# The First Field Application of High-Pressure Fuel Injection on a Two-Stroke Cycle, Large-Bore Reciprocating Engine

by: Rich Schoonover
Enginuity, LLC

---

## 1.0 Introduction

### 1.1 Overview

This paper presents the natural gas pipeline industry's experience with high-pressure fuel gas injection technology for enhancing the air / fuel mixing characteristics of the industry's large-bore, slow-speed, direct-injected, two and four stroke cycle engine prime mover horsepower base. The paper includes a discussion of the need for the technology; the theoretical foundation for understanding the role of air / fuel mixing in combustion; research and development efforts of the industry; and initial field implementation experience with high-pressure fuel gas injection technology by the industry.

### 1.2 Background

#### 1.2.1 Industry Background

The natural gas pipeline industry ("the industry") utilizes approximately 8,000 reciprocating IC engines to serve as prime movers of natural gas from gas reserves (supply) to the marketplace (demand). The majority of these engines are specifically designed to provide compression service via what is referred to as an "integral" design. The primary original equipment manufacturers (OEM's) of these engines are Cooper Bessemer, Clark, Ingersol Rand and Worthington. Of these IC engines, over 50% have been in service for more than 40 years. Approximately one third of these engines have now been in service for over 50 years.

The industry installed the majority of its compression infrastructure in the 1940 to mid-1960 timeframe. During that time, the industry represented nearly the entire market for integral engines. The primary requirement for these engines and thus the focus for the OEM's was reliability and longevity. Exhaust emissions were of no concern. Even fuel consumption and combustion quality, while of some concern to the OEM's, were not of great enough concern to warrant aggressive allocation of resources for research and development. The focus of the OEM's was primarily to manufacture engines that would provide many years of reliable service with a minimum of maintenance.

Even though the existing horsepower base is very aged, many years of productive service life remains. Economic analysis of horsepower replacement with more modern technology typically indicates that there is inadequate cost-based justification. Due to the age of its horsepower base the industry now has to fill the role of the OEM. Several of the industry's research organizations have assumed the responsibility for extending the useful life of these engines through aggressive research and development related to improvements related to emissions, efficiency, reliability and operability. Two of these organizations, the Gas Research Institute (GRI) and PRC *I*nternational, have been especially successful in providing solutions to some of the industry's most challenging technical issues in these areas.

### 1.2.2 Regulatory Background

Following the enactment of the 1990 Amendments to the Clean Air Act and subsequent EPA and state rulemakings regarding the reduction of NOx emissions from industrial sources, the natural gas pipeline industry ("the industry") became a primary target for contributing to the needed NOx reductions to satisfy attainment of the Title I National Ambient Air Quality Standards for Ozone. Many of the northeastern states involved in the 1995 RACT rulemakings called for low emissions combustion modifications (LEC), referring to the definition provided in the 1994 ACT document[i], for achieving the required NOx reductions.

LEC, as defined in the ACT document, is not a specific technology; it is a combination of technologies that beneficially exploit the fundamental relationship between NOx emissions and lean air/fuel ratios. Singly or in combination, these technologies enable an IC engine to obtain a certain pre-defined NOx emissions limit. The definition of LEC encompasses:

- Increased air mass
- Air mass cooling (or increase)
- Increased or high energy ignition
- Adequate air / fuel mixing

The common practical interpretation of LEC, especially by the regulatory community, is converting an engine to what has been called a lean or clean-burn configuration. This interpretation typically includes major modification of the engine, including replacement of major combustion components such as heads and piston crowns, the addition of pre-combustion chambers (PCC's), significant upgrade or replacement of turbocharger(s), significant upgrade or replacement of intercoolers and ambient coolers, significant upgrade or replacement of engine controls / instrumentation.

Prior to the major engine retrofit programs that the industry underwent to comply with 1995 RACT, this type of retrofit, offered by the OEM's, was the only option. Because of the enormous cost associated with this type of retrofit, however, the industry developed, through aggressive R&D programs sponsored by industry research committees, numerous other innovative and cost-effective technologies, including significantly improved OEM retrofit technologies. These technologies were employed by the industry to comply with 1995 RACT.

