Interstate Natural Gas Association of America

Feb. 1, 2016

Via www.epa.gov and email
Office of Air Quality Planning and Standards
U.S. Environmental Protection Agency

RE: Comments of the Interstate Natural Gas Association of America on the Cross-State Air Pollution Rule Update for the 2008 Ozone NAAQS
Docket ID No. EPA-HQ-OAR-2015-0500.

To Whom It May Concern:

The Interstate Natural Gas Association of America (INGAA) appreciates the opportunity to submit these comments to the Environmental Protection Agency (EPA or the Agency) on the Cross-State Air Pollution Rule (CSAPR) Update for the 2008 Ozone NAAQS.[1]

INGAA member companies primarily operate in the transmission and storage segment of the natural gas sector. Our 24 members represent the vast majority of the interstate natural gas transmission pipeline companies in the United States, operating approximately 200,000 miles of pipelines and serving as a vital link between natural gas producers and consumers.

Under the Proposed Rule, the compliance deadline for achieving reductions in emissions of nitrogen oxides (NOx) would be the 2017 ozone season. Consistent with the currently-effective CSAPR, and also the Clean Air Interstate Rule that preceded the CSAPR, the Proposed Rule only covers NOx emissions from electricity generating units (EGUs). In the preamble to the Proposed Rule, EPA explains explicitly that it is "not proposing to address non-EGU emission reductions in its efforts to reduce interstate ozone transport for the 2008 ozone NAAQS at this time."[2]

EPA's basis for this determination is an assessment included with the Proposed Rule: a Technical Support Document (TSD) on Non-EGU mitigation potential.[3] This TSD includes a number of findings:

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[1] 80 Fed. Reg. 75,706 (Dec. 3, 2015) (hereinafter "Proposed Rule").
[2] Proposed Rule at 75,733.
[3] Technical Support Document for the Cross-State Air Pollution Rule for the 2008 Ozone NAAQS: Assessment of Non-EGU NOx Emission Controls, Cost of Controls, and Time for Compliance. Docket ID No. EPA-HQ-OAR-

- “[T]he limited available information points to an apparent scarcity of non-EGU reductions that could be accomplished by the beginning of the 2017 ozone season.”[4]

- In particular, for non-EGU source groups potentially capable of achieving significant reductions, “the ability for control technology to be installed and operational in time for the 2017 ozone season seemed unlikely, with an overarching consideration being that non-EGUs of any type that are not currently required to monitor and report in accordance with 40 C.F.R. Part 75 will require additional time relative to EGUs that are currently equipped with Part 75 monitoring and reporting.”[5]

INGAA member companies own and operate equipment assessed in the Non-EGU NOx Emission Controls TSD, including gas turbines and reciprocating internal combustion engines (RICE) pipeline compressors. INGAA supports EPA’s proposal not to make these and other key non-EGU source categories subject to the updated CSAPR.

In particular, INGAA can confirm EPA’s view that it would not be feasible to require natural gas transmission industry non-EGU sources to meet NOx emission limits by the 2017 ozone season, which would be roughly a year after the expected finalization of the Proposed Rule.

As detailed in the attached July 2014 INGAA Foundation Report ***Availability and Limitations of NOx Emission Control Resources for Natural Gas-Fired Reciprocating Engine Prime Movers Used in the Interstate Natural Gas Transmission Industry***, one year would be insufficient for acquiring needed control technologies, hiring the labor required for retrofits, obtaining needed permits and authorizations, and managing the timing for staggering retrofits across facilities or across transmission systems.

Moreover, it is not reasonable to believe that owners of non-EGU sources could rely on allowance purchases in lieu of 2017 retrofits. For non-EGUs, EPA would need to resolve the monitoring issues it has cited in its TSD, including addressing smaller non-EGU sources not equipped with Continuous Emissions Monitoring Systems (CEMS). To include non-EGUs in a trading program, the Agency would need to also assemble all of the architecture associated with trading for a new set of sources – including setting up accounts, issuing allowances, etc. Owners and operators of non-EGUs also would need to assemble their own trading architecture and expertise, including trading desks and other features that EGUs set up years ago. These actions would take more than a year to complete.

2015-0500. U.S. EPA Office of Air and Radiation (November 2015) (hereinafter “Non-EGU NOx Emission Controls TSD”).

[4] Non-EGU NOx Emission Controls TSD, at 21.

[5] Non-EGU NOx Emission Controls TSD, at 21.

In its initial Clean Air Interstate Rule[6], adopted in 2005, EPA provided sound reasoning for providing industry with sufficient lead time to adopt its new standards. Specifically, EPA cited the unique nature of developing an appropriate labor pool to engineer retrofits, the complex nature required to acquire necessary capital required for air quality improvements, and the importance of allowing industry to take advantage of planned outages:

> From past experience in examining multi-pollutant emissions trading programs for SO_2 and NO_X, EPA recognized that the air pollution control retrofits that result from a program to achieve highly cost-effective reductions are quite significant and cannot be immediately installed. Such retrofits require a large pool of specialized labor resources, in particular, boilermakers, the availability of which will be a major limiting factor in the amount and timing of reductions. Also, EPA recognized that the regulated industry will need to secure large amounts of capital to meet the control requirements while managing an already large debt load, and is facing other large capital requirements to improve the transmission system. Furthermore, allowing pollution control retrofits to be installed over time enables the industry to take advantage of planned outages at power plants (unplanned outages can lead to lost revenue) and to enable project management to learn from early installations how to deal with some of the engineering challenges that will exist, especially for the smaller units that often present space limitations.[7]

For these reasons, the 2005 rule provided a *four* year period—up until 2009—before the first phase of the program was to be implemented. Since most non-EGUs are smaller sources of pollution than most power plants more time would be needed before bringing non-EGUs into the CSAPR program. Forcing the interstate pipeline sector into the CSAPR system in 2017 or 2018 that would require new CEMs and other market trading systems could be operationally disruptive.

For these reasons, INGAA supports EPA proposal not to include non-EGUs among the sources subject to the updated CSAPR. In addition, INGAA urges the Agency to continue seeking information and input from stakeholders regarding the feasibility of implementing non-EGU NOx mitigation measures.

INGAA is reviewing the Non-EGU NOx Emissions Control TSD and expects to provide its views to EPA on the TSD in the near future. As shown in the referenced INGAA Foundation report, the natural gas transmission industry, including its operators, vendors, suppliers, and

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[6] Rule To Reduce Interstate Transport of Fine Particulate Matter and Ozone (Clean Air Interstate Rule), 80 Fed. Reg. 25,162 (May 12, 2005) (hereinafter "CAIR").

[7] CAIR, at 25,197.

contractors, have long been focused on the complexities of implementing NOx emission reductions across the industry – and can provide additional insights to EPA in the future.

INGAA appreciates the opportunity to comment on the Proposed Rule. If you have any questions or wish to discuss these comments further, please contact Theresa Pugh, VP, Environment and Construction Policy at 202/216-5955 or tpugh@ingaa.org.

Sincerely,

Theresa Pugh

Availability and Limitations of NOx Emission Control Resources for Natural Gas-Fired Reciprocating Engine Prime Movers Used in the Interstate Natural Gas Transmission Industry

Prepared for:
The INGAA Foundation, Inc.

By:
Innovative Environmental Solutions, Inc. &
Optimized Technical Solutions

July 2014

INGAA Foundation Final Report No. 2014.03

Innovative Environmental Solutions, Inc.

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Executive Summary

New and proposed changes in air emission regulations are likely to impact the interstate natural gas transportation industry. Regulations that are expected to impact the industry include the ozone National Ambient Air Quality Standards (NAAQS) and the nitrogen dioxide (NO_2) one hour NAAQS. Since nitrogen oxides (NOx) react in the atmosphere to form ozone, it is regulated as a precursor to ozone. As emission control rules are developed and permitting actions implemented in response to these federal standards, there will be ongoing pressure to reduce emissions of NOx from existing equipment that has not yet been impacted by NOx control rules, or has been minimally impacted. For example, EPA and states have not yet implemented permitting requirements related to a recent revision to the NO_2 NAAQS. In addition, due to lawsuits and evolving EPA policy, states have been passive in recent years regarding the next set of rules to reduce NOx to address ozone NAAQS concerns. In response to a new ozone NAAQS planned for 2015, there is a potential for broad NOx controls in the eastern half of the U.S. to address NOx transport. Along with the revised ozone NAAQS and implementation of the NO_2 NAAQS, upcoming court decisions, including a Supreme Court decision on EPA authority to institute regional NOx rules, will likely break the regulatory logjam.

Based on these expected air regulation changes that result in new requirements to reduce NOx from existing equipment, a significant number of stationary engines that drive natural gas compressors in interstate natural gas transmission service will likely require modification to meet new federal or state NOx rules or permitting requirements. **Based on current technical resources, the projected time to implement retrofit NOx control (or replacement) is far in excess of typical regulatory schedules.**

The focus of the research for this report was to evaluate the resources required of the operating companies, emission reduction suppliers, engineering service providers, and contractors to implement NOx control regulations for low speed reciprocating engines used in the interstate natural gas transportation industry. The information gathered in developing this report included input solicited from both operating companies and vendors who provide emission reduction retrofit equipment. The assessment included an evaluation of an industry database to estimate the number and type of engines that would be impacted by changes to the emission regulations. Resource and schedule requirements assessed in this report are based on the actual fleet (i.e., make, model, NOx control status) from that database. This study found:

- The special technical expertise to design, construct, and commission emission reduction projects is not widely available to the industry for the slow speed integral engines prevalent in natural gas transmission. Regulations that require installation of NOx control on a large number of reciprocating engines will require a significant lead time to train and develop employees and service provider resources to implement emission reduction projects on a timely basis.
    - Availability of this special technical expertise and building this capability is the primary resource constraint that will affect the ability to meet regulatory obligations, if those regulations affect a large percentage of the existing fleet. Based on current capabilities and a scenario where NOx regulations broadly affect the existing fleet of uncontrolled reciprocating engines, the estimated time to complete upgrades to over 2600 engines is nearly forty years. Although strategies to comply may result in many engines (e.g., lower horsepower, lower use engines) being retired or replaced, scheduling implications due to the lack of available expertise would still extend far beyond the expected regulatory timelines. In addition, even if a smaller percentage of the fleet requires control, the required time (e.g., 15 years for 1000 engines) would likely exceed any expected regulatory schedule. Building this technical expertise to address regulatory implementation timelines are significant concerns.
- Engine NOx control projects are generally much less costly than engine replacement. If the anticipated regulations are implemented, capital costs to modify currently uncontrolled reciprocating

engines used in the interstate natural gas transmission industry are estimated at approximately $4 billion to achieve NOx emission rates of 3 grams per horsepower hour (g/hp-hr) and over $6 billion to achieve 1 g/hp-hr.

- The age of the impacted equipment (most of the engines are over 40 years old) requires additional time to engineer and construct reliable emission reduction modifications due to inaccurate or missing engineering records that reflect the current equipment configuration.
- Some engines with low specific power output will require extra time to properly design and construct emission reduction modifications and maintain the same power operating range.
- Based on previous experience, the timeline of obtaining air permits is a key parameter defining the overall schedule for completing a specific emission reduction project – i.e., permitting can slow the project timeline.
- Equipment outages that last several weeks to over a month to implement emission reduction modifications may have significant impact on available pipeline capacity and could cause significant capacity disruption, especially if the schedule overlaps with implementation of other regulations such as pipeline integrity testing.

1.0 Introduction

As shown below, air emissions from a natural gas compressor station are regulated by a complex web of federal and state regulation. This report focuses on the potential availability of resources – equipment, people, and expenditures – needed to modify these compressor stations to meet possible NOx emission requirements.

