Systematic Engine Uprate Technology Development & Deployment for Pipeline Compressor Engines through Increased Torque – Phase I

TECHNOLOGY STATUS ASSESSMENT

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Engine Uprate Summary

The objective of this project is to increase the capacity of the existing U.S. natural gas pipeline infrastructure by 1.5 billion cubic feet per day without adding new compressor units. This will be accomplished by retrofitting existing compressor engines with new technologies to increase power output, or "uprate", costing no more than 25% of new unit costs. At the same time, this program seeks to increase fuel efficiency, improve durability, and to reduce the environmental impact of the compressor engines to be considered. The term "systematic" refers to a prioritized approach to be implemented for specific engines over time such that costly, one-time expenditures are not necessary, and to minimize outage time. In total, the U. S. pipeline industry has approximately 8,000 reciprocating engines installed for natural gas compression with a capacity of 7 gigawatts (9.4 million horsepower). Of this total, approximately 2,000 engines totaling 2.5 gigawatts (3,440,000 horsepower) are candidates for uprate technologies[i].

Candidate Technology Summary

Multiple methods and technologies were investigated to identify those that were best suited for the natural gas engine uprate project. The investigation also looked at commercially available technologies as well as technologies that are in the development phase. The natural gas pipeline engines population was inventoried and analyzed for specific engine models that had a low BMEP and a relatively sizeable installed base. These selected engines were then investigated and analyzed for determining the uprating methods that were the most likely to produce the required benefits and remain cost effective. An uprate strategy has been created which identifies these methods that are available. Additional consideration and investigation was given for technical issues that could arise from increasing the output of these engines; this also included input from key industry personnel. An emission analysis was performed with respect to the target technologies for uprating the engines. A cost analysis was performed for each of the identified technologies and a theoretical case study for a TLA-6 was analyzed. The target cost of the uprate kit was not to exceed 25% of a new engine/compressor installation. This has been shown to be an attainable goal, even with the inherent cost fluctuations due to the uniqueness of each engine that would be uprated.
From this investigation into the uprating of natural gas pipeline engines, the following conclusions were reached:

- Speed increases can approach a harmonic of the natural resonance of some engine designs; due to this potential, increasing speed is in general not desired.
- Increasing torque will avoid the potential resonance issues mentioned above.
- Industry data has supported the conclusion that the engines have a large built in factor of safety, which will allow for the safe operation at the increased loads.
- Improved air delivery has long been demonstrated to reduce fuel consumption and emissions through leaner operation.
- Enhanced mixing can help reduce emissions, increase combustion stability, extend the lean limit, and decrease fuel consumption.
- Improved ignition techniques can reduce emissions, improve combustion stability, extend the lean limit, and decrease fuel consumption.
- HPFI, pilot fuel ignition or pre-combustion chambers, and increased boost are proven technologies and are planned for implementation in Phase I of this program.
- Emerging technologies, such as laser ignition and water injection, are not likely to be ready for implementation in this program. However, development progress will be monitored.
- Exhaust tuning benefits are engine specific and would have to be analyzed for each case. Engine modeling shows that the TLA-6 is an excellent candidate for exhaust tuning.

Candidate Technologies

1. Improved Air Delivery

To improve the air delivery system for the large bore natural gas engines, a turbocharger could be installed to offer a significant increase in the quantity of air delivered to the cylinders. With the addition of a turbocharger, or installing a larger capacity turbocharger, the performance of the engine can be increased. The benefits from the installation of a turbocharger are the following:

- Reduced fuel consumption
- Enables leaner operation
- Allows for greater loads
- Removal of parasitic load (if an engine driven blower system is pre-existing)
- Reduced NO_x when engine is operated leaner, possibly facilitated by improved mixing and/or enhanced ignition
- Intercooler system can be easily adapted for additional performance increase

Installation of a turbocharger is a common practice today as is upgrading to a larger capacity turbocharger. It is important to size a turbocharger appropriately since the cost of a turbocharger unit can be a significant percentage of the hardware cost. Potential turbocharger suppliers include Man Turbo, Elliott Company, or Universal Compression.

2. Enhanced Mixing Benefits

Enhanced mixing provides direct benefits towards the stated goals of this project. Advantages of enhanced mixing are generally found in extending the lean limit, reduction of emissions, improved flame propagation, increased engine efficiency, increased combustion stability, and improved engine speed stability. Most of these benefits are directly related to the improvements of the mixing due to an increase in the turbulence level in the cylinder[ii].