High-pressure fuel gas injection technology is one of the technologies that has emerged based primarily on the aggressive R&D efforts of the industry. This technology addresses one of the fundamental problems associated with large-bore, slow speed, direct injected engines – inadequate air / fuel mixing. Based on development conducted by Woodward Governor, with GRI funded testing and in conjunction with Colorado State University's Engines and Energy Conversion Laboratory, high pressure fuel injection technology has demonstrated the ability to significantly enhance air / fuel mixing and combustion. The tests at C.S.U. demonstrated the high-pressure fuel injection's ability to reduce emissions and improve engine performance to levels that where previously unattainable[ii].

## 2.0 Theoretical Background

In the study of combustion of fuels, the most fundamental parameter governing or significantly affecting the combustion process is air / fuel ratio. Air / fuel ratio is the mass ratio of air to fuel.

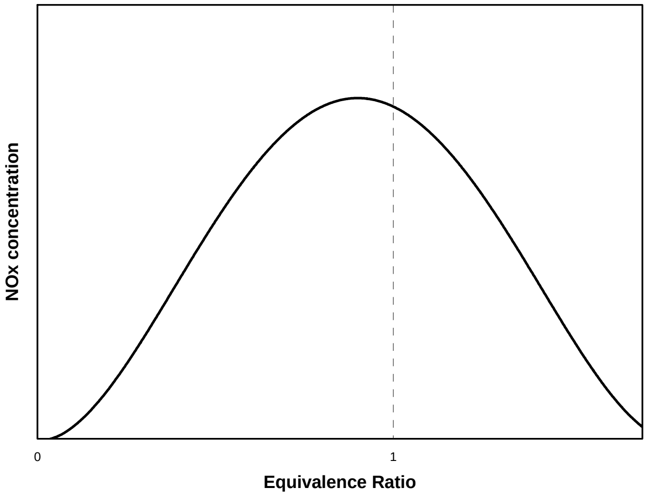
This parameter is often normalized by the specific stoichiometric air / fuel ratio[1] and referred to as equivalence ratio. A fuel / air equivalence ratio of 1.0 signifies stoichiometric air / fuel ratio. A number less than 1.0 signifies lean; greater than 1.0 signifies rich. Specific performance measures of combustion typically involve correlations with an air / fuel ratio type parameter.

Often, however, these correlations and performance measures assume that air and fuel are perfectly mixed prior to combustion. While this is necessary to establish a theoretically perfect process, as with any physical process, there is often great disparity between this ideal process and the real process. In the case of air / fuel mixing in natural gas- fired, direct-injected, large-bore IC engines, such as those employed by this industry, this is a very important issue; one that was largely ignored until efforts to reduce emissions to very low levels with traditional LEC technology fell short of the mark. These challenges turned the attention of the industry to the air / fuel mixing process, wherein discoveries were made regarding the significance of the problem, especially for certain engine makes / models.

## 2.1 Emissions

According to the Arrenhius reaction rate law, the rate of NO formation increases exponentially with temperature, assuming the presence of sufficient oxygen and nitrogen. Figure 2.1.a presents a classic NOx versus fuel / air equivalence ratio plot. Notice that NOx emissions reach a maximum level just lean of stoichiometry, at the point where slightly excess oxygen allows the most complete combustion of the fuel with the least in-cylinder heat capacity, thereby producing the highest combustion temperature. Also notice that NOx emissions can be significantly reduced by operating significantly rich or lean of this point, however, because of the desire for minimizing fuel consumption, NOx emissions reduction that is achieved without the use of catalyst technology typically involves lean or ultra-lean air / fuel ratio combustion.

**Figure 2.1.a**
**NOx vs Equivalence Ratio**



---

[1] Stoichiometric air / fuel ratio is the mass ratio of air to fuel that represents the chemically correct or perfect mixture of air and fuel to completely combust the fuel to produce combustion products including

Even with ultra-lean overall air/fuel ratios, however, local areas of higher or lower air fuel ratios caused by non-uniform mixing within the combustion chamber can create excessive NOx and cause combustion instability. Because the rate of NOx formation increases exponentially with temperature, richer and hotter portions of the charge generate significantly greater NOx than leaner/cooler portions. Therefore, any non-uniformity (heterogeneity) of the mixture at very lean conditions can produce NOx in excess of the same bulk mixture in a homogeneous state.