Air emissions continue to be a major regulatory issue, and air quality regulations pose a risk to normal operations of existing natural gas transmission infrastructure. NOx emissions are the primary air pollutant of interest from natural gas-fired combustion sources. NOx can react in the atmosphere to form ozone, so NOx is regulated as a precursor to ozone. NOx can also react to form nitrates, and ammonium nitrate is an aerosol that comprises a portion of atmospheric fine particulate ($PM_{2.5}$). The U.S. Environmental Protection Agency (EPA) establishes NAAQS for six criteria pollutants, including ozone, NO_2, and $PM_{2.5}$. NOx emissions are comprised of NO and NO_2, but all NOx emissions are generally considered NO_2 under the NO_2 NAAQS.

Based on ambient air monitoring, if the air quality in a particular location does not meet (i.e., "attain") the NAAQS, that geographical area will be designated as a "nonattainment" area. Then, state or local agencies are required to develop regulations that decrease emissions from *existing sources* to reduce ambient pollutant levels and attain the NAAQS. In addition, NOx emissions may be evaluated by regulatory agencies using a model that simulates the behavior of the exhaust plume (i.e., a "dispersion model") to assess whether NO_2 impacts beyond the compressor station fence line exceed the NO_2 NAAQS. If so, mitigation would likely be required.

For example, NOx Reasonably Achievable Control Technology (RACT) regulations may be adopted by a state to address ozone nonattainment within the state. These rules may apply to limited in-state areas (e.g., urban nonattainment areas) or statewide. In addition, many urban and eastern U.S. areas have already reduced NOx emissions, but NOx transported from upwind states contributes to nonattainment. This phenomenon is referred to as "NOx transport," and EPA may adopt multi-state regional rules to reduce NOx across the eastern U.S. and mitigate NOx transport. For natural gas-fired combustion sources, NOx is the primary pollutant that may be regulated by these rules. Emissions of other pollutants such as formaldehyde, which is regulated as a hazardous air pollutant (HAP), may also trigger emission controls. However, it is generally expected that existing catalyst control providers can meet demands to address new regulatory requirements.

Thus, this report focuses on potential resource constraints associated with regulations that require retrofit installation of NOx emission control technologies. More specifically, the report focuses on combustion-based technologies – i.e., low emissions combustion (LEC) – for lean burn reciprocating engines commonly used in interstate transmission and most likely subject to retrofit NOx control in the future (i.e., this older equipment is typically "grandfathered" and many units have not been subject to NOx regulations to date). The reciprocating engines of interest are low speed "integral" engines uniquely used for gas compression, where the compressor and its driver – i.e., the reciprocating engine used to power the compressor – are integrated into a single piece of equipment with a common crankshaft. These legacy integral engines comprise a large portion of the horsepower capacity in interstate natural gas compression and can also be found in gas processing and, to a lesser extent, in gathering compression. Although these engines have been in service for many years, because they were designed specifically to compress natural gas, natural gas-fired integral engines remain the most efficient option for gas compression.

LEC is the preferred approach to reduce lean burn engine NOx emissions, but EPA or states may consider additional controls such as selective catalytic reduction (SCR). Rich burn reciprocating engines may require non-selective catalytic reduction (NSCR) to reduce NOx and formaldehyde, but rich burn engines are a smaller percentage of interstate transmission prime movers and many rich burns already use NSCR emissions control in response to the federal HAP standard or state requirements.

The focus of this report is to assess the availability of resources to implement air emission modifications on the reciprocating engines used to transport natural gas on the interstate pipeline system. For example, there are currently a handful (or less) of service providers that provide LEC control for reciprocating engines. Thus, depending upon the breadth and timing of emission control requirements, there is a concern that resource constraints may impact timely compliance or the reliability of gas delivery.

This report will identify potential constraints, including potential bottlenecks in the supply chain, regarding availability of capital equipment and technology service providers to address retrofit NOx control of the existing fleet of equipment. Scheduling issues will be discussed, including constraints that may point to the need for phasing regulatory compliance.

The regulatory context is based on an expectation that existing reciprocating engines that do not include NOx control technology will eventually be required to retrofit NOx control technology in response to recent or upcoming revisions to the federal ozone or NO_2 NAAQS. NOx control resource availability for reciprocating engines is the most probable resource constraint due to the limited service providers and trained labor in this field, so this report focuses on potential resource limitations and the time required to control these engines, especially lean burn engines.

In addition to this Introduction, the report includes:

- An Executive Summary.
- Section 2 discusses the study approach.
- Section 3 provides an overview of reciprocating engine NOx control technologies,
- Section 4 discusses engine demographics (population and type) for interstate transmission prime movers.
- Section 5 presents NOx related air quality regulatory concerns and analysis assumptions and methodology.
- Section 6 presents methodology and results related to costs and schedule.
- Section 7 presents the analysis and discussion of limitation by project phase, and Section 8 provides conclusions.
- Appendices provide a list of acronyms and the survey questions used for discussions with operators, equipment manufacturers, and service providers.

2.0 Study Approach

The information in this report was gathered confidentially by Innovative Environmental Solutions (IES) and Optimized Technical Solutions (OTS) and the information has been consolidated in a manner that the individual responses cannot be broken out by the vendor or operator supplying the information. This is done to prevent business strategies or other competitive information from reaching competitors. All efforts were made to prevent the communication of information that could result in anticompetitive practices.

Interviews were performed with multiple emission reduction vendors and operating companies. In addition, a literature review was performed, and relevant information is cited. There is significant uncertainty regarding the requirements (e.g., required emission levels), geographical breadth, and timing of NOx regulations. Since there are many possible regulatory outcomes, specific dates and regulations are not a focus, but a general discussion of the NOx control regulatory threat is provided in Section 5. Instead of considering a specific regulation, the analysis in this report focuses on identifying potential resource constraints based on an assumption that many legacy prime movers without NOx control will eventually require upgrade (or replacement). To consider technology needs, costs, and scheduling, the analysis considers the engine types (i.e., model) based on an available database. Two NOx targets are considered (i.e., 3 g/bhp-hr or 1 g/bhp-hr) based on previous experience for likely regulatory endpoints and guidance from advisors, and a general ranking of regulatory risk for three geographical areas is used when assessing implications. States were categorized as high risk/stringency (where regulations may already be in place in some cases – e.g., northeast state where much of the fleet is already controlled), moderate risk (e.g., midwest and eastern states where compressor stations may be implicated as contributors to eastern U.S. NOx transport), and lower risk states, where regulation is less likely (e.g., northern plains states, where control is less likely unless EPA initiates broad national requirements for existing equipment). In addition, costs were considered under the premise that NOx control would be widely required for uncontrolled units either due to NOx regulations (e.g., in response to ozone nonattainment) or permitting actions to address conformance with the NO_2 NAAQS.

This effort began with interviews of multiple interstate gas pipeline operating companies that had previous experience with NOx reduction projects. In addition, independent interviews were conducted with six different suppliers of equipment and services that modify reciprocating engines used in the interstate natural gas transportation industry. Interviews covered all aspects of the execution of NOx reduction projects from start to finish. Specific topics in project execution included:

- **Permitting** – Permitting is the process of obtaining air emission permits from the regulating agency – typically a state agency. This phase requires an initial engineering analysis to determine the modifications required and the expected air emissions for each emission source at a facility for the permit application. Defined technologies must be settled upon prior to completing the permit.
- **Initial design** – This portion of the project assesses: (1) which emission reduction technologies are suitable for a facility and the associated suppliers for the emission reduction equipment, (2) the reduction in air emissions that can be expected with the applicable emission reduction equipment, and (3) the initial design for the equipment changes. Input from the suppliers of emission reduction equipment is usually required during this portion of the project. Initial design information is also necessary to provide information for the permitting process, but other, more detailed design considerations are also addressed under this topic.
- **Cost estimating and scheduling –** This part of the project establishes the expected timeframe and financial costs expected to modify the equipment for emissions control. Personnel resource availability and allocations are also typically performed in this portion of the project execution.
- **Contracting and procurement** – In this portion of the project, detailed cost and schedule information to implement an emission control project is solicited from suppliers and contractors. This requires the creation of design specifications, evaluation criteria, and contractual terms and conditions.
- **Detailed design** – This phase involves developing detailed designs based on specific emission control equipment selected. Detailed design includes but is not limited to the development of material lists, drawings, engine control system modifications, and commission plans.
- **Construction** – This portion of the emission control project is where physical modifications are made to the engine and ancillary equipment.

- **Commissioning** – This is the phase of the emission control project where calibration, configuration, and tuning of the engine is performed to ready the engine for continuous operation. Training of the operating and maintenance personnel is also often performed during this phase.
- **Operation and maintenance** – This is the post-conversion and commissioning portion of the project. Proper operation and maintenance of the engine and emission control equipment is required to ensure compliance with the emission limits.

This report discusses resource constraints for each of these phases for reciprocating engine NOx control projects, as described by the operators and suppliers of emission reduction equipment. For NSCR application to rich burn engines, a higher level review was conducted because it is likely that there are an adequate number of vendors to address market demand and fewer engines are likely to be affected.

Cost and schedule estimates are based on the number and size of engines to be converted, information provided by pipeline operators and suppliers of emission reduction equipment, and reference publications. Factors that influence technology requirements and costs for reciprocating engines include:

- Combustion cycle (two-stroke, four-stroke),
- The engine make and model,
- Brake mean effective pressure (BMEP) of the engine,
- Engine aspiration type (natural, turbocharged), and
- The number of power cylinders.

Based on engines identified in an industry database, this information was used to determine the most probable type of modifications needed to achieve the target NOx emission level.

3.0 Reciprocating Engine NOx Emission Reduction Technology Overview

NOx control technologies for reciprocating engines are discussed below. LEC technologies for lean burn engines are discussed in Section 3.1, and NSCR for rich burn engines is discussed in section 3.2. Section 3.3 discusses SCR. Although SCR has not been applied to existing integral engines, it could be considered by regulatory agencies, especially for lean burn engines where LEC is not available or cannot achieve the target NOx level.

3.1 Reciprocating Internal Combustion Engines – LEC for Lean Burn Engines

An overview of LEC NOx control technologies for lean burn reciprocating engines is described in this section. [1] [2] [3]

NOx emissions from natural gas combustion are formed from nitrogen and oxygen in the combustion air, and NOx emissions increase significantly at higher combustion temperatures. LEC achieves lower NOx by providing sufficient excess air to reduce the maximum combustion temperature and minimize NOx formation. The use of LEC to control NOx is possible on fuel-injected two-stroke cycle engines and many four-stroke cycle engines. Since the excess air may hinder combustion or light-off of the air-fuel charge in the cylinder, LEC-equipped engines generally require a high energy ignition source. This is most commonly implemented by the use of pre-chamber combustion systems that ignite a smaller charge that then ignites the in-cylinder air-fuel mixture. The power operating range may decrease on two-stroke cycle engines when converted to LEC.

Since peak combustion temperatures are influenced by the amount of excess air and air-fuel mixing, there are several methods that can be used to minimize peak temperatures and NOx formation during lean combustion. Regulatory agencies use the term "LEC" broadly and a number of technology approaches can be used depending on the engine and NOx emission limit. In many cases, multiple LEC related technologies may be required – e.g., additional air through new or upgraded turbocharging, higher energy ignition /precombustion chambers, and enhanced mixing. Several primary technologies are described below. For the engine types in the fleet, the analysis considered the proper technology approach to achieve target NOx emissions of 3 g/hp-hr or 1 g/hp-hr.

3.1.1 Enhanced Mixing

Pockets of rich fuel can exist in engines equipped with direct fuel injection. The resulting locally rich fuel mixtures result in localized higher combustion temperatures with an associated increase in NOx formation. Engine modifications to produce enhanced air/fuel mixing can counteract this effect. For example, "high pressure" fuel injection systems have been developed that take advantage of the higher pressure gas available from the pipeline to greatly improve air-fuel mixing. On some engines, enhanced mixing modifications may also require high energy ignition modifications to prevent engine misfires.

