Interior
EPA	Environmental Protection Agency
TRES-IRS	US Treasury and Internal Revenue Service
USEPA	United States Environmental Protection Agency

Technical

AFR	Air-to-fuel ratio
AP-42	Estimates of emissions from engines
BMP	Best management practices
CAFE	Corporate average fleet efficiency
CBM	Coal-bed methane
CO	Carbon monoxide, a regulated air pollutant
CO_2	Carbon dioxide, an unregulated greenhouse gas
EGR	Exhaust gas recirculation, a method of reducing NO_x formation
HAP	Hazardous air pollutants, a group of chemicals that are identified by the USEPA as being particularly hazardous and are more strictly regulated than other air pollutants
HC	Unburned hydrocarbons, see VOC
HEUI	Hydraulic-electric unit fuel-injection system for diesel engines
HPDI	High-pressure direct injection, a trademarked gaseous fuel-injection system developed by Westport Innovations, Inc.
LB	Lean-burn combustion system for natural-gas fueled engines
NCBMG	Natural and coal-bed methane gas
NG	Natural gas
NMHC	Non-methane hydrocarbons, a regulated air pollutant
NO_x	Mixed oxides of nitrogen, a regulated air pollutant consisting chiefly of nitrous oxide (NO) and nitric oxide (NO_2)
NSCR	Non-selective catalytic emissions reduction
Oxicat	Oxidation catalyst emissions reduction
PM	Particulate matter, a regulated air pollutant. PM_{10} has a diameter less than 10 microns, and $PM_{2.5}$ has a diameter less than 2.5 microns.
R&D	Research and development
RB	Rich burn combustion system for natural-gas fueled engines
SCR	Selective catalytic emissions reduction
SO_x	A mixture of sulphur dioxide (SO_2) and sulfur trioxide (SO_3), a regulated air pollutant

TC	Turbocharged or turbocharger
VOC	Volatile organic compounds, a regulated air pollutant

Other

AOCERT	Allowance, offsets, and credits emission reduction trading
BERTC	Baseline emission reduction trading concepts
CapT	Caps and trades emission reduction program
CDM	Clean development mechanism
CFR	Code of Federal Regulations
CO	Colorado
ETP	Emission trading program
ETS	Emission trading system
FCTF-AQV	Four Corners Task Force on Air Quality and Visibility
GasSTAR	A voluntary program for reducing greenhouse gas emissions sponsored by USEPA
MOU	Memorandum of Understanding
NSR	New source review
NM	New Mexico
OGI	Oil and gas industry
POG	Policy Oversight Group
SERP	This Strategic Emissions Reduction Plan
SIP	State Implementation Plan
US	United States
WEB	Western Backstop Emissions
WRAP	Western Regional Air Partnership

Appendix A: Preliminary Engine Survey

An initial limited two-producer engine survey was conducted during the summer of 2005. Data was collected engine model number, age, load cycle, size (e.g., bhp), power load, and pre- and after treatment emission controls (e.g., turbocharged, electronic fuel injection, TC/aftercooled, lean combustion (air/fuel ratio), NO_x absorbers, nonselective/ selective catalytic reduction). The survey revealed three types of engines, natural gas – lean and rich burn and diesel fired engines are operated by these producers within the San Juan Basin. A description of types of engine operating and the key data collected in the survey are summarized below.

Engine Types

Three engine types are typically used in oil and gas fields: lean-burn natural gas, rich-burn natural gas, and diesel. Combustion characteristics of the three types are markedly different and they require different abatement technologies.

1. Rich-Burn Natural Gas

A rich-burn natural-gas engine operates with a uniform mixture of air and fuel at a nearly stoichiometric air/fuel ratio. There is a small latitude in the choice of air/fuel ratio; it can be slightly rich or slightly lean. The maximum flame temperature also occurs near the stoichiometric air/fuel mixture, so production of NO_x is favored. However, because there is little unconsumed oxygen in the exhaust, aftertreatments can be effective at reducing the NO_x emissions.

If the engine is operated at a slightly richer than stoichiometric air/fuel ratio, combustion of the fuel will be incomplete, and some of the fuel will be partially oxidized to carbon monoxide (CO) instead of fully oxidized to carbon dioxide (CO_2). The CO can be effectively removed with an oxidation catalyst if a small amount of air is pumped into the exhaust manifold.