### 2.2 The Large-Bore Direct Injected Engine Challenge

When considering the mixing of two substances, perhaps the most difficult challenge is mixing two gases wherein a less dense (lighter) gas is injected into a more dense (heavier) gas. This is the case for direct-injected natural gas fired engines. The problem is even more pronounced when considering the specific conditions that exist with large-bore, direct-injected engines. Consider that natural gas, at approximately 55 – 60% the density of air, is injected in a relatively short period of time into a relatively large volume at a ratio of approximately one part fuel to 25 – 40 parts air (and residual gases), depending on how lean the engine is being operated.

This is particularly a problem in the design of 2-cycle engines. Effective scavenging of two stroke cycle engines necessitates significant overlap between the exhaust and intake events. This precludes any form of fuel and air premixing upstream of the combustion chamber in this type of engine, since the excessive slip of fuel into the exhaust would result in excessive fuel consumption and unacceptable hydrocarbon emissions. Consequently, these engines must inject fuel in the cylinder (typically at pressures of ~15-40 psi) once the ports or valves are closed. This results in varying levels of charge stratification[2].

A variety of engine design factors cause this variation in air/fuel mixing characteristics, including the following:

- fuel injection timing
- fuel injection duration
- fuel injection pressure
- fuel valve location
- fuel valve orientation and shrouding
- scavenging efficiency
- in cylinder bulk and local air motion

The inherent air/fuel mixing characteristics of various gaseous-fueled lean-burn engine models also explains some of the variability of pre-controlled NOx emissions. Different mixing patterns in the cylinder reflect differing tradeoffs of Original Equipment Manufacturer (OEM) designs, and for NOx emissions are the distinguishing characteristic between engines, which are otherwise similar in power, speed, and combustion cylinder dimensions.

In comparison, smaller four stroke cycle engines utilizing a carburetor, or other forms of premixing, can achieve low NOx emissions at significantly less lean air/fuel ratios than the ultra lean air/fuel ratios required by larger pipeline engines. This premixing ensures optimum mixture

---

[2] It is important to note that some of this stratification may not have been totally unintentional. It would appear that some engine designers in the 40's and 50's intentionally stratified the charge to obtain relatively rich mixtures near the spark plug to ensure the mixture would be ignited.

homogeneity, thereby eliminating locally "rich" hot spots that generate disproportionately higher levels of NOx emissions.

## 3.0 The Development of High Pressure Fuel Gas Injection

### 3.1 Theoretical Basis for High Pressure Fuel Gas Injection

High-pressure gas injection can increase turbulence and mixing in the cylinder. There are two basic ways to introduce turbulent energy into the cylinder by gas injection: (1) high-pressure fuel injection and (2) high-pressure non-fuel gas injection (e.g. nitrogen or other inert gas). Both do basically the same thing with regard to increasing the turbulence level and subsequent turbulent mixing in the cylinder. High-pressure fuel injection changes the fuel jet shape, momentum, and velocity, which in turn affects the rate of entrainment of air by the fuel and penetration of the fuel into the air charge.

### 3.2 Initial Development and Testing at Colorado State University

In response to the challenges of operating these large-bore, direct-injected engines in compliance with federal and state air regulations, the industry, through funding by two subscription based research organizations, commissioned the Colorado State University Engines and Energy Conversion Laboratory (EECL) to test a prototype high pressure fuel gas injection system (called PLGAV for pipeline gas admission valve) developed by the Woodward Governor Company. This testing was conducted in 1996 on the Cooper GMV-4TF at the EECL. Outfitted with high speed electro-hydraulic fuel gas valves supplied with approximately 500 psig, the engine was tested over a broad range of operating conditions and various configurations of ignition systems including screw-in pre-combustion chambers. Comparisons of the engine operated with both a mechanical valve (MGAV) and a low-pressure electronically actuated gas valve (EGAV) were made.

Results from testing indicated that the use of high-pressure fuel gas injection produced significant changes in the air / fuel mixing and combustion process. A summary of results follows:

- Fuel consumption was reduced by up to 8% when compared the traditional mechanical injection valve with low-pressure fuel supply.
- The lean air / fuel limit was significantly extended, thereby allowing a reduction of $NO_x$ for a given boost pressure.
- Combustion stability was improved significantly as characterized by misfire rate and standard deviation of both peak combustion pressure and location of peak pressure.