3.1.2 Mechanical Modifications

Modifications that can be used to reduce NOx emissions include upgrading or conversion to turbocharging, adding additional turbocharger after-cooling, installing different cam shafts, installing different (e.g., electronic) fuel injection valves, etc. These are not discussed in detail here as they usually result in minor reductions as an independent action, but are typical technologies that may be included as part of the emissions reduction project. Since dispersion modeling may be required to ensure that modeled offsite impacts do not exceed the NO_2 NAAQS, stack height extensions are a modification that can reduce modeled ground level concentrations. In general, a stack height that is at least 1.5 times the height of the compressor building peak height is desired to avoid building-induced "downwash" that brings the plume to ground level sooner and results in higher modeled impacts.

3.1.3 Operational Control – Ignition Timing

The peak combustion pressure (and thereby the peak combustion temperature) can be lowered by retarding (or delaying) the ignition timing of the engine. The lower combustion temperature results in lower NOx emissions. Only nominal NOx reductions are achieved when used in isolation and fuel consumption increases. This may also reduce the maximum power the engine can produce, and typically increases carbon monoxide (CO), volatile organic compounds (VOCs), and total unburned hydrocarbons (THC) emissions. VOCs are regulated as an ozone precursor and are a subset of THC (the methane and ethane components of THC are excluded from VOCs because these two hydrocarbons are minimally reactive in ozone producing atmospheric reactions).

3.1.4 Operational Control – Air/Fuel Ratio

Altering engine control methods can reduce the formation of NOx and improve the reliability of maintaining emissions at the prescribed level. On engines that utilize air/fuel controls, some NOx reductions may be possible by changing the control curve to operate the engine leaner without other engine modifications. This control change is limited by the amount of air available from the turbocharger and the ability of the ignition system to ignite the leaner mixture without misfires.

3.1.5 Other (non-LEC) Technologies

The technologies described above are not intended to be a comprehensive list. There are other control methods such as exhaust gas recirculation that are not covered here due to their limited effectiveness and limited use on the types of engines typically utilized in interstate natural gas transmission.

3.2 Rich Burn Reciprocating Internal Combustion Engines – Nonselective Catalytic Reduction

Rich burn engines are designed to operate with minimal excess air – i.e., with combustion air approximately equal to the amount required to completely combust the fuel with minimal excess air. The "stoichiometric" amount of air is the exact amount required to burn the fuel with no excess. For reciprocating engines that operate near stoichiometric conditions (excess oxygen in the exhaust <0.5%), NSCR is the accepted emissions control option. This type of exhaust control technology is commonly used on automobiles and also referred to as a 3-way catalyst because emissions of NOx, CO, and VOCs can be reduced. For this control technology to work effectively for all three pollutants, an air to fuel ratio controller (AFRC) is required that maintains the AFR over a very narrow operating band. With too little air, NOx will be low, but CO and VOCs may significantly increase. With too much air (and thus too much oxygen available), CO and VOCs will be reduced (i.e., NSCR operates as an oxidation catalyst), but NOx reduction across the catalyst will be impacted and post-catalyst NOx will significantly increase.

Catalytic elements used in NSCR can be contaminated by engine oil carryover and other operating factors. Cleaning and replacement is required on a periodic basis. Unburned hydrocarbons in the exhaust stream reduce the life of the catalyst. This is the common technology of choice for rich burn four-stroke cycle engines.

3.3 Selective Catalytic Reduction for Lean Burn Engines

For NOx control from lean burn engines, this report focuses on LEC. SCR is discussed here because it is often considered by regulators when assessing NOx controls for combustion equipment and future control rules may require SCR in some cases (e.g., if LEC is not effective on a particular engine model). SCR is an exhaust control for lean combustion (i.e., excess air is available) that reduces NOx by reaction with ammonia or urea over a catalyst. [4] [5] Ammonia or urea injection is required with precise reagent feedrate control based on the NOx concentration and the NO/NO_2 ratio of the NOx. The reagent and NOx "selectively" react on the catalyst to (ideally) form water and molecular nitrogen (N_2). To date, SCR application to U.S. gas transmission sources has been very limited, and SCR has not been applied to an existing integral engine. Technical concerns about the SCR performance for gas transmission engines include exhaust temperature requirements, reagent control (and sophistication of current systems), and treatment of potential variations in the reciprocating engine exhaust NO/NO_2 ratio.

SCR has been more commonly applied to larger utility scale turbines and boilers, with very limited gas transmission applications to date. Recently, some new 4-stroke cycle lean burn engines have been sited with SCR, but retrofit application to lean burn prime movers has not occurred. While NSCR for rich burn engines exploits the chemical processes available at stoichiometric combustion to reduce multiple pollutants, SCR "selectively" reduces NOx. The use of SCR is most effective when operating in the exhaust temperature range of 480 to 800 °F. The minimum operating temperature of the catalyst is dependent on the composition of the exhaust gases and the type of catalyst materials used, and the typical exhaust temperature range for some lean burn engines may present challenges. Engines that have variable power loads require more sophisticated controls to inject the proper amount of reagent, and it is not evident that robust control schemes have been developed for transmission applications. The installation of a continuous emissions monitor could be required to effectively control the amount of reagent necessary to achieve the desired NOx emission rate.

SCR catalytic elements can be contaminated by byproducts of combustion (such as oil ash) and engine oil carryover. Cleaning and replacement is required on a periodic basis, and extra management is required to ensure adequate inventories of reagent are maintained.

Due to the issues described above and the desire to prevent NOx formation rather than controlling NOx in the exhaust, LEC is preferred over SCR for existing lean burn engines.

4.0 <u>Reciprocating Engine Demographics</u> (Population and Type)

An INGAA engine database (originally developed by PRCI and GRI over 10 years ago) includes 3665 *low speed* reciprocating engines used in the interstate natural gas industry. It should be noted that the number of engines in the tables below reflect large bore, low speed reciprocating engines. There are other engines used in the natural gas transportation industry. Most of the other engines are newer high-speed four-stroke cycle engines that are already equipped with low NOx emissions (typically LEC or NSCR) technology, such as best achievable control technology (BACT) required during permitting of new units or technology to meet New Source Performance Standards (NSPS) and National Emission Standard for Hazardous Air Pollutants (NESHAP) regulations.

Although this database is not complete (e.g., it was estimated to include over 80% of interstate transmission facilities when it was compiled), and changes in the fleet have occurred since the database was last updated, the information from this source still provides a reasonable basis to assess counts of existing engines and technology requirements for NOx control. Of the 3665 low speed engines, 35 are known to have been abandoned or replaced leaving a net of 3630 engines. These engines were categorized by engine type and geographical region as described in Section 5, where regulatory risk (i.e., likelihood and level of control) was used to categorize states into three regulatory risk categories depending on the state where the engine is located. Table 4-1 shows engine counts for each category for the three primary engine types. (The states in each risk category are identified in section 5.)

Table 4-1. Engine Type by Geographical Regulatory Risk Category.

Engine type	Category 1	Category 2	Category 3	Total
2-stroke cycle	321	1975	344	2640
4-stroke cycle lean	82	320	51	453
4-stroke cycle (rich)	50	405	82	537
Total	453	2700	477	3630

The average engine size is 2145 brake horsepower with an average of 12 power cylinders per engine. To assess technology requirements and potential resource issues, these engines have been grouped or classified based on different engine types/subtypes and current emission control capabilities. Each group type requires a different approach to NOx reduction with an associated impact on costs and schedules. The two-stroke cycle and four-stroke cycle lean engines are candidates for LEC and the four-stroke cycle rich burn engines are candidates for NSCR NOx control technologies. For the purposes of this discussion, the "rich burn" engines include older, horizontal engines that do not include air to fuel ratio control and may operate near stoichiometric conditions (i.e., "rich") or leaner (i.e., with excess air). The term "stoichiometric" refers to the condition where the amount of oxygen available from the combustion air is equivalent to the amount required to completely combust all of the fuel without any excess oxygen. Rich burn engines operate near stoichiometric conditions, while lean burn engines have excess air. Regulatory definitions, such as the federal NSPS and NESHAP standards, typically use ten percent excess air (which is equivalent to two percent excess oxygen in the exhaust) as the threshold between rich and lean operation.

To estimate the number of engines that would require NOx emissions control, and assess associated capital costs and timeline, the INGAA database of engines was analyzed by current emission levels as shown in Table 4-2. Note that this table excludes 417 low BMEP four-stroke rich burn engines that are assumed to have NSCR catalysts as described in Section 4-2.

Table 4-2. Engine Counts by NOx Emission Levels.

Emission capability	Category 1	Category 2	Category 3	Total
NOx $\leq$ 1 g/hp-hr	64	0	0	64
1 < NOx $\leq$ 3 g/hp-hr	339	162	36	537
NOx > 3 g/hp-hr	0	2238	374	2612
Total	403	2400	410	3213

The majority of reciprocating engines used in the interstate natural gas transportation industry were installed before 1960. Most have been exempt from clean air regulations issued after they were installed since existing units are "grandfathered" – i.e., exempt from regulations that affect new sources. A common exception is engines that have been controlled in response to NOx RACT or similar rules adopted to decrease the NOx inventory from existing sources as a strategy to address ozone nonattainment. A discussion follows on each of the primary engine categories, related engine counts, and NOx control technology available.

4.1 Horizontal engines

Horizontal engines are four-stroke cycle naturally aspirated engines with four double acting power pistons. These engines were manufactured by Cooper-Bessemer (Type 22 through Type 26) and Worthington (24X36 and 26X36). These engines are the first type of reciprocating engines widely used to compress natural gas for transportation. They are a derivative of horizontal steam engines. The double acting power cylinders (combustion occurs on both sides of the piston) have very large cylinder bores (22" to 26") and strokes (typically 36"). It is difficult to control the air/fuel mixture for these units – e.g., for use with post-combustion catalytic control. Likewise, they are not suited to LEC conversion. Per the INGAA database, there are 120 engines in this group, where a retrofit NOx control technology is not available, with an average power rating of 1530 hp.

Figure 4-1. Horizontal Engine

Because these engines have higher operating and maintenance costs, they are generally operated on a last on, first off basis in response to demand. Therefore, their annual operating hours tend to be lower than newer engines operating at the same facility.

Since technology upgrades are not available, the assumed "NOx control" option for these engines is replacement. For cost estimating purposes, the assumed replacement equipment is 3000-4000 hp gas turbines equipped with dry low NOx (lean premixed) combustors. Although larger gas turbines would reduce the capital replacement costs, smaller gas turbines are a better match (although still larger) to the engines being replaced. Larger engines do not have the necessary turndown capability to match the horizontal engines. Gas turbines were selected over other engine types due to the lower capital costs. Where minimizing fuel is a major consideration, high speed four-stroke cycle reciprocating engines would be selected as the replacement engine. All of these engines are located in geographical regulatory risk Categories 2 and 3 as shown in Table 4-3. These engines are a subset of the four-stroke rich burn engines found in Table 4-1. All horizontal engines are assumed to have NOx emission rates greater than 3 g/hp-hr.

Table 4-3. Number of horizontal engines.

Engine Type	Category 1	Category 2	Category 3	Total
4-stroke – horizontal	0	105	15	120

4.2 Low BMEP four-stroke cycle naturally aspirated engines

Like the horizontal engines, the low BMEP four-stroke cycle engines (see Figure 4-2) used in natural gas transmission sometimes operate near stoichiometric conditions and other times operate lean. These engines differ from horizontal engines in that they can generally be fitted with air-fuel controls to enable operation with NSCR. However, depending on the units, operation with NSCR sometimes requires higher exhaust temperatures than the unit was initially designed. Alternatives technologies include converting to LEC (with the addition of a turbocharger) [6] or installing SCR. SCR has had very limited application to existing reciprocating engines, and installation of SCR may limit the ability of the engine to operate at rated power.