A method of fuel injection that has shown positive results is high-pressure fuel injection (HPFI). Improvements for the mixing of the air/fuel mixture are likely due to the higher injection pressures, which induce turbulence. In work by Willson, et al[iii], HPFI was tested on the Cooper-Bessemer GMV-4TF at Colorado State University's Engines and Energy Conversion Laboratory (EECL). It was found that the lean-limit could be extended significantly. NO_x formation was reduced dramatically, and CO formation increased slightly.

A field implementation of HPFI on a TCV-16 has shown positive results similar to that of the research results gained from experiments performed at the EECL. The TCV-16 had an electronic gas admission valve system, which was then upgraded to the commercially available Enginuity *HPFi*™ system. The NO_x levels were decreased from 5.0 gm/bhp-hr to 2.5 gm/bhp-hr, a 50% reduction. The BSFC was reduced from 7350 btu/bhp-hr to 6850 btu/bhp-hr, a 6.8% reduction. With the fuel delivery improvement and increased efficiency, surprisingly, the turbocharger demand decreased from 21" Hg to 15.5" Hg. Ultimately a NO_x level of 1.1 gm/bhp-hr was achieved at 20" Hg of boost. This reduction was not "free" though; the BSFC increased to 6950 btu/bhp-hr. These results though show a 78% reduction in NO_x with essentially no additional fuel efficiency penalty (or improvement) and nearly the same load on the turbocharger[iv].

High-pressure fuel injection systems are commercially available and are currently offered through their respective manufacturers. Potential suppliers for this technology are Enginuity Inc. and Hoerbiger Corporation of America.

3. Improved Ignition Techniques

Spark ignition is the standard method of initiating combustion in nearly all large-bore natural gas fired engines. This method, although effective, is quite susceptible to misfires due to fluctuations in the air/fuel ratio as well as the degree of heterogeneity of the charge in the cylinder. This phenomenon becomes especially apparent when trying to operate near the lean limit. Several methods have been developed to offer an alternative to the standard spark ignition system. Two promising methods are pre-combustion chambers and micro-liter quantity pilot ignition (dual fuel engine).

Pre-Combustion Chambers

The most common solution to the problem of meeting more stringent emissions regulations has been lean burn combustion. At extremely lean conditions, both CO and hydrocarbon emissions become unacceptably high due to misfires and other combustion instabilities. In order to combat this, a pre-combustion chamber (PCC) ignition system has been developed.

There are several advantages to this type of ignition system. Since ignition in the main chamber is distributed over a larger volume, the ignition event is less affected by lean regions or by poor mixing around a single ignition point; this results in increased combustion stability. Also, since the ignition energy is much higher, PCC's can ignite an overall leaner mixture. This effectively extends the lean limit of combustion, allowing for cooler in-cylinder temperatures without the cycle-to-cycle variation[v,vi].

A disadvantage of the pre-combustion chamber technology is the creation of a high temperature zone within the pre-chamber, which leads to a localized spike in NO_x formation. This can lead, to some extent, to a cancellation of the benefit of the overall NO_x reduction due to the operation near the lean limit. Additionally, due to this localized high temperature and the continued use of a spark plug to initiate the combustion event, the spark plugs remain a maintenance item, which adds to the overall long-term cost.

This technology has been a commercially available method for many years from a variety of after-market and OEM manufacturers. There are screw-in pre-combustion chambers available from sources such as Diesel Supply Inc. and Compressor Engineering Company, Inc. (CECO). There are also cylinder heads with integrated pre-combustion chambers available. These can be purchased through Dresser-Rand Co. and Cooper Compression.

Pilot Fuel Ignition

The pilot fuel ignition system has similarities to both diesel and spark ignition engines. These similarities come from the components that make up the dual fuel. The dual fuel is introduced into the chamber where the primary fuel is combusted as it would be in any engine, but the pilot fuel is introduced to provide the initiation of the combustion process, instead of a standard spark plug. This pilot fuel accomplishes this by reaching the auto-ignition point due to the temperature and pressure within the cylinder. With the dual fuel ignition system, misfires are reduced and the flame propagation speed is improved. For a natural gas fired engine, the natural gas is still the primary fuel. It is introduced in traditional methods; either mixed with the intake air or injected directly into the cylinder. Because natural gas has a high auto-ignition point, the air/fuel mixture does not automatically combust. With a small amount of the pilot fuel added to the air/fuel mixture, the auto-ignition point of the pilot fuel is reached and the combustion process is started. There are many different pilot fuels that can be used, but diesel is the most common due to its availability and relatively low cost.