The performance improvements from the PLGAV are most likely from a combination of increased mixing and increased turbulence in the cylinder at spark. As discussed above, both can influence cycle-to-cycle combustion variations, namely ignition delay and subsequent misfire. The reduction in cycle-to-cycle combustion variations is probably responsible for most of the changes observed.

## 4.0 Field Demonstration of Commercial High Pressure Fuel Injection

Following the successful demonstration of high-pressure fuel gas injection at CSU, Enginuity International, Inc., utilizing key Woodward Industrial Controls components, has installed a pre-production high-pressure fuel gas injection system - *HPFi* ™ - at Williams Gas Pipeline's Unionville, VA compressor station. This installation represents the first field application of high-pressure fuel gas injection on a large-bore, slow-speed integral engine, specifically a Clark TCV-16 equipped with a Woodward Autobalancer 5000.

Design specifications for the TCV-16 engine are as follows:

| | |
|---|---|
| Rated Brake Horsepower: | 5500 |
| Rated Speed (RPM): | 300 |
| Rated BMEP (psi): | 105.2 |
| Bore (in): | 17 |
| Stroke (in): | 19 |
| Air Supply: | Dual Clark turbochargers w/ intercoolers |
| Ignition System: | Altronic CPU-2000 w/ Spark Plugs |

One of the primary reasons for selecting this engine for the pilot installation is the significant evidence that of the population of the industry's large-bore engines, the Clark family of engines appear to suffer from the poorest air and fuel mixing. Evidence for this includes relatively poor combustion stability and $NO_x$ and CO emissions that are significantly higher when compared to other similarly designed engines operating at the same fuel / air equivalence ratio.

The baseline configuration for the engine used the OEM style, low-pressure electronic gas admission valves (EGAV) used in the Woodward Autobalance 5000 system. Tests included varying the air manifold pressure from the standard operating level of 16"Hg to a high of 31"Hg. As will be detailed later in this paper, the range of the *HPFi*$^{tm}$ boost map was significantly reduced do to the enhanced mixing within the cylinder. In addition to the "boost" maps multiple point load/speed maps were performed that covered the breadth of the engines operating range.

When comparing performance of the baseline engine configuration and the *HPFi*$^{TM}$ system it should be noted that the level of optimization achieved by in the baseline tests is not typical of a "stock" TCV engine using mechanically actuated fuel injection valves. Although the injection characteristics (pressure and event duration) of the EGAVs are similar to the mechanical fuel valves, the autobalancing system allows the peak pressure spread across the power cylinders to be maintained at, or below, 15 psig at all operating conditions. This "optimized" power cylinder balance is far beyond that which would be attainable, or maintainable by manual balancing methods. Due to the continuos and optimized balancing of the power cylinders, the results shown for the EGAV configuration (baseline) show a level of performance beyond that which would be achievable with a "stock" TCV.

### 4.1 System Description

In order to accommodate the *HPFi*$^{TM}$ system, a high-pressure fuel gas system was designed which would meet all applicable DOT and intercompany requirements. The fuel gas supply system provides fuel measurement, regulation, filtration and system/unit isolation valves. Additionally the TCV-16 had previously been fitted with a Woodward Governor Autobalance 5000 that allowed the pilot program to make use of the existing electric and hydraulic infrastructure.

The heart of the *HPFi*$^{TM}$ system is the high-pressure injection valve (*HPiV*$^{TM}$) that directly replaces the existing OEM style valve (Figure 4.1.a). An INPULSE Plus$^{TM}$ programmable fuel injection controller and electro-hydraulic actuator, both manufactured by Woodward Industrial Controls, perform actuation of the *HPiV*$^{TM}$. Standard engine operating parameters, which include failsafe monitoring, start /stop sequencing, air/fuel ratio and load control are by the existing engine controller. The *HPFi*$^{TM}$ system interacts with the existing controller as depicted (Figure 4.1.b) to control engine speed by “governing on duration” (i.e. changing the duration of the injection event).