In practice, rich-burn engines are often operated slightly lean of the stoichiometric mixture where the flame temperature is lower than the maximum. This decreases the emission of both NO_x and CO, but it does not leave so much unconsumed oxygen in the exhaust that a catalyst has difficulty reducing the NO_x.

2. Lean-Burn Natural Gas

Unlike gasoline engines, which demand a nearly stoichiometric air/fuel ratio, a natural-gas fueled engine will operate at a lean air/fuel ratio. As the air/fuel ratio is leaned from the stoichiometric mixture, the excess air acts as a diluent and the flame temperature decreases. Since NO_x production is a direct function of flame temperature, less NO_x is produced as the air/fuel mixture is made leaner. It is generally much easier to not produce NO_x than it is to remove it after it has been produced.

One of the effects of leaning the air/fuel ratio is to reduce the flame speed. At a stoichiometric air/fuel ratio, the flame speed is high enough that nearly all of the mixture in the cylinder burns in the time available for the combustion event. At very lean air/fuel ratios, the flame may not traverse the entire combustion chamber in the time available for combustion. If this happens, emissions of CO and methane will rise as the air/fuel ratio is leaned. Ultimately, at very lean air/fuel ratios the flame may not propagate at all,

and the engine will not run. Operation of a lean-burn engine depends on selecting an air/fuel ratio that is lean enough that very little NO_x is formed but not so lean that CO and methane emissions rise. The power output of a lean-burn engine is controlled by regulating the amount of fuel that enters the cylinder rather than by throttling fuel-air mixture as is done with a rich-burn engine. At maximum power output, a lean-burn engine may operate with a nearly stoichiometric mixture. Minimum power output is limited by how lean the mixture can be and still propagate the flame throughout the cylinder. This is an important limitation of a lean-burn engine because the lower power limit is typically about 50% of its maximum power output.

Because a lean mixture can be difficult to ignite, many lean-burn engines use a pre-chamber, which is charged with a nearly stoichiometric fuel/air mixture and ignited with a spark plug. The burning mixture then sprays into the main combustion chamber with enough energy to ignite the lean mixture. A few lean-burn engines use a small spray of diesel fuel to ignite the lean methane/air mixture. These are typically dual-fuel engines that can run entirely on diesel fuel when natural gas is not available.

3. Diesel

Diesel engines are characterized by the injection of liquid fuel into the cylinder. The heat of compression of the air inside the cylinder causes an exothermic reaction with the fuel that raises the temperature of the fuel to the point where it ignites without an external spark. There is a brief pre-mixed combustion stage in which vaporized fuel mixed with air burns. This is followed by a slower diffusion-combustion stage in which fuel vaporizing from droplets of liquid fuel diffuses outward toward the air and air diffuses inward toward the fuel droplet.

At a microscopic level the fuel/air ratio ranges from 100% fuel at the surface of the droplet to nearly 100% air “far” from the droplet. In between there is a range of fuel/air ratios where combustion proceeds. Since the fuel/air ratio varies continuously from very rich to very lean, at some point the mixture will be nearly stoichiometric and the flame will be the hottest. The hotter the flame, the more rapidly oxides of nitrogen (NO_x) is produced, and this is the major source of NO_x emissions from a diesel engine. Diesel engines normally operate with overall fuel/air ratios that are lean, that is, not all of the oxygen in the air is consumed by the burning fuel. It is particularly difficult to remove oxygen atoms from NO_x because the unconsumed oxygen in the cylinder tends to force the chemical reaction in the opposite direction. Thus, when NO_x is formed, it is difficult to get rid of it.

At other locations, the fuel/air ratio will be rich, and the hydrogen atoms will be stripped from the fuel molecules leaving carbon particles that agglomerate to form particulate matter (PM). Some of the PM will burn up when it mixes with air in the cylinder, but some will escape with the exhaust. NO_x and PM are the major pollutants emitted from diesel engines.

Existing Engines

Two data bases of engines in the San Juan Basin exist. Neither is complete. The larger one contains about 1260 engines but does not identify the type of emission controls on those engines. Further, no emissions estimates are available for some of the engines in the data base. When only those engines for which data is available are considered, the total drops to 1084 engines. The data base was subdivided into three categories: small engines (less than 200 hp), medium engines (between 200 and 600 hp), and large

engines (more than 600 hp). The reduction in the data base was not uniform across the engine-size categories; the number of large engines was reduced in greater proportion than the number of small engines. The original data base contained 23 large engines, but the reduced data base contains 16, a 30% reduction. The original data base contained 1006 small engines, but the reduced data base contains 888, a 12% reduction. The reduction of medium engines was 21%. For each engine, the emission factor was multiplied by its power rating to compute its potential to emit if it were run at its maximum power. Key data from the larger data base is shown in Table 1.