This method also allows for stable operation at lean limit conditions. With the air/fuel ratio increased with the addition of more boost, or with the reduction of the quantity of natural gas injected into the cylinder, an engine with a spark plug ignition system begins to suffer from numerous misfires. This is not the case for the pilot fuel ignition system since the pilot fuel is injected into and becomes distributed within the primary air/fuel mixture. The pilot fuel is able to reliably begin the combustion process of the natural gas farther into the lean region.

In experiments at the EECL on a Cooper-Bessemer GMV-4TF two-stroke, natural gas fired engine, this method has demonstrated significant performance improvements. All of the data indicated that improvements in emissions and performance could be realized by replacing the spark ignition system with an open chamber pilot ignition system at medium and low compression ratios. The greatest benefit is the ability to reduce the NO_x formation while still maintaining combustion stability at an increased boost where normal spark ignition systems would not be able to ignite the lean air/fuel mixture. No disadvantages were observed by running the engine with the pilot ignition system other than at low compression ratios where the fuel consumption would increase[vii].

Pilot fuel ignition systems that have been developed at the EECL inject such small quantities of diesel into the combustion chamber that commercially available automotive market hardware has been successfully implemented. The fuel injectors that have been used in development and field test studies have been purchased through Delphi. Hardware, such as the fuel injectors, can be purchased through Delphi, Bosch Corp., or Denso Corp.

4. Candidate Technology Summary Table

	ENGINE MODEL (Percent of Overall Fleet)					
	BA, HBA, HLA	TLA	KVG	KVS	GMV, GMVA	GMW, GMWA
	(7.5)	(7.1)	(3.1)	(4.4)	(5.1)	(9.3)
UPRATE TECHNOLOGY	**✓ Indicates Uprate Technology is applicable to engine model***					
Turbo Installation/ Upgrade • Pro: can help reduce emissions, increase engine output and extend the lean limit. • Con: may not be economical for units <1,500 HP	✓	✓	✓	✓	✓	✓
High Pressure Fuel Injection • Pro: Can extend the lean limit, increase combustion stability, and reduce emissions. Commercially available. • Con: may require turbo to gain full benefits	✓	✓	✓	✓	✓	✓
Pre-Combustion Chamber • Pro: Commercially available, extends the lean limit and increase combustion stability. • Con: may require turbo to gain full benefits	✓	✓	✓	✓	✓	✓
Pilot Fuel Ignition • Pro: Eliminates spark plugs, increases combustion stability, and reduction of emissions. Applicable to low-BMEP, non-turbocharged engines. • Con. Require second fuel source. Commercialization efforts needed.	✓	✓	✓	✓	✓	✓

*While there are no known technical constraints for the uprate technologies identified at this time, this may change during the course of this research. Some engines may not be candidates for certain uprate technologies due to: 1) mechanical stress limitations, or 2) economies-of-scale for lower-HP engines.

[i] Schmitt, D., Olsen D., Willson, B., "Systematic Engine Uprate Technology Development and Deployment for Pipeline Compressor Engines", Final Report, GRI –04/0065, 2004.

[ii] "Literature Review Fuel/Air Mixing in Large Bore Natural Gas Engines", Final Report, PRCI Contract #PR-258-9618, 1999.

[iii] Willson, B., Hutcherson, G., Hawley, S. and Willett, K., "Relative Performance of High-Pressure Fuel Gas Delivery on Large-Bore, Two-Stroke Natural Gas Engines", PCRC Gas Machinery Conference, Austin, Texas, Oct. 6-8, 1997.

[iv] Hutcherson, Gary. "Assessment of operational characteristics of high pressure fuel gas injection technology on large-bore, two-stroke natural gas fired engines." Master's Thesis, Colorado State University, 2003.

[v] Iocco, David E, "Retrofit precombustion chamber helps cut engine NOx emissions", Pipe Line and Gas Industry, pp. 41-46, October, 1995.

[vi] "Precombustion Chamber Fuel Metering with an Electronic Fuel Valve", Draft Final Report for GRI, 2004.

[vii] Brown, Jacob. "On-engine investigation of a micro-liter quantity pilot ignition system for a large bore natural gas engine." Master's Thesis, Colorado State University, 2003.