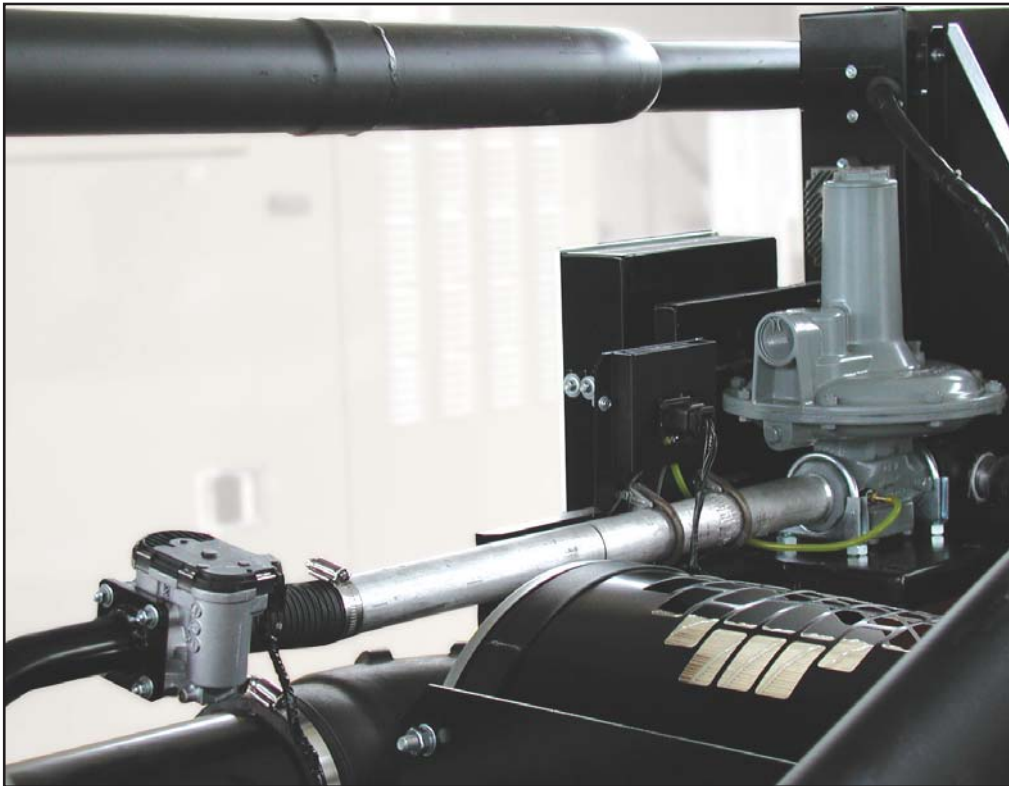


## Bi-Fuel Engine Generators

### WHITE PAPER



### INTRODUCTION

Within the context of power generation and automotive engines, the terms bi-fuel and dual-fuel are being used inconsistently by manufacturers, after-market installers, industry organizations and government agencies. Depending on the source, either term may be used to describe one of two different schemes for internal combustion:

- 1) Simultaneous combustion of two fuels
- 2) Redundant fuel supply systems, where a second fuel type can be used if the primary fuel supply is interrupted, depleted or intentionally switched off, but only one fuel is burned at a given time.

In any discussion, understanding the difference and clarifying terminology can help avoid confusion. Attention to the scheme used should identify the design, regardless of it being referred to as bi-fuel or dual-fuel.

**Generac uses the term bi-fuel for the simultaneous combustion of two fuels in an engine.** With the products we offer, bi-fuel can be further defined as the simultaneous combustion of diesel fuel and natural gas (methane) in a compression ignition (diesel) engine. Note that this concept has also been referred to at times as fumigation, meaning natural gas is fumigated into the combustion air supply for a diesel engine.

## HISTORY

The concept of using bi-fuel on diesel engines is not new. Rudolf Diesel, who invented the engine bearing his name, experimented with enriched combustion air mixtures in the early 1900's. Before long, natural gas became popular as an enriching fuel for two main reasons:

- 1) Its combustion characteristics are reasonably compatible with typical diesel engine designs
- 2) Extensive distribution infrastructure has been developed to make it an economical, commonly available, utility supplied fuel

Throughout the Twentieth Century, various methods were developed to properly deliver natural gas into a diesel engine. Extreme care is required during this process, as an excess concentration of natural gas can cause engine damage due to pre-ignition, or "knock" (this will be discussed in further detail later in this paper). Early bi-fuel designs used conventional mechanical control systems of the day to control the process. Due to limited capabilities of these controls, performance was compromised and commercial success was restricted to niche applications. More recently, microprocessor controls along with advanced automotive sensor and actuator technologies have provided new opportunities to meet the challenges.