Table 1: Key data from the larger data base

	< 200 hp	200-600 hp	> 600 hp	TOTAL
Count	888	180	16	1,084
Installed hp	76,714	61,769	11,874	150,357
Percentage of installed hp	51%	41%	8%	100%
Subtotal NO_x, kg/hr	934	270	48	1,253
Percentage of TOTAL NO_x	75%	22%	4%	100%
Average NO_x,g/hp-hr	12.2	4.4	4.1	8.3
Subtotal CO, kg/hr	509	236	20	765
Percentage of TOTAL CO	66%	31%	3%	100%
Average CO, g/hp-hr	6.6	3.8	1.7	5.1
Subtotal VOC, kg/hr	33	70	8	111
Percentage of TOTAL VOC	30%	63%	7%	100%
Average VOC, g/hp-hr	0.4	1.1	0.7	0.7

The immediate conclusion is that the smaller engines, which account for 51% of the installed power account for 75% of the NO_x emissions while the medium and large engines emit proportionately less NO_x. A similar conclusion may be drawn regarding the CO emissions. The figure for VOC is skewed because many of the smaller engines are identified as producing no VOCs. This is probably because the information for VOCs was not available so it was marked as zero

The average NO_x produced by the smaller engines is 12.2 g/hp-hr, indicating that few of them have emissions controls. If that figure could be reduced to no more than 2 g/hp-hr, the subtotal of NO_x produced by those engines would be reduced from 934 kg/hr to 153 kg/hr, and the TOTAL NO_x produced by the engines in the data base would be reduced from 1253 kg/hr to 472 kg/hr, a 62% reduction. However, the overall average NO_x produced by the engines in the data base would only be reduced to 3.1 g/hp-hr.

Table 1 shows that the average NO_x productions of the medium and large engines are 4.4 g/hp-hr and 4.1 g/hp-hr, respectively. These NO_x amounts are also higher than desired. If the average NO_x produced by the medium-sized engines were reduced to 1.5 g/hp-hr and the average NO_x produced by the large engines were reduced to 1.0 g/hp-hr in addition to the reductions for the small engines, the NO_x total would be reduced from 1253 kg/hr to 257 kg/hr, an 80% reduction. This would require adding emissions controls to the engines that do not already have them and upgrading the emissions controls on the engines that have them. The overall average NO_x emission would be reduced to 1.7 g/hp-hr. Similar reasoning would apply to the CO emission.

The smaller data base contains only 173 engines for which data is available, but it identifies each engine by the type of emission control it uses. Unlike the first data base, most of the installed power is represented by the large engines, which account for 70% of the installed power. The medium-sized engines account for 26% of the installed

power, and the small engines account for only 4% of the installed power. Data for the smaller data base is summarized in Tables 2a – 2d.

Table 2a: Key data for small engines (<200 hp) in the smaller data base

	Rich Burn	Lean Burn	RB-NSCR	LB-Oxicat	Diesel-SCR	TOTAL
Count	16	22	0	0	0	38
Installed hp	1,392	4,224				5,616
Percentage of installed hp	1%	3%				4%
Subtotal NO_x, kg/hr	21.2	6.3				27.6
Percentage of GRANDTOTAL NO_x	9%	3%				12%
Average NO_x,g/hp-hr	15.3	1.5				4.9
Subtotal CO, kg/hr	42.1	11.1				53.3
Percentage of GRAND TOTAL CO	14%	4%				18%
Average CO, g/hp-hr	30.3	2.6				9.5
Subtotal VOC, kg/hr	1.5	4.2				5.7
Percentage of GRAND TOTAL VOC	1%	3%				4%
Average VOC, g/hp-hr	1.1	1.0				1.0

Table 2b: Key data for medium-sized engines (200 - 600 hp) in the smaller data base