Figure 4-2. Ingersoll-Rand KVG

The analysis in this report assumes that NOx reductions would be achieved with installation of NSCR, with engine modifications completed as necessary to accommodate higher exhaust temperatures. However, existing rich burn engines at "major sources" (i.e., larger facilities such as compressor stations with multiple reciprocating engines) were required to install NSCR to comply with an EPA regulation, with compliance required by 2007 for the 2004 RICE NESHAP rule. Therefore, resource limitation were not assessed and costs to modify these engines are not estimated here because any incremental costs (e.g., to better tune the air to fuel ratio controller (AFRC) for NOx reduction) should be minimal. It is likely that some of these engines will require control or additional modifications to achieve required NOx reductions. The number of these engines in each geographical regulatory risk category can be found in Table 4-4. This is a subset of the four-stroke cycle rich burn engines in Table 4-1.

Table 4-4. Number of low BMEP four-stroke cycle engines.

Engine Type	Category 1	Category 2	Category 3	Total
4-stroke cycle low BMEP	50	300	67	417

4.3 Opposed piston two-stroke cycle engines

The gas pipeline transportation industry employs about 14 two-stroke cycle opposed piston engines such as the Fairbanks-Morse engine shown in Figure 4-3. These engines typically use superchargers to provide scavenging air.

The engines utilize two power pistons per power cylinder with intake and exhaust ports at opposite ends of the cylinder liner. The two pistons are connected to separate crankshafts which are synchronized through a vertical driveshaft and bevel gears. Because of the higher number of moving parts on these engines, they tend to have higher maintenance costs than other engines used in this industry.

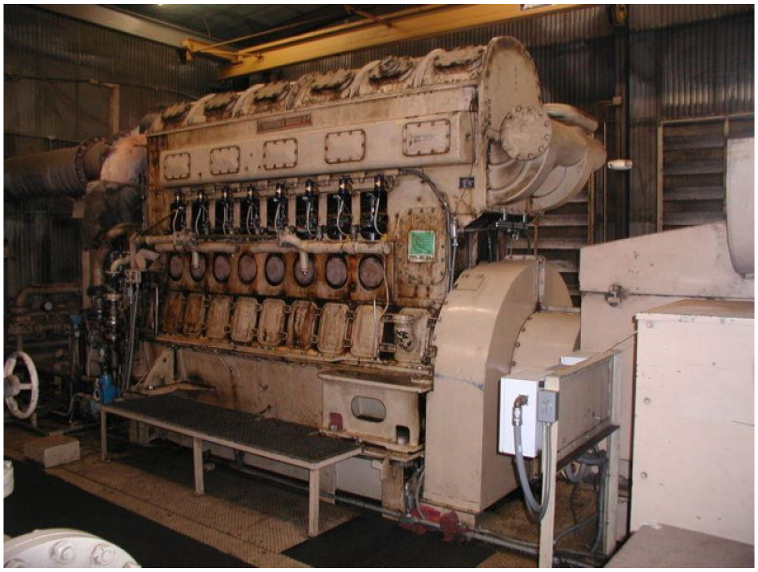

Figure 4-3. Fairbanks-Morse MEP-8

The engines can be converted to lean burn combustion or controlled using post-combustion catalytic reduction. NOx emission rates below 3 g/hp-hr are difficult to achieve at full load and speed on these engines through lean combustion alone. Based on the operating cost of these engines and emission characteristics, the analysis in this report assumes emission reduction is achieved with lean burn conversion and an emission rate of 3 g/hp-hr. Replacement is assumed if lower emission rates are required. The location of these engines by geographical regulatory risk category is in Table 4-5. This is a subset of the two-stroke cycle engines in Table 4-1.

Table 4-5. Number of opposed piston two-stroke cycle engines.

Engine type	Category 1	Category 2	Category 3	Total
2-stroke cycle opposed piston	1	13	0	14

4.4 Medium and higher BMEP four-stroke cycle turbocharged engines

Medium and higher BMEP four-stroke cycle turbocharged engines (see example in Figure 4-4) operate too lean to utilize NSCR for NOx reduction, and these engines are generally suited to NOx control through lean burn combustion and enhanced mixing methods – i.e., LEC technologies.

Figure 4-4. Ingersoll-Rand 616KVT

For cost estimating and resource availability assessment purposes in this study, reducing emissions to 3 g/hp-hr is assumed to be achieved through lean combustion. To lower NOx emissions to 1 g/hp-hr requires the addition of enhanced fuel mixing. The assumed emissions and location of these engines by geographical regulatory risk category can be found in Table 4-6. This table is a subset of four-stroke cycle rich and four-stroke cycle lean engines in Table 4-1.

Table 4-6. Number of medium and higher BMEP four-stroke cycle turbocharged engines.

Emission type	Category 1	Category 2	Category 3	Total
NOx $\leq$ 1 g/hp-hr	36	0	0	36
1 < NOx $\leq$ 3 g/hp-hr	46	26	5	77
NOx > 3 g/hp-hr	0	308	46	354
Total	82	334	51	467

4.5 Low BMEP two-stroke cycle engines

Low BMEP two-stroke cycle engines are generally older engines (i.e., the "first generation" of pipeline integral 2-stroke engines) that utilize low volume pumps or blowers to provide engine scavenging (Figure 4-5). To reduce NOx emissions, LEC is applied through the removal of the mechanically driven scavenging and installation of turbochargers with after-cooling and precombustion chambers. Because of the low BMEP of these engines, there is typically less exhaust energy to support turbocharger operation. As a result, the power turndown range of converted units is limited. The addition of enhanced fuel mixing technologies would extend the power operating range for these engines.

Figure 4-5. Clark HBA Low BMEP Engine

Therefore, conversion to 3 g/hp-hr of NOx is assumed to require both conversion to leaner combustion and the installation of enhanced fuel mixing. With these modifications, the engines are capable of achieving 1 g/hp-hr of NOx in a narrower range near rated speed and power.

Adding a turbocharger sometimes allow these engines to operate at a higher rated power. This can increase the available turndown range of these engines as more heat energy is available to drive the turbocharger. Power increases of 5-40% are possible. The ability to increase the rated power of the engines is dependent on the design of the mechanical, structural, and auxiliary components (crankshaft, connecting rods, pistons, foundation, jacket water cooling, etc.) to handle the higher loads on the engine. The gas compressor cylinders may also require modifications to be able to utilize the additional power. This is usually achieved by installing larger compressor pistons and additional unloaders.

An increase of the engine power rating usually requires modifications to the air permit and filing with the Federal Energy Regulatory Commission. In some cases, the update of several engines could allow the abandonment of another engine thereby eliminating the need (and associated costs) to control emissions for that engine.

On a per horsepower basis, the costs of NOx control conversion for these units are generally more than the costs for higher BMEP two-stroke cycle engines (discussed below). This is due to additional intake/exhaust manifold modifications and the installation (versus an upgrade) of a turbocharger/after-cooler system. The assumed emission limits and location of these engines by geographical regulatory risk category is shown in Table 4-7. This is a subset of the two-stroke cycle engines in Table 4-1.

Table 4-7. Number of low BMEP two-stroke cycle engines.

Emission type	Category 1	Category 2	Category 3	Total
NOx ≤ 1 g/hp-hr	5	0	0	5
1 < NOx ≤ 3 g/hp-hr	72	0	0	72
NOx > 3 g/hp-hr	0	461	44	505
Total	77	461	44	582

4.6 Medium and higher BMEP two-stroke cycle engines

Medium and high BMEP two-stroke cycle engines are engines that utilize centrifugal blowers and/or turbochargers to provide engine scavenging (Figure 6). These engines are generally larger than the first generation low BMEP 2-cycle engines discussed above. They are well suited to lean burn combustion to reduce NOx formation. A reduction in the power operating range can be expected on some of these engines in order to maintain very low NOx emissions. The addition of enhanced fuel mixing technologies extends the operating range of these engines and/or further reduces NOx emissions.

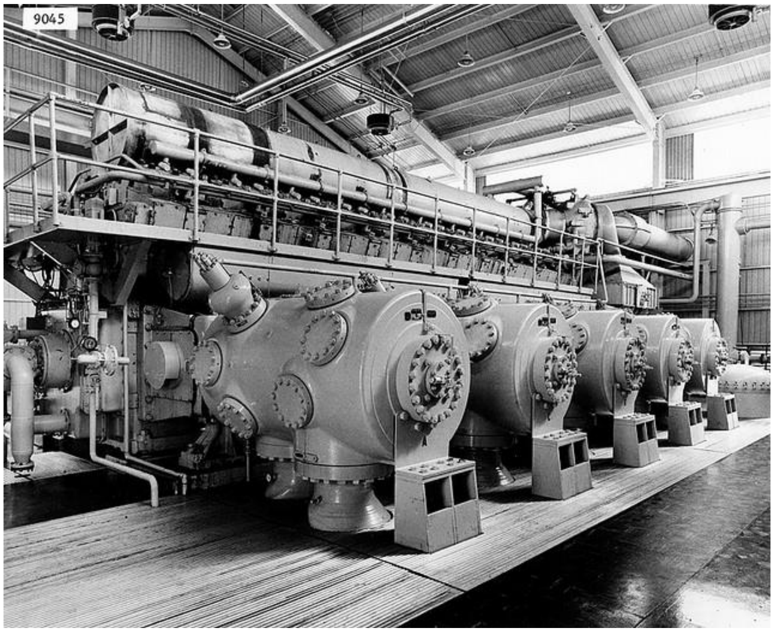

Figure 4-6. Cooper-Bessemer Z330

For the cost estimating purposes of this study, reducing emissions to 3 g/hp-hr is assumed to be achieved through lean combustion. This emission level is consistent with NOx limits for retrofit control of lean burn engines in federal and status rules, and is an expected upper bound target in upcoming rules. However, it is possible that lower NOx emission levels, such as 1 g/hp-hr limits, will be pursued in some jurisdictions. Lower emission limits also require the addition of enhanced fuel mixing. The assumed emission limits and location of these engines by geographical regulatory risk category is shown in Table 4-8. This is a subset of the two-stroke cycle engines in Table 4-1. Note that this group includes many engines, and often these engines are more highly utilized than smaller, older low BMEP engines discussed in the previous section. Thus, the medium to high BMEP two-stroke cycle engines are a prime candidate for regulation when states or EPA consider NOx control regulations.

Table 4-8. Number of medium and high BMEP two-stroke cycle engines.

Emission type	Category 1	Category 2	Category 3	Total
NOx $\leq$ 1 g/hp-hr	23	0	0	23
1 < NOx $\leq$ 3 g/hp-hr	221	134	31	386
NOx > 3 g/hp-hr	0	1372	269	1641
Total	244	1506	300	2050

5.0 Regulatory Background and Analysis Assumptions and Methodology

NOx emission regulations continue to evolve and are not fully defined at this time. However, as EPA and the states implement regulations in response to ozone NAAQS nonattainment and the NO_2 NAAQS, it is expected that new regulations and permitting actions over the next 5 to 15 years will impact the status of many engines that are currently uncontrolled. The following section provides an overview of NOx regulations and regulatory risk, and section 5.2 discusses assumptions used to assess implications.