**Figure 4.1.a: Clark TCV High-Pressure Fuel Injection Valve *(HPiV*$^{tm}$*).***

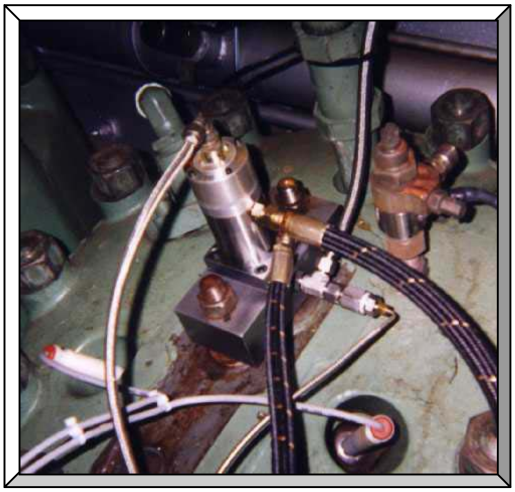
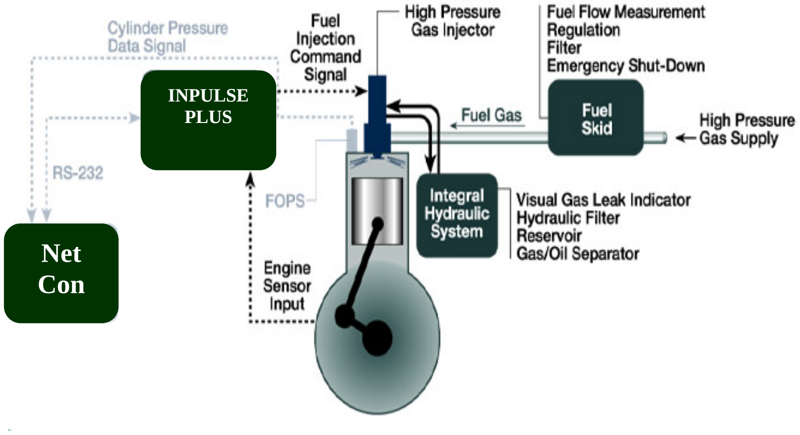


**Figure 4.1.b: System Schematic**



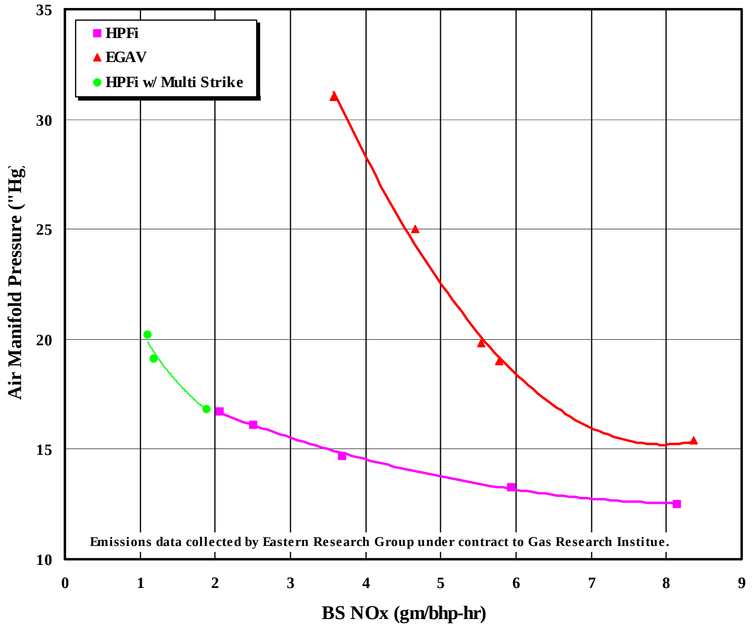
### 4.2 Results and Discussion

Test results presented in this paper are from the three performance tests performed to date on the TCV-16. The emissions data presented here was collected by Eastern Research Group under contract to Gas Research Institute using an FTIR and accepted test protocols. The presentation of data has been limited to that which was collected when compiling the "boost maps" as it shows the broadest variance and is essentially independent of the engine's air/fuel ratio control algorithms. Although data related to changes in speed and torque were collected, the results of those tests primarily show the ability of the engine control package to control emission levels at all points in the operating range.