	Rich Burn	Lean Burn	RB-NSCR	LB-Oxicat	Diesel-SCR	TOTAL
Count	4	75	1	0	0	80
Installed hp	1,096	34,001	421			35,518
Percentage of installed hp	1%	25%	0%			26%
Subtotal NO_x, kg/hr	23.8	68.2	0.4			92.4
Percentage of GRANDTOTAL NO_x	10%	30%	0%			41%
Average NO_x,g/hp-hr	21.7	2.0	1.0			2.6
Subtotal CO, kg/hr	2.2	57.8	0.6			60.6
Percentage of GRAND TOTAL CO	1%	20%	0%			21%
Average CO, g/hp-hr	2.1	1.7	1.3			1.7
Subtotal VOC, kg/hr	1.2	63.9	0.3			65.4
Percentage of GRAND TOTAL VOC	1%	46%	0%			47%
Average VOC, g/hp-hr	1.1	1.9	0.7			1.8

Table 2c: Key data for large engines (>600 hp) in the smaller data base

	Rich Burn (RB)	Lean Burn (LB)	RB-NSCR	LB-Oxicat	Diesel-SCR	TOTAL
Count	0	21	16	6	12	55
Installed hp		29,679	19,984	10,713	35,064	95,440
Percentage of installed hp		22%	15%	8%	26%	70%
Subtotal NO_x, kg/hr		47.1	27.3	8.7	24.5	107.6
Percentage of GRANDTOTAL NO_x		21%	12%	4%	11%	47%
Average NO_x,g/hp-hr		1.6	1.4	0.8	0.7	1.1
Subtotal CO, kg/hr		78.6	47.3	23.7	31.6	181.2
Percentage of GRAND TOTAL CO		27%	16%	8%	11%	61%
Average CO, g/hp-hr		2.7	2.4	2.2	0.9	1.9
Subtotal VOC, kg/hr		29.7	20.0	10.7	7.0	67.4
Percentage of GRAND TOTAL VOC		21%	14%	8%	5%	49%
Average VOC, g/hp-hr		1.0	1.0	1.0	0.2	0.7

Table 2d: Key data for GRAND TOTALS in the smaller data base

	Rich Burn (RB)	Lean Burn (LB)	RB-NSCR	LB-Oxicat	Diesel-SCR	GRAND TOTAL
Count	20	118	17	6	12	173
Installed hp	2,488	67,904	20,405	10,713	35,064	136,574
Percentage of installed hp	2%	50%	15%	8%	26%	100%
Subtotal NO_x, kg/hr	45.0	121.6	27.7	8.8	24.5	227.6
Percentage of GRANDTOTAL NO_x	20%	53%	12%	4%	11%	100%
Average NO_x,g/hp-hr	18.1	1.8	1.4	0.8	0.7	1.7
Subtotal CO, kg/hr	44.4	147.7	47.8	23.7	31.6	295.2
Percentage of GRAND TOTAL CO	15%	50%	16%	8%	11%	100%
Average CO, g/hp-hr	17.8	2.2	2.3	2.2	0.9	2.2
Subtotal VOC, kg/hr	2.7	97.8	20.3	10.7	7.0	138.5
Percentage of GRAND TOTAL VOC	2%	71%	15%	8%	5%	100%
Average VOC, g/hp-hr	1.1	1.4	1.0	1.0	0.2	1.0

Table 2d shows that the rich-burn engines account for only 2% of the installed power, but they account for 20% of the potential NO_x emissions. These engines are concentrated in the small size, but four of them are medium sized engines. If these engines were either converted to Non-Selective Catalytic Reduction (NSCR) aftertreatment or replaced with new engines having NSCR, which could reduce the average NO_x emission of these engines to 1.4 g/hp-hr, their total NO_x emission could be reduced from 45.0 kg/hr to 3.5 kg/hr. This would reduce the grand total NO_x emission from 227.6 kg/hr to 186.1 kg/hr, an 18% reduction. Similarly, the lean-burn engines account for 53% of NO_x emission, although their NO_x emission is not as far out of line with the installed power as the rich-burn engines is. If an oxidation catalyst were added to these lean-burn engines (assuming that ignition timing can be adjusted to decrease NO_x emission) or new lean-burn engines with oxidation catalysts were purchased to replace the uncontrolled lean-burn engines, the total NO_x emission could be reduced from 121.6 kg/hr to 54.0 kg/hr. The combined effect of these two changes would reduce the grand total NO_x emission from 227.6 kg/hr to 118.5 kg/hr, a 48% reduction. The overall average NO_x emission rate would be reduced from 1.7 g/hp-hr to 0.9 g/hp-hr.