5.1 NOx Regulations – Background and Regulatory Risk

For existing equipment, NOx regulations are generally in response to concerns with ozone NAAQS nonattainment because NOx is an ozone precursor – i.e., it reacts in the atmosphere to form ozone. In addition, 2010 revisions to the NO_2 NAAQS increased the stringency of that rule. If offsite impacts (i.e., beyond the facility fence line) of NO_2 determined using a dispersion model exceed the NAAQS, then mitigation may be required. At this time, the most likely triggers for retrofit NOx control for natural gas transmission prime movers are:

- NOx RACT Rules: Revisions to the ozone NAAQS planned for 2014 – 2015 will likely increase the number of nonattainment areas, and result in new state-level NOx RACT rules later this decade. Such rules are highly likely to occur unless EPA provides a different regional solution, and state rules could result in different requirements and applicability (e.g., statewide or county-specific rule) from state to state. States tend to rely on rules developed by other states, so states that are early actors in the next few years could provide "model rules" that would be broadly implemented.
- Regional Rule: EPA may implement a broad (e.g., eastern half of U.S.) regional rule similar to the 2004 NOx SIP Call Phase 2 Rule that required NOx reductions from large sources. Over 200 natural gas-fired prime movers were controlled in response to the 2004 SIP Call Rule. A similar new regional rule could supplant or supplement state NOx RACT Rules (see previous bullet), could quicken the schedule, and would likely affect many eastern U.S. engines. EPA may be hesitant to pursue this (and instead defer to the states) due to legal issues that remain to be resolved with a regional rule for electric utilities.
- NO_2 NAAQS mitigation: To date, there have been minimal regulatory actions in response to the 2010 NO_2 NAAQS revision. However, example modeling has shown that the relatively short stacks common for reciprocating engines and conservatism in AERMOD (the regulatory dispersion model) may result in offsite impacts that exceed the 100 ppbv 1-hour NO_2 NAAQS for uncontrolled reciprocating engines. Although there has been limited action to date, this could result in state or federal requirements to mitigate these impacts, and agency actions could be prompted by litigation or pressure from third parties. For existing facilities, EPA or the state could require modeling at any time, such as when the operating permit undergoes its five year renewal. Third party challenges could also force states or EPA to act regardless of the permit renewal schedule. This issue has the potential to impact many existing, uncontrolled reciprocating engine prime movers. Mitigation may require multiple measures, including

NOx control, increasing stack height, and/or increasing the property buffer (e.g., land purchase, moving the fence to the property line).

Regarding the ozone NAAQS, EPA planned to revise the NAAQS in 2011 in response to legal challenges. This was delayed and it was decided to complete the next revision under the schedule that requires NAAQS review every 5 years. That schedule currently plans for a proposed rule in the spring of 2014 and a final rule by mid-2015. That rulemaking will likely result in more nonattainment areas than under the current 75 ppbv NAAQS. This is illustrated in Figure 5-1 and Figure 5-2.

Nonattainment is determined by assessing whether the 3-year average value (from ozone monitoring) exceeds the NAAQS. Projected nonattainment areas from EPA maps in 2010 for an ozone NAAQS of 60, 65 or 70 ppbv are shown in the left map in Figure 5-1. Those ozone levels were being considered for the 2011 rule that was deferred. The right map shows actual ozone nonattainment areas determined in 2012 for the current 75 ppbv standard. The projections for 60 to 70 ppbv were based on 2006 – 2008 data. The nonattainment areas defined in 2012 are based on a 3-year average from 2008 – 2010 or 2009 – 2011. The eastern U.S. had a cool and wet summer in 2009, and hot, sunny weather is more conducive to ozone formation. Thus, states and third parties are challenging EPA and would like to plan for broader nonattainment and address NOx transport from upwind states. Figure 5-2 shows an analysis completed by the Ozone Transport Commission, a group of 12 northeastern states that collaboratively assess air quality in that area. If 2009 data is excluded and the 3-year average is based on 2010 – 2012 data, the figure shows significantly more areas above 75 ppbv and also shows areas that would not achieve a lower, 70 ppbv standard.

Thus, if upcoming summers are not cool (like 2009), and EPA fulfills expectations to lower the ozone NAAQQS to a level between 60 and 70 ppbv in 2015, nonattainment areas will more likely resemble the 60 – 70 ppbv map on the left in Figure 5-1; or, for the northeast, the map in Figure 5-2. This would result in either a broad regional NOx control rule or requirements for many states to develop or update NOx RACT regulations for existing sources.

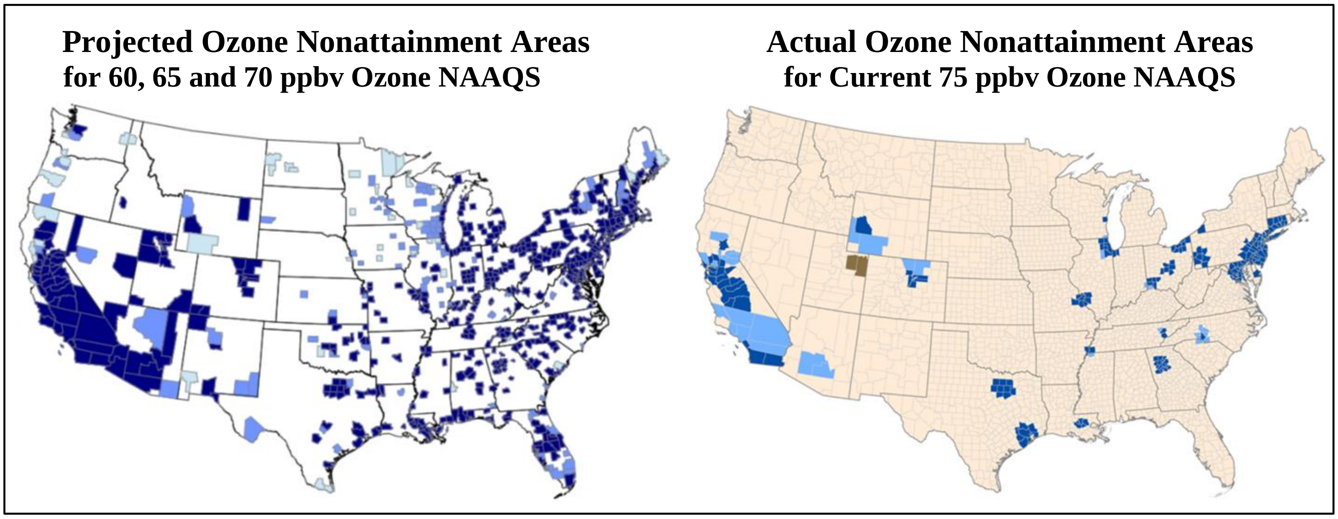

Figure 5-1. Projected ozone nonattainment areas (left map) for ozone NAAQS of 60 ppbv (light blue), 65 ppbv (blue) or 70 ppbv (dark blue) and actual ozone nonattainment areas (right map) for the 75 ppbv ozone NAAQS (dark blue – whole county; light blue – partial county; green – unclassifiable).

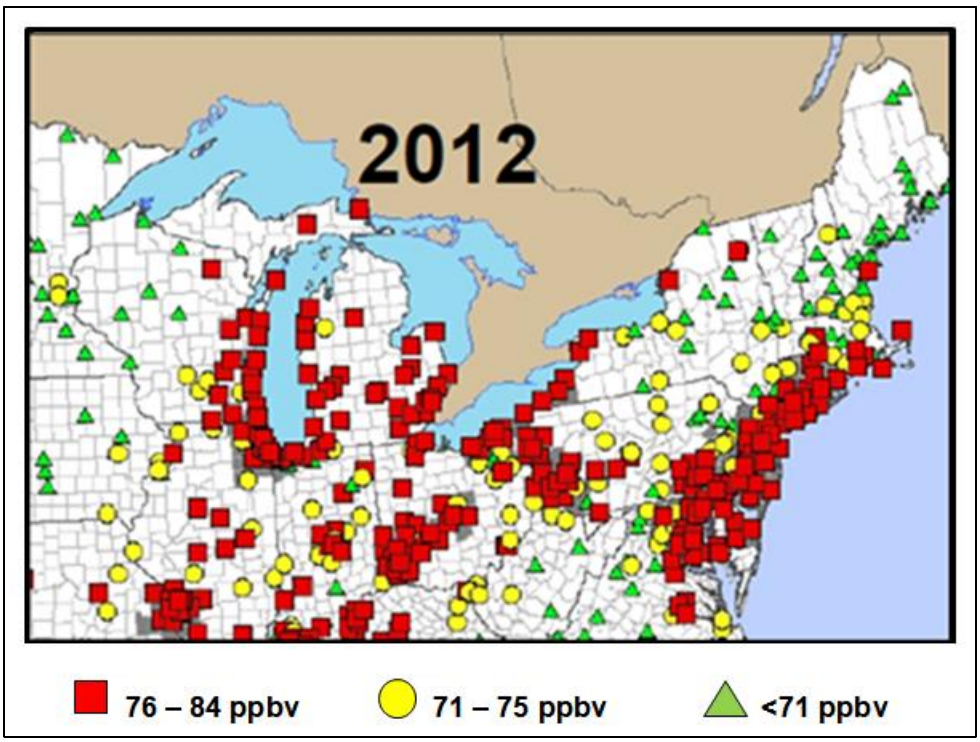

Figure 5-2. Updated northeast U.S. ozone air quality projections from the Ozone Transport Commission based on 2010 – 2012 ozone data (3-year average).

Regarding the NO_2 NAAQS, a committee of state and federal modelers has published example modeling results that show "typical" compression facilities with offsite impacts well above the NAAQS. [7] In Pennsylvania, a third party has requested that the state require modeling for all compressor facilities based on an independent report presenting modeling results with impacts above the NAAQS. [8] To date, the state has provided analysis and data to justify not requiring such modeling, but additional third party challenges are likely. Thus, although requirements in response to the 2010 NO_2 NAAQS have not yet been common, the 2010 NO_2 NAAQS provides a platform for requirements that could broadly affect reciprocating engines that are not equipped with low NOx technology.

Thus, although schedules and mandates are highly uncertain, implementation of current and pending regulations will likely require retrofit NOx control (or replacement) for many existing natural gas-fired reciprocating engines. For this report, the specific timing and count of affected units was not defined. The analysis conducted, based on the actual engines in the fleet discussed in Section 4, focused on available resources and the cost and schedule to install controls based on NOx endpoints of 3 g/bhp-hr or 1 g/hp-hr. These emission levels are based on anticipated emission limits for typical NOx rules, with the lower limit based on potential requirements in more aggressive states.

In judging the likelihood of control and target NOx level (i.e., 3 or 1 g/bhp-hr), states were divided into three categories based on a judgment of the risk of NOx control and stringency over the next 5 to 15 years. This assessment was based on experiences with different states, proximity to areas that have previously failed to attain the ozone NAAQS or are expected to not attain if the ozone NAAQS is lowered in 2015, or within an area that has been targeted by eastern U.S. nonattainment areas as a “NOx transport” area. When considering the time required to install NOx controls, engine location and this ranking were considered (e.g., likelihood that a NOx level of 1 g/hp-hr NOx would be required). For assessing the likelihood of control and the NOx endpoint (3 g/hp-hr or 1 g/hp-hr), states were placed into one of three regulatory risk categories:

- Category 1 (high risk and stringency) – geographical region (i.e., states) where stringent NOx emissions limits are already in place (e.g., northeast states, California, Colorado); if NOx control is not in place, there is a high probability engine modifications will be required;
- Category 2 – geographical region where there is a moderate probability that lower NOx emission limits will be required (e.g., Midwest and southeast states implicated as contributors to NOx transport); and,
- Category 3 – geographical region with a lower probability that lower NOx emission limits will be required.

The INGAA database includes engines in forty-one states, and the list of states and their ranking is shown in Table 5-1.

Table 5-1. Regulatory Risk Category for States with Engines in the Database.