Perhaps the most astonishing finding of the tests is the significant reduction of air manifold pressure required to achieve any given NOx emission level. As the level of NOx reduction increases the air manifold pressure required to achieve the desired emission level is significantly reduced through the use of *HPFi*$^{TM}$ (Figure 4.1.a). Likewise the overall range (minimum / maximum) of boost required is significantly reduced over the engines operating range. Whereas 27"Hg boost is required to achieve a NOx level of 4 gm/bhp-hr with the EGAV (OEM style) valves, the same NOx level was achieved with only 14.5"Hg when operating on *HPFi*$^{TM}$.

**Figure 4.1.a**

**Air Manifold vs. NOx Tradeoff**
**Clark TCV-16**

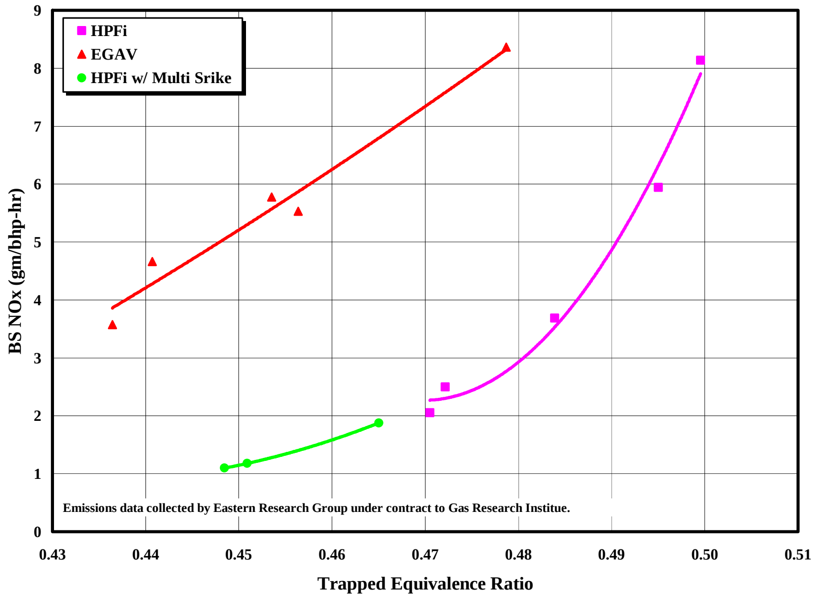


Emissions data collected by Eastern Research Group under contract to Gas Research Institue.

The more uniform mixing created by injecting fuel at high pressure significantly reduces stratified rich zones within the cylinder resulting in an overall lower bulk temperature at a richer fuel/air equivalence ratio. The improved homogeneity of the fuel/air charge allows a given NOx emission level to be attained at a much richer fuel/air equivalence ratio than would be the case with traditional LEC technologies. This reduction in disproportionate levels of NOx emissions being produced by localized "hot spots" reduced the measured NOx emission levels by as much as 80% at a given fuel/air equivalence ratio (Figure 4.1.b).

## Figure 4.1.b

**BS NOx vs. Trapped Equivalence Ratio**
**Clark TCV-16**

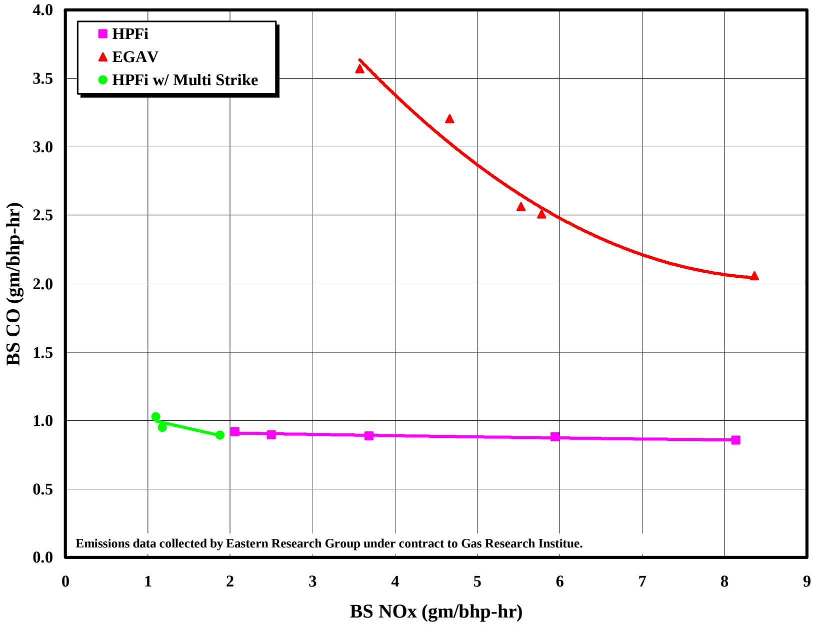


Emissions data collected by Eastern Research Group under contract to Gas Research Institue.