## WHY BI-FUEL?

The desire for bi-fuel engines is driven by several environmental and economic factors. Combining diesel fuel with natural gas in bi-fuel operation provides several benefits compared to engines fueled only by diesel or natural gas. Major benefits include:

- Extended run time capabilities
- Reduced diesel fuel storage requirements
- Lower capital cost per kilowatt (kW) compared to spark-ignited engines
- Improved reliability with redundant fuel supply
- Reduced maintenance costs
- Potential for less fuel costs
- Lower exhaust emissions than diesel engines

Each of these points will be discussed further in the "Generac Bi-Fuel Benefits" section, found later in this paper.

## OVERVIEW OF BI-FUEL METHODS AND OPERATION

Since bi-fuel operation utilizes compression ignition, some traits of the basic diesel engine will first be reviewed. Several characteristics distinguish the diesel engine from four-cycle spark ignited (also referred to as Otto cycle) engines commonly used today to burn gasoline or vaporized fuels such as natural gas:

- A diesel engine uses compression ignition rather than spark ignition. The heat generated by compressing air to high pressures provides the source of ignition for the diesel fuel.
- A diesel engine compresses only air and then injects fuel directly into the cylinder for combustion. Most Otto cycle engines mix the fuel with air before it enters the cylinder(s), using either a carburetor or "indirect" fuel injector(s), often referred to as throttle body or port fuel injection. After the mixture is compressed in the cylinder, an electrical spark (delivered through a spark plug) provides the energy to ignite the fuel.
- Since diesel engines compress only air, they can safely operate at higher compression ratios (typically 13:1 ~ 23:1 compared to 8:1 ~ 12:1 for spark-ignited engines) without concern for pre-ignition. A major benefit of the higher compression ratio is that diesel engines are inherently more energy efficient than lower compression spark-ignited engines. In other words, more of the fuel energy gets converted to mechanical energy rather than being rejected as heat (this was the primary motivation for Diesel's invention in the first place.)

Natural gas ignites at a much higher temperature (1150° - 1200° F) compared to diesel fuel (500° - 750° F). A diesel engine cannot operate on 100% natural gas, because the heat generated during compression is not sufficient to ignite this fuel. To create ignition in bi-fuel engines, a small amount of diesel fuel must be injected. Cylinder temperatures are high enough to ignite the diesel fuel, and the flame created reaches a temperature sufficient to ignite the natural gas.

A bi-fuel engine uses a conventional diesel engine as its basis. With most designs, the diesel fuel is delivered using the injectors that already exist on the engine. Additional components are installed to deliver natural gas into the combustion chamber. There are three proven methods that have been employed to do this:

- **Low pressure injected natural gas (LPING)** introduces the natural gas using port injection, so it mixes with combustion air just before it enters the cylinder. This is done under moderate pressure, usually less than 50 pounds per square inch (psi). As many diesel engines use turbochargers to feed air into the cylinders, injection pressures must be greater than the boost pressure developed. This approach has been used in large stationary installations, but is more recently finding use in trucking applications. Requirements for injectors at each cylinder, a gas compressor and a multiple line fuel delivery add substantial cost to this type of engine.
- **High pressure injected natural gas (HPING)** delivers natural gas directly into the combustion chamber under extremely high pressures of approximately 3000 psi<sup>1</sup>. This is necessary since the natural gas is injected when the cylinder pressure is very high - at the end of the compression stroke and after diesel fuel has been injected to initiate combustion. This approach has found application in very large bi-fuel engines that typically operate for extended periods, producing prime or continuous power. This is due to the economics involved, as separate high pressure natural gas injectors (or sophisticated combination diesel/natural gas injectors), pumps and fuel delivery lines system drive a large price premium for these engine systems.
- **Combustion air gas integration** introduces the natural gas with intake combustion air just prior to the turbocharger. Since a single, low pressure delivery system is used, additional engine component costs are minimized. Advanced microprocessor, sensor and actuator technologies can now economically provide the precision and response necessary to control the system. This approach was selected by Generac because it offers the broadest range of operation at the lowest cost, and is best suited for the standby generator market.