The producer who supplied the smaller data base is in relatively good shape at reducing emissions from his engines. Not all of the engines would need to be modified to bring the overall NO_x emission rate below 1.0 g/hp-hr

Appendix B: Emissions Abatement Technologies

Several types of emissions abatement technologies are available. Few are adaptable to all engine types. A summary of the important types of emissions abatement technologies follows.

Retarding the Ignition

One of the easiest and most common techniques for decreasing NO_x is to simply retard the timing of the spark in natural-gas engines or to retard the timing of the fuel injection in diesel engines. This times the main heat release of the fuel so it occurs during the down stroke of the piston rather than near top dead center. The effect is to decrease the maximum combustion temperature so less NO_x is formed. Undesirable side effects are increased heat loss to the cylinder walls and a small fuel economy penalty.

Exhaust-Gas Recirculation (EGR)

This is an important method of controlling NO_x formation in diesel and rich-burn natural-gas engines. It works by diluting the oxygen concentration in the combustion chamber, which lowers the combustion temperature. EGR is only useful in lean-burn engines operating near maximum power output. At lower output, the excess air serves as a diluent because the oxygen in the excess air does not participate in the combustion.

Some diesel-engine manufacturers do not like EGR because the particulate matter in the exhaust may increase wear in the engine. Use of EGR decreases formation of NO_x at the expense of increasing particulate emissions.

Fast-Burn Combustion Chamber

A fast-burn combustion chamber is applicable to natural-gas engines. By making the combustion chamber as compact as possible with the spark plug near its center and by introducing carefully controlled turbulence, the effective flame speed can be increased. This allows the ignition to be retarded while keeping the timing of the piston's push against the crankshaft near its optimum. For lean-burn engines, it allows the engine to operate at a lower minimum power output than would otherwise be possible. This technology is not easily added onto the engine since it affects the engine design and is the result of the manufacturer's product research effort. It is more likely to be found in modern engines rather than older ones.

Intercooling

All modern diesel engines and most of the natural-gas engines are turbocharged. Only the smaller natural-gas engines are likely to be not turbocharged. Most of the turbocharged engines use intercooling to decrease the temperature of the air entering the cylinders. This has the beneficial effects of reducing the combustion temperature (hence decreasing NO_x production slightly) and reducing the pumping losses of the pistons.

Advanced Fuel injection

Advanced fuel-injection systems are applicable to diesel engines. Conventional fuel-injection systems are limited in their ability to adjust the injection timing and pressure, and they are limited to a single injection per combustion event. An electronically controlled injection system adds a controllable solenoid valve to the system. This allows the injection timing to be adjusted within the limits of the mechanical system.

A Hydraulic Electronic Unit Injector (HEUI) system uses hydraulic pressure amplification to provide higher injection pressure at the nozzle. This improves the atomization of the fuel and reduces emission of PM. The electronic control allows the injection timing to be optimized. Generally, the timing will be retarded to reduce NO_x emissions at the expense of more PM emissions. However, with the better fuel atomization, PM emissions will be no worse that is the case with conventional injection, and NO_x emissions will be less.

Common-rail fuel-injection systems are the norm in European automobile applications, but they are just beginning to gain foothold in American heavy-duty diesel engines. In this system a high-pressure fuel pump charges a manifold (the common rail) that feeds all of the fuel injectors. Each injector is electronically controlled. Injection pressure as well as the injection timing can be electronically controlled. In addition, multiple injections per power stroke are possible. Multiple injections allow the heat-release rate to be controlled to limit the maximum combustion temperature and pressure to minimize the formation of NO_x.

Cummins and Westport have teamed up to develop an engine in which natural gas is injected directly into the cylinders. The advantages of the Cummins-Westport engine are that it operates on natural gas, it has near diesel-like thermal efficiency, and it produces low emissions. The engine is still under development as a commercial product.

Selective Catalytic Reduction

Selective catalytic reduction (SCR) uses a catalyst (typically vanadium or a zeolite) and a reductant (typically ammonia or urea, but sometimes a fuel) to chemically reduce NO_x to molecular nitrogen. It is typically used with diesel or lean-burn natural-gas engines that have unconsumed oxygen in the exhaust. The unconsumed oxygen in the exhaust inhibits removal of oxygen from the NO_x molecules. The catalyst decomposes the reductant to release hydrogen, which reacts with the oxygen in the exhaust to create a local oxygen depletion near the catalyst. Some of the hydrogen reacts with the NO_x molecules to form nitrogen and water.