In addition to the significant reduction of NOx emissions, CO emissions were reduced a minimum of 60% at any given NOx level (Figure 4.1.c). The step change in CO emission levels verifies that the level of mixing within the cylinder has significantly improved over the EGAV configuration thus allowing more complete combustion and oxidation of CO to occur. The flat characteristic of the CO curve indicates a shift in the lean misfire limit with respect to NOx. Although the *HPFi*$^{TM}$ CO levels begin to rise somewhat below 2 gm/bhp-hr NOx, EGAV CO levels begin to rise significantly below 8 gm/bhp-hr NOx.

## Figure 4.1.c

**CO vs. NOx Trade Off**
**Clark TCV-16**



Emissions data collected by Eastern Research Group under contract to Gas Research Institue.

*HPFi™* significantly improved the bulk mixing within the cylinder resulting in NOx and CO emission levels previously unattainable on a TCV with open chamber spark ignition. However, the improvement in overall combustion stability, though improved, did not match the emission reductions in magnitude. The standard deviation of peak firing pressures improved slightly with *HPFi™* at any given NOx emission level (Figure 4.1.d) yet did not reach levels indicative of precombustion chamber performance. Though combustion stability was not vastly improved, it degraded at a slower rate than when operating on EGAVs resulting in a relatively flat brake specific fuel consumption across the range tested (Figure 4.1.e).

**Figure 4.1.d**

**STDV of Peak Pressure vs. BS NOx Trade Off**
**Clark TCV-16**

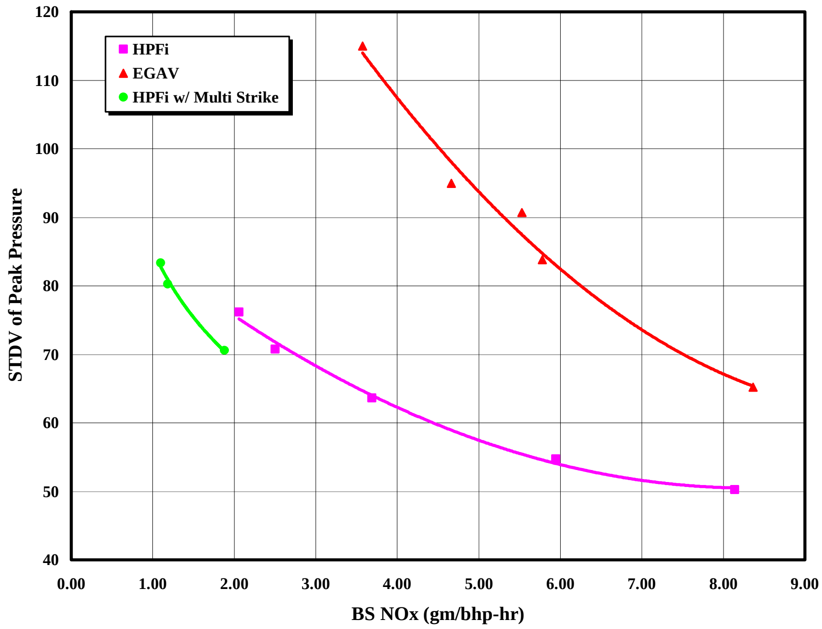
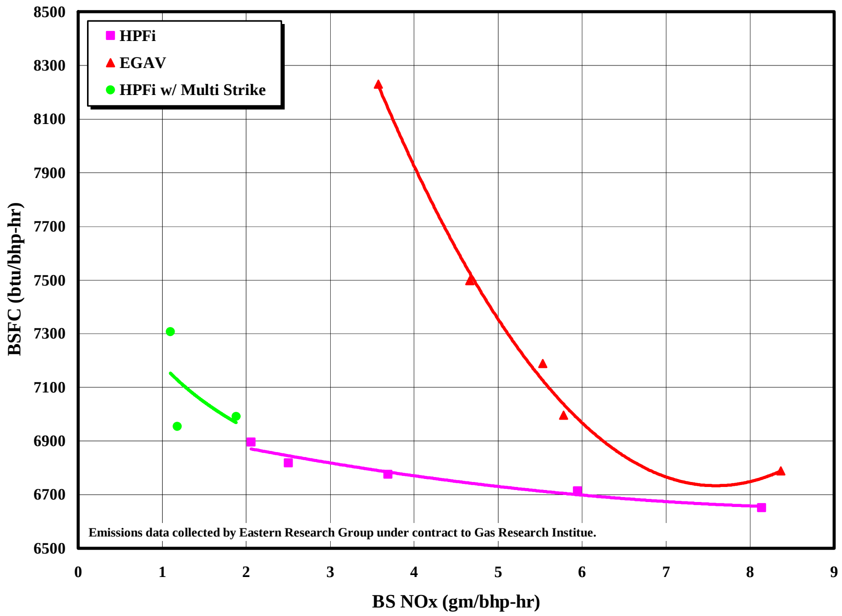