State	Risk Category
Alabama	2
Arizona	2
Arkansas	2
California	1
Colorado	1
Connecticut	1
Florida	2
Georgia	2
Idaho	3
Illinois	2
Indiana	2
Iowa	3
Kansas	2
Kentucky	3
Louisiana	2
Maryland	1
Michigan	2
Minnesota	3
Mississippi	2
Missouri	3
Montana	3
Nebraska	3
New Jersey	1
New Mexico	2
New York	1
North Carolina	2
Ohio	2
Oklahoma	2
Oregon	3
Pennsylvania	1
Rhode Island	1
South Carolina	3
Tennessee	2
Texas	2
Utah	3
Virginia	2
Washington	3
West Virginia	2
Wisconsin	3
Wyoming	3

5.2 Assumptions and Methodology for Reciprocating Internal Combustion Engines (NOx)

The following assumptions and methods were used when assessing technology and resource requirements, schedules, and costs.

- Many rich burn engines employed in interstate natural gas transmission have been modified to reduce HAP emissions under the 2004 RICE NESHAP. Typically these four-stroke cycle rich burn engines added NSCR technology, including the associated engine air-to-fuel ratio control (AFRC). This technology also reduces NOx emissions. As such, four-stroke cycle rich burn engines were excluded from this analysis. It is believed that this is a reasonable assumption with the following caveats:
  - Some of the smaller four-stroke cycle rich burn engines or engines at small facilities may not have installed NSCR.
  - Some engines may require additional modifications or more attention to AFRC to meet NOx limits. This may be achieved by installing a larger catalyst or an upgraded AFRC.
- Some engines (i.e., horizontals) do not have suitable control technologies to reduce NOx emissions as they sometimes operate near stoichiometric conditions (rich) at full load and lean conditions at reduced load. These engines lack the ability to control the air to fuel ratio across the load range. In addition, the engines are of older designs that have limited parts availability and higher operating costs. For the purposes of this study, it is assumed these engines are replaced with new engines and the associated compressor and ancillary equipment. Specific engine types include:
  - Cooper-Bessemer four-stroke cycle horizontal engines, and
  - Worthington four-stroke cycle horizontal engines.
- Some of the engines in the INGAA database have been removed from service since the database was last updated. Those units were removed from the analysis where information was provided by the operator or the author had personal knowledge regarding those units.
- For cost estimating purposes, the following scope of work was assumed for NOx control:
  - 3 g/hp-hr NOx emission rate limit:
    - NOx control through low emissions combustion,
    - High energy ignition system is assumed to be precombustion chamber, either:
      - Screw-in, or
      - Head replacement;
    - Turbocharger modifications are required for lean combustion,
    - Turbocharger after-cooling enhancements are required, and
    - May or may not require (depending on engine model):
      - Fin fan after-cooler upgrades,
      - Coolant surge tank modifications,
      - Auxiliary generator upgrades,
      - Air inlet piping and filter modifications, and/or
      - Exhaust manifold, silencer, and exhaust stack modifications.
    - Alternate or additive approaches (depending on the engine and emission target) include:
      - Enhanced mixing with or without high energy ignition system modifications, and
      - Post-combustion treatment utilizing SCR in select cases.
  - 1.0 g/hp-hr NOx emission rate limit:

    - Modifications for 3 g/hp-hr NOx as outlined above plus enhanced mixing and/or post-combustion treatment utilizing SCR.

- To identify those engines already controlled, existing emission capabilities were assumed based on descriptions and attributes in the INGAA engine database. Specifically, engines were assumed to be controlled to:
  - 3 g/hp-hr NOx or lower if:
    - The engine was identified as having low NOx emission controls,
    - The engine was identified as having post-combustion catalytic treatment (i.e., this implies that permitting closely scrutinized emissions),
    - The engine make and model number is known to be a low NOx emissions unit,
    - The engine is located in a state where control is already required for reasonably available control technology (RACT), or
    - The operating company and/or emission reduction vendor identified specific engines that have been modified to achieve low NOx emissions.
  - 1 g/hp-hr NOx or lower if the operating company and/or emission reduction vendor identified specific engines that were modified to be capable of this emission level.
- As discussed in Section 5-1 and shown in Table 5-1, U.S. locations were divided into three areas based on a judgment of the risk of NOx control requirements and stringency over the next 5 to 15 years.
- New air emission regulations or permitting requirements are expected to eliminate the grandfather provision in many cases and institute NOx control requirements for existing engines that currently are not controlled. The timing that the States (or other agencies) will implement NOx reduction rules and the level of NOx reduction cannot be defined at this time. For assessing the likelihood (and stringency) of control, States were categorized into three geographical regulatory risk categories as discussed above and shown in Table 5-1.
- To understand worst case scenarios in regards to the number of affected engines and a conservative cost projection, it was generally assumed that some level of control would be required for uncontrolled units. For example, engines in northern plains states that may not be affected by a regulation to address nonattainment could still require control to address NO_2 modeled impacts. In general, with the exception of the rich burn engines in Table 4-4, engine counts without controls (e.g., horizontal engines; engines >3 g/hp-hr) from Section 4 tables were included in the cost estimate and scheduling assessment, and additional engines (i.e., units currently controlled but with emissions between 1 and 3 g/hp-hr) are considered for the 1 g/hp-hr NOx limit, depending on location. These total over 2600 uncontrolled engines and over 500 engines that may require additional control if NOx requirements are reduced to 1 g/hp-hr. At this time, it is not expected that the lower NOx level would be broadly required. So, while costs are estimated for the 1 g/hp-hr endpoint to provide that estimate in the report, the schedule to complete all retrofits judges the engine location when assessing the likelihood of a 1 g/hp-hr NOx requirement.

6.0 Cost and Schedule Estimates

The primary purpose of this report is to assess resource constraints associated with retrofit NOx control. In assessing technology requirements and resource constraints, costs were also determined. Cost and schedules are discussed in this section, and Section 7 discusses resource availability (i.e., skill sets and staffing) for each project phase. Information is tabulated for:

- Capital cost for NOx control to achieve NOx emissions of either 3 or 1 g/hp-hr (see Tables 6-1 and 6-2). Separate costs are shows for each emission level, and these costs are not incremental.
- Annual engine retrofits (or replacements) that can be completed based on *current* staffing levels for key technology and engineering service providers (see Table 6-3).
- Time required to complete retrofits (or replacements) for the projected engine counts, based on an emission level of 3 or 1 g/hp-hr and current staffing levels.
  - Table 6-2 shows the number of years required to control engines to 3 g/hp-hr.
  - Marginally longer time is required to achieve 1 g/hp-hr for some engine types. Table 6-5 shows the *incremental time required* to achieve the lower NOx limit.
- The regulatory risk "categories" shown in the tables are based geographical assignment of regulatory risk by state as discussed in Section 5.1 and shown in Table 5-1.

6.1 Capital costs

The costs to modify or replace engines to reduce NOx emissions were gathered through interviews with operating companies, other published sources, and the author's experience.

As described above, unit (engine and compressor) replacement was assumed for horizontal and in some cases opposed piston two-stroke cycle engines. Replacement units were assumed to be dry low NOx gas turbines. Replacement costs were estimated at a fixed cost per unit ($1,800,000) plus a variable cost proportional to engine size ($895/hp). In the case of horizontal and opposed piston two-stroke cycle units, one new turbine unit was assumed for every two units that were replaced.

In select cases where SCR was considered, costs were estimated at a fixed cost per unit ($250,000) plus a variable cost proportional to engine size ($375/hp). Lean burn combustion modifications were estimated at a fixed cost per unit ($152,000) plus a variable cost proportional to engine size ($725/hp). Because of additional turbocharger and after-cooling requirements for two-stroke cycle engines, multipliers for the variable costs (for lean combustion conversion only) are 1.22 and 1.08 for low BMEP and medium/high BMEP two-stroke cycle engines respectively.

Enhanced mixing modifications were estimated at a fixed cost per unit ($235,000) plus a variable cost proportional to engine size ($85/hp). When both lean combustion and enhanced mixing modifications are implemented at the same time (e.g., converting from > 3 g/hp-hr to <1 g/hp-hr) costs were estimated at a fixed cost per unit ($427,000) plus a variable cost proportional to engine size ($785/hp).

Costs were assessed for affected engines to reduce emissions to 3 g/hp-hr. For reducing to less than 1 g/hp-hr, the additional costs were determined for further reducing emissions from these engines. In addition, costs were determined for additional engines that are already controlled to 3g/hp-hr that require additional reductions to achieve 1 g/hp-hr. Note that the costs to modify engines for NOx control are significantly lower than the replacement costs. This is due in large part to the fact that both the engine and the gas compressor must be replaced if the engine is replaced. As a general rule, the replacement equipment has a lower overall unit efficiency[8] and therefore uses more fuel (and by correlation has higher CO_2 emissions) than the units they are replacing.

The total estimated NOx control capital costs to modify reciprocating engines used in the natural gas transportation industry are summarized below. Table 6-1 represents the costs to reduce emission rates to less than 3 g/hp-hr, and Table 6-2 represents the costs to reduce emission rates to less than 1 g/hp-hr. For 3 g/hp-hr, total costs are nearly $4 billion and "average" costs per unit for the different engine types were about $1 to $1.5 million for 2-stroke engines and $2 million for 4-stroke engines. Replacement costs exceeded $2 million per unit.

Note that these two tables are exclusive, i.e., the tables present costs to achieve either 3 or 1 g/hp-hr and are not to be added together. In addition, while many units may need to achieve NOx limits on the order of 3 g/hp-hr, it is currently not expected that a large percentage of the fleet will need to achieve 1 g/hp-hr. For example, engines in higher risk areas (Category 1) are more likely to face the more stringent emission limit, while engines in lower risk Category 3 would be far less likely to require a 1g/hp-hr emission limit. Thus, costs to achieve 1 g/hp-hr NOx are a conservative upper bound (i.e., broad NOx regulations are more stringent than expected) for the engine fleet in the INGAA database.

Table 6-1. Costs to achieve 3 g/hp-hr ($ in thousands).

Emission type	**Category 1**	**Category 2**	**Category 3**	**Total**
Horizontal engines	$0	$236,308	$36,054	$272,362
Opposed piston	$756	$14,311	$0	$15,067
Med & high BMEP 4-stroke	$0	$660,355	$89,798	$750,153
Low BMEP 2-stroke	$0	$685,751	$65,811	$751,562
Med & high BMEP 2-stroke	$0	$1,770,389	$330,588	$2,100,977
Total	$ 756	$3,367,114	$522,251	$3,890,121

[8] Generally reciprocating engines drive reciprocating compressors while gas turbine engines drive centrifugal compressors. As a general rule, reciprocating engines are more fuel efficient than gas turbines. Likewise, reciprocating compressors are generally more efficient than the centrifugal compressors. There are exceptions where the gas turbine unit is the more efficient option. An example would be a high speed, low BMEP reciprocating engine driving a reciprocating compressor with small valve flow area replaced with a gas turbine/centrifugal compressor.

Table 6-2. Costs to achieve 1 g/hp-hr ($ in thousands).

Emission type	Category 1	Category 2	Category 3	Total
Horizontal engines	$0	$236,308	$36,054	$272,362
Opposed piston	$2,108	$38,100	$0	$40,208
Med & high BMEP 4-stroke	$18,235	$807,287	$111,779	$937,301
Low BMEP 2-stroke	$24,290	$629,647	$60,415	$714,352
Med & high BMEP 2-stroke	$94,840	$3,645,435	$680,204	$4,420,479
Total	$ 139,473	$5,356,777	$888,452	$6,384,702

6.2 Schedule

Starting in 1999 as part of the NOx State Implementation Plan (SIP) Call (an eastern U.S. regional NOx rule for large existing sources), approximately 200 natural gas transmission engines were converted to LEC. From interviews with the operators and the emission reduction equipment suppliers, the conversion process took six years in total to fully implement. Additional engines were controlled in the late-1990's through about 2009 in response to state RACT rules.