Cost of SCR, maintenance requirements, and the need to keep a supply of ammonia or urea are significant barriers to the use of SCR. The amount of ammonia in the exhaust after the catalyst needs to be monitored and the ammonia or urea feed rate adjusted to prevent ammonia slippage. Causes of ammonia slippage are too much ammonia being fed for the conditions and the exhaust stream temperature being too cold or too hot. The desired exhaust stream temperature is 450-850 °F.

NO_x-Trap Catalytic Reduction

NO_x-trap catalytic reduction is a newer technology than SCR, and it is not as well

developed. Like SCR the NO_x trap is applicable to diesel and lean-burn natural-gas engines. It is a two-stage process: (1) absorption of NO_x and (2) release and reduction of NO_x. In the first stage, the catalyst (typically an alkali-metal oxide) absorbs NO_x and removes it from the exhaust stream. After a period of time the catalyst is filled with NO_x, and it is taken out of the exhaust stream for the second stage. At this time a reductant (typically a fuel) is sprayed on the catalyst, which releases the NO_x, decomposes the reductant to release its hydrogen, and reacts the hydrogen with the NO_x to form nitrogen and water.

Barriers to the use of NO_x traps are its developmental status and the propensity for fuel-borne sulfur to permanently poison the catalyst.

Non-Selective Catalytic Reduction

Non-selective catalytic reduction (NSCR) is similar to the three-way catalytic converters used in automobiles. These typically use platinum as the catalyst and are capable of oxidizing unburned hydrocarbons and CO as well as reducing NO_x. They are applicable only to rich-burn engines. To operate successfully the air/fuel ratio must be carefully controlled so the unconsumed oxygen does not exceed 1 percent. Typically an exhaust oxygen concentration of 0.5 percent is the goal. These catalysts can reduce NO_x emissions by 80-90% and CO emissions by 90%.

Cost of the platinum catalyst is the main disadvantage of the technology. The need to carefully control the air/fuel ratio is an issue, but oxygen sensors and control strategies are well developed. Reductant slippage is not an issue since none is required.

Oxidation Catalysts

The purpose of oxidation catalysts is to remove unburned hydrocarbons and CO from the exhaust stream by oxidizing them. They are applicable to all engine types, although NSCR does the same function in addition to reducing NO_x in rich-burn engines. They are particularly effective with lean-burn engines if the exhaust temperature is hot enough to keep the catalyst active. Reductions of 60-90 percent for CO and unburned hydrocarbons can be achieved. Diesel engines do not produce much CO or unburned hydrocarbons, but the hydrocarbons that are produced tend to be adsorbed onto the PM. Oxidation catalysts can reduce the mass of the PM by 25 to 50 percent.

Particulate Filters

Particulate filters are applicable to diesel engines where they can remove 80-90 percent of the particulates. After a period of time the filters become clogged with PM and they must be cleaned. This process is called regeneration. The filter temperature is raised, typically by adding fuel to the exhaust stream, and the heat, aided by a catalyst in the filter, oxidizes the PM as well as unburned hydrocarbons and CO. Some particulate filters regenerate continuously rather than cyclically.

This is a relatively new technology that has recently moved from the research stage to being a commercial product. Continued research will yield improvements in the technology and reduce costs.

Appendix C: Example Best Management Practices (BMPs) for Methane Gas Loss Reduction

The Natural Gas STAR Program's recommended Best Management Practices (BMPs) are listed by sector below:

Production - Core BMPs

•	BMP I: Identify and replace high-bleed pneumatic devices.
•	BMP II: Install flash tank separators on dehydrators.

Transmission and Distribution

Distribution Systems **-** Core BMPs

	BMP I: Implement directed inspection and maintenance programs at gate stations and surface facilities.
	BMP II: Identify and rehabilitate leaky distribution pipes.

Transmission Systems **-** Core BMPs

	BMP III: Implement directed inspection and maintenance programs at compressor stations.
	BMP IV: Consider use of turbines at compressor stations in lieu of reciprocating engines.
	BMP V: Identify and replace high-bleed pneumatic devices.

Processing - Core BMPs	
	BMP I: Replace gas pneumatics with instrument air systems.
	BMP II: Install flash tank separators on glycol dehydrators.
	BMP III: Implement directed inspection and maintenance at gas plants and booster stations.