**Figure 4.1.e**

**Brake Specific Fuel Consumption vs. BS $NO_x$**
**Clark TCV-16**



### 4.3 Overall Performance

The TCV-16 is currently configured to operate at a NOx emission level of 2.5 gm/bhp-hr across its full operating range. With *HPFi*$^{TM}$ this has been achieved at a brake specific fuel consumption of 6850 btu/bhp-hr. Prior to the retrofit the engine had been configured to operate at approximately 5.0 gm/bhp-hr with a brake specific fuel consumption of 7350 btu/bhp-hr. Additionally the demand on the turbochargers has decreased, as the current air manifold pressure is 15.5” Hg whereas it had been operating at a 21” Hg setpoint with the EGAVs.

During the performance tests it was requested that the lowest maintainable NOx emission level be determined. The criteria for this operating point stipulated that the engine operation meet or exceed OEM specifications for peak firing pressure, standard deviation of peak firing pressure, and fuel consumption. Based on this criteria the lowest NOx emission level was 1.1 gm/bhp-hr with a brake specific fuel consumption of 6950 btu/bhp-hr on 20”Hg air manifold pressure. This point was achieved with standard spark plugs using multi-strike ignition. At this operating point the average standard deviation of peak firing pressures was 80psi with a peak pressure spread of 15psig.

In addition to the emissions performance, station personnel have noted a significant improvement in engine startup reliability. Remote start reliability has increased from approximately 50% to over 90%. Also noted is the absence of detonations during startup, which is a characteristic of Clark engines.

## 5.0 Conclusions

Based on the discussion presented herein, the following conclusions are offered:

- Large-bore, direct injected, gas-fired engines present a difficult challenge for adequate air / fuel mixing. Due to design limitations, these engines exhibit relatively poor air / fuel mixing as evidenced by poor combustion stability and higher NOx and CO emissions at a specific equivalence ratio.

- Poor air / fuel mixing limits the effectiveness of traditional LEC technologies. In poor mixing engines, LEC retrofits must compensate by operating at significantly leaner air / fuel ratios to obtain similar emissions and performance, thereby increasing the cost and complexity of the retrofit.

- High pressure fuel gas injection technology has demonstrated, both in the lab and in field application, the ability to significantly enhance air /fuel mixing and combustion in large-bore, direct-injected, gas-fired engines such that:
  - the lean air / fuel ratio limit is lowered
  - lower emissions (NOx and CO) are achievable at richer air / fuel ratios
  - fuel consumption, combustion stability and speed stability are improved

---

[i] Alternative Control Techniques Document -- NOx Emissions from Stationary Reciprocating Internal Combustion Engines (EPA-453/R-93-032)

---

[ii] Hutcherson, G., Willson, B., Hawley, S., and Willett, K., “Relative Performance of High-Pressure Fuel Gas Delivery on Large-Bore, Two-Stroke Natural Gas Engines”, Gas Machinery Conference Proceedings, October 1997, Austin, Texas.