Based on interviews with pipeline operations and emission reduction equipment suppliers having experience with previous conversion projects, NOx control for each engine requires between 1 and 2 ½ years to complete (from inception to completion of commissioning). The longer duration projects are those that require more infrastructure modifications (such as cooling equipment and auxiliary generators), on-engine modifications (after-coolers, turbochargers, lubrication systems, cooling systems, fuel systems, pre-chambers, intake/exhaust systems, and controls), and engine overhaul. Generally, older engines require more time to design the conversion. This is due to inaccurate or missing engineering records on the current configuration of and ancillary equipment used on the engine.

Taking into account both the lead time and conversion time and based on *currently available resources* (i.e., trained personnel), the average number of units that can be modified to lean combustion on a sustained basis is ***approximately 75 engines per year***. This is the key resource constraint that will affect NOx control requirements that affect these engines, even if only a subset of engines (e.g., a quarter of the current total capacity) is affected by new NOx control rules. Note that this projection is somewhat higher than the approximately 50 units per year converted under the NOx SIP Call even though additional technical resources are not in place at this time. The higher number of units converted per year assumes some efficiency of scale will be achieved based on processes and standards developed from previous efforts. A relatively optimistic projection for the annual number of conversions was selected so that the analysis reflects an "optimistic" scenario without considering how staffing and training will respond to market demand.

The estimated number of engines that can be retrofit per year is based on *current* resource availability. While a dramatic increase in market demand would likely result in hiring and training of additional resources, the special skills associated with this niche market would require time to build that resource. In addition, until new regulations are adopted the market and timing is not clear, thus this resource base will not grow until the market is clear.

Based on the engine counts in Section 4 and the regional location of the engines, an estimate of the number of engines that can be modified per year is shown in Table 6-3, and the resulting number of years necessary to address NOx controls for the reciprocating engines used in natural gas transmission is presented in Tables 6-4 and 6-5.

The number of engines that can be modified per year depends on differences in scope related to the engine type (e.g., some engines are configured for lean combustion while others are not). The estimated number of engines that can be modified per year by engine type and emission level is shown in Table 6-3. The count varies for different engine types and emission level due to the complexity of the retrofit (e.g., need for additional equipment such as turbochargers, need to upgrade ancillary support such as cooling, etc.). It is not anticipated that the number of annual engine conversions can be significantly improved upon within a short timeframe (e.g., if demand for NOx control significantly and quickly increases) because specific skills and specialized training are necessary to serve this market.

Table 6-3. Estimated number of engines that can be modified/replaced per year.

	Modified to achieve NOx emission levels of:	
Engine type & initial emissions	**≤ 3 g/hp-hr**	**≤ 1g/hp-hr**
Horizontal engines	40	40
Opposed piston	40	40
Med & high BMEP 4-stroke > 3 g/hp-hr	75	64
Med & high BMEP 4-stroke ≤ 3 g/hp-hr	N/A	82
Low BMEP 2-stroke > 3 g/hp-hr	60	50
Low BMEP 2-stroke ≤ 3 g/hp-hr	N/A	75
Med & high BMEP 2-stroke > 3 g/hp-hr	75	64
Med & high BMEP 2-stroke ≤ 3 g/hp-hr	N/A	80

Based on the number of engines to be controlled (engine counts from the INGAA database as shown in Section 4) and the estimated number of engines that can be modified per year, the estimated time required to implement modifications to achieve 3 g/hp-hr is shown in Table 6-4.[9]

For NOx levels of 1 g/hp-hr, far fewer engines will be affected. To provide an upper bound on capital costs for control, , costs in Table 6-2 were estimated assuming that all of the affected units would need to achieve the low NOx level. The schedule to achieve the lower NOx level and timing presented in Table 6-5 considers a much smaller subset of engines, such as engines in a high risk location such as the northeast (Category 1). While Table 6-2 shows the costs to control all engines to 1 g/hp-hr, Table 6-5 shows the nominal *incremental time* required for this smaller subset of "high regulatory risk" engines to achieve 1 g/hp-hr.

Based on current technical resources, the projected time to implement retrofit NOx control (or replacement) is far in excess of typical regulatory schedules. Primarily due to the large number of engines in Category 2 (units primarily in southeast and midwest states), *Table 6-4 shows that it would take **decades** to address NOx controls for a large number of engines*, even if the annual rate of retrofit conversions is doubled. Since the retrofit market is currently very limited (i.e., rules are not currently

[9] While the elapsed time for an engine retrofit or replacement from inception to completion may take 1-2 calendar years, the work can be performed by multiple engineering firms and construction companies resulting in an average resource time of less than one year per project.

requiring installation of retrofit NOx controls), *there is no incentive to increase capacity* at this time. So, this limitation will not be addressed until indicated by market demand and confirmed regulations. Section 7 includes additional discussion of manpower and other resource constraints on a project level basis.

Table 6-4. Time required to modify engines to achieve 3 g/hp-hr (in years) [10]

Emission type	Category 1	Category 2	Category 3	Total
Horizontal engines	0.00	2.6	0.4	3.0
Opposed piston	0.03	0.3	0.00	0.3
Med & high BMEP 4-stroke	0.00	4.1	0.6	4.7
Low BMEP 2-stroke	0.00	7.7	0.7	8.4
Med & high BMEP 2-stroke	0.00	18.2	3.6	21.8
Total	0.03	32.9	5.3	38.2

A small number of engines (e.g., in Category 1) may require control to the more stringent 1 g/hp-hr NOx level. Table 6-5 shows the *incremental* time required to address that more stringent mandate and shows minimal impact on schedule to achieve the lower NOx level. However, considering capital costs in Tables 6-1 and 6-2, a lower NOx limit will have a significant cost impact, with engine-specific costs on average about 65% higher to achieve 1 g/hp-hr.

Table 6-5. Incremental time required to modify a subset of high risk engines to 1 g/hp-hr rather than 3 g/hp-hr (in years).

Emission type	Category 1	Category 2	Category 3	Total
Horizontal engines	0.00	0.07	0.01	0.08
Opposed piston	0.00	0.01	0.00	0.01
Med & high BMEP 4-stroke	0.00	0.06	0.01	0.07
Low BMEP 2-stroke	0.00	0.15	0.01	0.16
Med & high BMEP 2-stroke	0.00	0.28	0.06	0.34
Total	0.00	0.57	0.09	0.66

7.0 Resource Analysis and Limitations by Project Phase

This section discusses resource requirements and constraints chronologically by project phase. The resource considered in this section is available manpower – i.e., staffing and expertise by topical area. All phases of project planning and execution are discussed even though several have minimal impact on schedule or cost. The information gathered identified several constraints and concerns associated with the available resources to implement NOx emission reduction projects. Constraints are due to the availability of skilled or expert staff necessary to complete key project tasks, and the requirements and limitations are discussed qualitatively by project task.

[10] Unless resource constraints are addressed via staffing and training, the overall timeline cannot be shortened by executing the projects for multiple regions/engine types simultaneously. For example, replacing all of the horizontal engines in Categories 2 and 3 will take about 3 years even if the work for both categories is performed at the same time. This is because executing projects in Category 3 states concurrently with projects in Category 2 states will require the reallocation of resources away from Category 2 states.

Interview subjects included multiple operating companies and six different suppliers of equipment and services to modify natural gas transmission reciprocating engines.

7.1 Permitting

The permitting portion of the project typically involves evaluating many different cases. Design iterations are made to determine technology requirements to reduce emissions to required levels within the required timeframe. Secondary factors include the impact the proposed retrofit NOx control technology has on equipment efficiency and operational turndown. Due to the workload of the permitting agencies, the permitting process typically takes a long time to complete (months to years in some cases). Because of the long lead time involved, air quality permit applications are often filed before design optimization for the NOx control equipment can be completed.

Complicating factors may include other regulatory limits. For example, implementing significant modifications to a piece of equipment to reduce air emissions may require modifications to reduce noise emissions to conform to local noise regulations. In addition, special care must be made to ensure retrofitting NOx control technology does not adversely impact emissions of other pollutants such as THC and CO, or additional controls (i.e., oxidation catalyst for CO or hydrocarbons) are considered to address this situation.

The operators expressed concern that regulations to reduce NOx emissions will result in constraints at the state regulating agencies (e.g., timing to process permits and potential backlog due to state budget and staffing issues). The result could include:

- Slow response time in issuing air permits. This can result in delays to the project execution schedule, and can make it difficult to comply with new regulations with a hard deadline for implementation.
- Limited flexibility in approving new emission reduction technologies (i.e., time constraints due to agency staffing).
- Limited ability to modify the design for optimization after the permit application has been submitted without causing further delays.

These concerns could be mitigated somewhat if longer or phased implementation schedules are allowed. States generally propose a short compliance schedule (e.g., 18 months to two years from the rule date). It is incumbent upon the affected industry to try to convince the state during rule development to allow longer schedules, including phased schedules. Thus, operators need to be proactive in working with states (or EPA) to achieve “reasonable” schedules. However, it is highly unlikely that a decades long implementation scenario indicated by Table 6-4 will be achievable.

7.2 Initial design

Based on the expected number of engines to be modified, pipeline operating companies will require additional engineering staff to perform initial design of NOx reduction modifications. Some of this will be achieved through the hiring of additional staff. However, based on the current trends and practices, most of this resource will be provided by firms that provide contract engineering services or turnkey solutions from LEC technology providers. Examples include: Black & Veatch, E-N Engineering, Mustang Engineering, Cameron, Dresser Rand, Hoerbiger, GE Oil and Gas, and many others. The experience and knowledge of these engineering firms for retrofit NOx control projects is varied and in most cases is limited. This is due in part to high turnover that occurs in these firms and the wide variability of equipment to be modified. The use of engineering staff additions and/or engineering services will require a significant learning curve and training. This will require more time to execute initial engine modification designs. As experience improves over time, the project execution duration should be reduced.

During this phase of project execution, providers of emission reduction equipment such as Cameron, Dresser Rand, and Hoerbiger will receive numerous requests for potential options for emission reduction technologies. This is especially likely where:

- Very low emission rates are required,
- Few engines of the make/model have previously been modified for low NOx technology,
- The engine has a unique design and configuration that requires specialized engineering analysis, and/or
- The engine is required to operate in special modes (e.g., requires a wide power range).

This demand for quotes is a potential resource constraint for the emission reduction equipment providers, especially when demand initially increases. In general, the unique attributes associated with legacy integral reciprocating engines provide a common theme regarding personnel / expertise based constraints. If regulatory timelines can be extended for projects that are unique in design or configuration, this can be mitigated.

Some emission reduction equipment providers will provide turnkey services (design, procure, construct, commission). However, there are currently only a handful of companies that provide this service for NOx control of legacy integral units. The number of engines modified using turnkey services will be limited to what emission reduction equipment providers can provide with moderate increases in qualified technical staff through using contract employees, part time staff, subcontractors, and retirees.

7.3 Procurement

Provided adequate personnel resources and experience exist in the initial design phase to produce procurement specifications, the actual procurement process should have minimal resource constraints. Qualified procurement personnel are available on a contract basis. In many cases, the pipeline operating company will use the same contract engineering services to perform the procurement process.

Discussions with NOx emission control equipment suppliers indicated that manufacturing production can be increased to provide the equipment within a reasonable time period (assumed to be *at least 3 years*). As such, the procurement of the hardware required for NOx emission reduction projects is not expected to be a constraint as long as reasonable regulatory schedules are negotiated, trends for increased demand are understood, and production responds accordingly.

7.4 Cost estimating and scheduling

The cost estimating and scheduling phase typically use the same resources used in the initial design. This phase is not expected to have a significant resource constraint.

7.5 Detailed design

Detailed design for emission reduction projects will encounter much of the same resource constraints as described under initial design. The difference in this phase is more resources will be required to produce engineering drawings and project specification documents. Like the initial design phase, this will be achieved through a mix of additional employees for the pipeline operating company, contract services, and turnkey providers, with turnkey LEC technology companies the predominant resource – unless rapid growth in market demand prompts an alternative in the future.

At this phase of the project, the pipeline operating company will require additional resources to provide detailed project management oversight for the life of the project. Again, this will likely be achieved through the use of a mix of new employees and contract services with an associated training and learning curve period.

7.6 Construction

Pipeline operating companies and turnkey emission reduction vendors typically use contract construction services to implement the physical modifications to engines. These resources are generally available and should not be a constraint unless there are a number of major pipeline construction projects that would overlap with the timing of the engine emission reduction projects. Review of the potential for competing infrastructure projects is beyond the scope of this report, but other studies are available, such as the INGAA Foundation Report on midstream infrastructure projections through 2035. [9]

There is one exception; there is currently a shortage of welders qualified for natural gas piping. Modifying a large number of engines to reduce NOx emissions (e.g., 25%, 50%, or possibly the vast majority of over 2600 engines identified in Section 4) would further constrain this resource. Increasing the timeline available to implement engine modifications and avoiding an overlap in the execution of those projects with major pipeline expansion projects would help mitigate this constraint.

During the construction period, the equipment is not available for the transportation of natural gas. To minimize the impact on pipeline capacity and associated disruption for shippers, outages are optimized by:

- Scheduling the construction during periods of low system demands (such as during the summer for pipeline systems that have peak demands during the winter heating season),[11]
- Scheduling outages such that only one or two engines are out of service at any one station during any period of time, and
- Scheduling outages such that outages at compressor stations are staggered (e.g., start with outages at Stations A, C, E, & G, and when the modifications at those stations are completed, then Stations B, D, F, & H)

Future PHMSA regulations [10] may require pipeline operators to complete hydrostatic testing of pipelines (e.g., those installed prior to 1970). If the schedule to install NOx controls overlaps with other pipeline regulations, a reduction in available pipeline capacity may occur. This is exasperated by the overlapping vintage of the pipe that may be affected by PHMSA rules and the compressor engines likely to require NOx control. The result could result in shortages of natural gas in some areas of the country. To mitigate this possibility, it is important to understand not only air quality (or safety) regulatory schedules, but possible implications from different compliance activities across all regulations that occur in the same timeframe. Possible implications from overlapping requirements need to be communicated to regulators to try to avoid impacts on pipeline capacity and natural gas delivery.

[11] With the increase in the number of natural gas fueled power plants installed over the last decade, many interstate pipelines that historically had peak loads during the winter heating season now also have peak demand periods in the summer. Off peak periods for these pipelines are now during the spring and fall.

7.7 Commissioning and Start-up

Proper commissioning of NOx reduction equipment is critical to assure the modified engine reliably meets air emission limits. The process of commissioning and safely placing into service an engine with new NOx control technology requires many different skills and specialized equipment, including:

- Engine mechanical specialist to tune the operation of the engine and equipment to measure the developed engine power,
- Control technicians to calibrate additional measurement points, verify pump rotations, etc.,
- Control system specialists to modify control software (to accommodate additional measurement points and control algorithms) and tune control loops,
- Qualified operating personnel to safely introduce fluids and energize systems,
- Subsystem specialists with specific expertise in control valves, gas measurement, and communications,
- Air emissions testing equipment and analysts, and
- Specialists to train the equipment operators on the operation and maintenance of the new equipment.

Due to the specialized skills required during this phase and expectations that demand will exceed the currently available resources, *these are personnel resources that are likely to be constrained* for NOx control projects. Mitigation measures include utilizing available temporary resources (such as qualified contractors and retired employees), hiring and training new staff, and extending the timeline for modifications.

7.8 Operation and Maintenance

Within the first year after commissioning an engine, additional adjustments are commonly required after break-in and to address changes to seasonal ambient conditions. This typically requires the same technical personnel and equipment used to commission the engine as discussed above. The same mitigation measures described above would apply to operation and maintenance of the equipment.

If adequate operating spares for the newly installed equipment are purchased as part of the project, material resources should not be a constraint.

8.0 Conclusions

There is a great deal of uncertainty about the breadth (i.e., how geographically broad), depth (i.e., stringency of the rule), and schedule for new NOx regulations that will affect existing natural gas-fired reciprocating engines. Litigation and scheduling delays have slowed the regulatory process. Although the timing and breadth of new NOx control regulations remains uncertain, it is likely that many of the natural gas-fired reciprocating engines in the existing prime mover fleet will require NOx control by 2025. There are several thousand legacy natural gas-fired reciprocating engines driving compressors in interstate transmission, and their location (i.e., in rural areas where emission rules are more rare) and history (i.e., operating prior to rulemakings that affect new equipment) make these engines candidates for future regulation.

Based on previous projects and interviews with industry experts, modifying these engines will require significant time and capital. The capital required to address the fleet of engines without low NOx technology is significant. In addition, the lack of available expertise is likely to be a primary constraint in addressing broad, new regulations on a timely basis.

Based on interviews with operators, equipment vendors, and service providers, the primary conclusions from this study include:

- The special technical expertise to design, construct, and commission emission reduction projects for the low speed integral engines prevalent in natural gas transmission is available from a handful of companies, and with few NOx rules being adopted in recent years, this expertise may be migrating to other markets. Regulations that require installation of NOx control on a large number of reciprocating engines will require a significant lead time to train and develop resources to implement emission reduction projects. For example, if upcoming NOx regulations impact 25% of the current fleet of legacy reciprocating engines, the number of units requiring NOx control (over 600) would exceed the total number of units that have been controlled over the last 20 years. A higher percentage could be impacted (e.g., 50% of units affected is over 1300 units; even high impacts are possible), and market demand could significantly exceed the available resource base of skilled professionals.
- **Availability of this special technical expertise and building this resource is the primary resource constraint that will affect the ability to meet regulatory obligations that affect a large percentage of the fleet. Based on current capabilities and a scenario where NOx regulations broadly affect the existing fleet of uncontrolled reciprocating engines, *the estimated time to complete upgrades to over 2600 engines is nearly forty years.***
  - Although regulations may affect a smaller subset of engines or compliance strategies may result in many engines (e.g., lower horsepower, lower use engines) being retired or replaced, schedule implications due to the lack of available expertise will likely extend far beyond the required regulatory timeline (e.g., 1000 engines would require 15 years).
  - There is no incentive to begin to build this resource base until it is clear that a market will exist – i.e., the regulations and associated schedule are in place. Since lawsuits and EPA priorities have slowed the next cycle of NOx regulations, it is not possible to project the timing, stringency, number of affected units, or schedule for implementing new NOx rules.
  - In addition to regulatory risk associated with NOx rules in response to nonattainment with the ozone NAAQS, revisions that increased the stringency of the NO_2 NAAQS in 2010 could trigger new NOx control requirements for existing facilities through the permitting process – e.g., during permit renewal. This issue has the potential to trigger NOx control requirements *sooner* than the current ozone NAAQS timeline.
- Due to this resource constraint, it is imperative that companies engage state and federal regulators when NOx rulemakings commence. Emission regulations typically allow only one to two years to implement controls, and additional time and phased implementation will be needed to provide a more reasonable schedule. However, once the next round of NOx rules are initiated, it is unlikely that a decade(s) long schedule will be allowed. The schedule conflicts associated with regulatory timelines, market demand, current supply (i.e., available resources), and service provider growth will likely present a significant challenge over the next 5 to 10 years.
- Engine NOx control projects are generally much less costly than engine replacement. Capital costs to modify the fleet of currently uncontrolled reciprocating engines used in the interstate natural gas transmission industry are estimated at $3,890 million and $6,385 million to achieve NOx emission rates of 3 g/hp-hr and 1 g/hp-hr respectively.
- The age of the impacted equipment (most of the engines are over 40 years old) requires additional time to engineer and construct reliable emission reduction modifications due to inaccurate or missing engineering records that reflect the current equipment configuration.
- Some engines with low specific power output will require extra time to properly design and construct emission reduction modifications and maintain the same power operating range.

- Based on previous experience, the timeline to obtain air permits is a key parameter defining the overall schedule for completing a specific emission reduction project – i.e., permitting can slow the project timeline.
- Equipment outages to implement emission reduction modifications may have a significant impact on available pipeline capacity, especially if the timeline overlaps with implementation of other regulations, such as pipeline integrity assessments that may be required by PHMSA.

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Appendix A: Acronyms

AFRC	Air to Fuel Ratio Controller
BACT	Best available control technology
BHP	Brake horsepower
BMEP	Brake mean effective pressure
CO	Carbon monoxide
EPA	Environmental Protection Agency
g	Grams
hp	Horsepower
Hr	Hour
INGAA	Interstate Natural Gas Association of America
LEC	Low emission combustion
MACT	Maximum achievable control technology
NAAQS	National Ambient Air Quality Standards
NESHAP	National Emission Standard for Hazardous Air Pollutants
NO_2	Nitrogen dioxide
NOx	Nitrogen oxides
NSCR	Nonselective catalytic reduction
NSPS	New Source Performance Standard
O_2	Oxygen
PHMSA	U.S. Dept. of Transportation Pipeline and Hazardous Materials Safety Administration
RACT	Reasonably available control technology
RICE	Reciprocating internal combustion engine
SCR	Selective catalytic reduction
SIP	State implementation plan (Dresser-Rand and others also use "SIP" for screw-in pre-chamber.)
THC	Total unburned hydrocarbons
VOC	Volatile organic compounds (For gas-fired combustion, VOCs are THC excluding methane and ethane, which are the two most prevalent exhaust hydrocarbons). Formaldehyde is also a VOC but is excluded from some regulations (e.g., it is more difficult to measure than THC and may not be included in data used to establish a VOC standard or emission limit).

Appendix B: Survey Questions for Operator and Service Provider Interviews

1. Over the last three years, approximately how many engines has your company modified (as prime contractor) to meet emission levels of 3 g/hp-hr or less?

2. How many of those modifications were achieved through lean emission reduction?

3. Over the last three years, approximately how many engines has your company supplied parts, equipment, material, start-up support, or training to operating companies so they could modify their engines to meet emission levels of 3 g/hp-hr or less?

4. Over the last three years, approximately how many engines has your company supplied parts, equipment, material, start-up support, or training to other vendors or contractors so they could modify their engines to meet emission levels of 3 g/hp-hr or less (acting as a subcontractor)?

5. Over the last three years, approximately how many engines has your company modified (as prime contractor) to meet emission levels of 1 g/hp-hr or less (this should be a subset of (1) above)?

6. How many of those modifications were achieved through lean emission reduction (this should be a subset of (2) above)?

7. Over the last three years, approximately how many engines has your company supplied parts, equipment, material, start-up support, or training to operating companies so they could modify their engines to meet emission levels of 1 g/hp-hr or less (this should be a subset of (3) above)?

8. Over the last three years, approximately how many engines has your company supplied parts, equipment, material, start-up support, or training to other vendors or contractors so they could modify their engines to meet emission levels of 1 g/hp-hr or less (acting as a subcontractor) (this should be a subset of (4) above)?

9. Estimate average number of employees and subcontract staff (i.e. full time equivalent positions) utilized to support the emissions reduction projects over the last three years.

10. Over the last three years, the qualified staffing to support emission reduction projects has:
    a. Increased significantly
    b. Increased some
    c. Stayed about the same
    d. Decreased some
    e. Decreased significantly

11. Based on current staffing, estimate the number of projects per year your company can support acting as the prime contractor.

12. Based on current staffing, estimate the number of projects per year your company can support acting as a subcontractor/parts provider.

13. Based on the technical skills required, estimate the time required to hire and fully train new staff to support emission reductions projects:
    a. Up to six months
    b. Six months to one year
    c. One to two years
    d. More than two years

14. Please describe any issues or concerns associated with implementing a large number of emission reduction modifications over a three year time span.