### GENERAC'S SOLUTION

Figure 1 shows a diagram of the system used in Generac bi-fuel generators. A base turbocharged and after-cooled diesel engine generator is equipped with a natural gas delivery system, additional engine sensors and a microprocessor to monitor and control bi-fuel operation. The required pressure for natural gas supply to the bi-fuel unit is 3 to 5 psi.

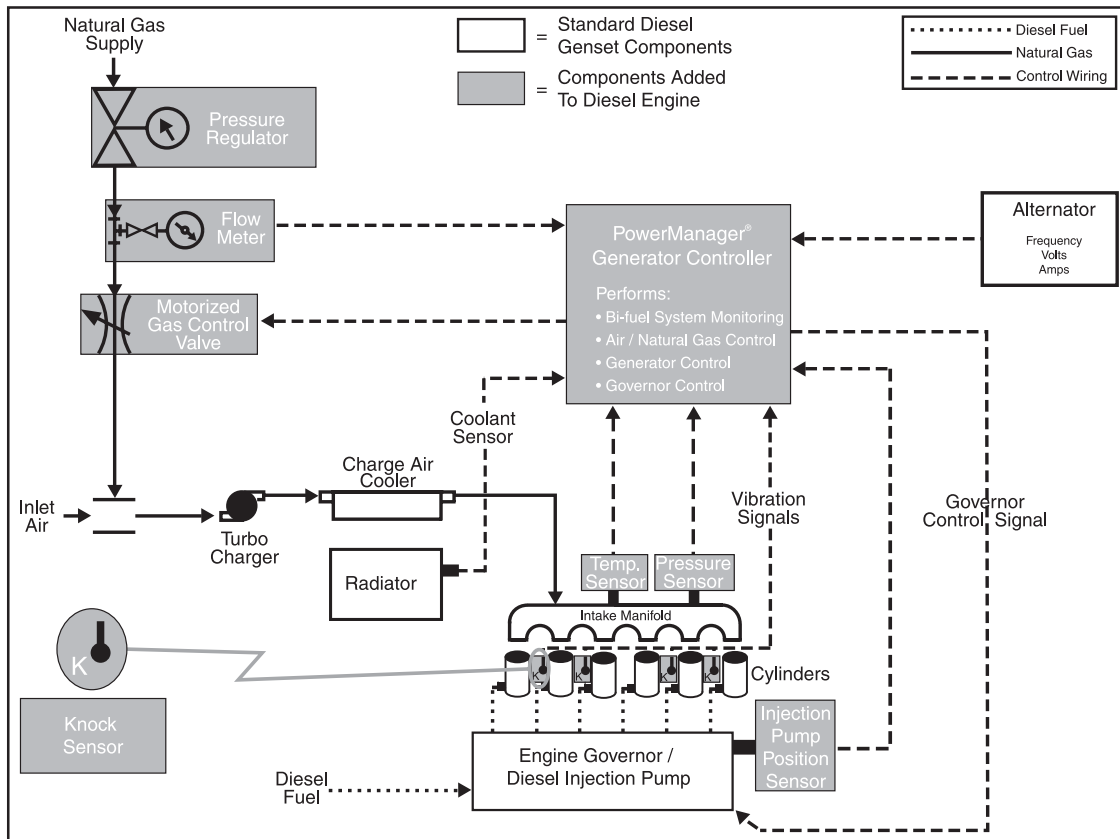


Figure 1 – Generac Bi-Fuel Circuit

During initial startup, the engine operates on 100% diesel fuel. After certain permissive criteria are satisfied (for instance, the engine coolant temperature reaching 160° F, or acceptance of the electrical load), the microprocessor commences bi-fuel operation. The system meters in an increasing amount of natural gas with the intake air. A dynamic gas control valve with positive supply pressure is used to provide precise metering. As more fuel energy is provided by the natural gas, the engine governing system automatically cuts back on the amount of diesel fuel injected.

Throughout the process, the controller continuously monitors a variety of engine and generator parameters, including intake air temperature, engine coolant temperature, intake manifold temperature and pressure, kW load, engine speed, and engine vibration at each cylinder. Through extensive mapping of these variables and their effect upon engine performance, the microprocessor automatically adjusts the bi-fuel ratio and fine tunes the mixture for optimum engine operation.

Figure 2 shows fuel percentage versus load for a given intake air temperature. Similar curves have been developed across the range of temperatures to develop a 3-dimensional curve used by the microprocessor to determine fuel ratios. With the Generac system, the optimum bi-fuel ratio under typical operation is approximately 90% natural gas and 10% diesel.

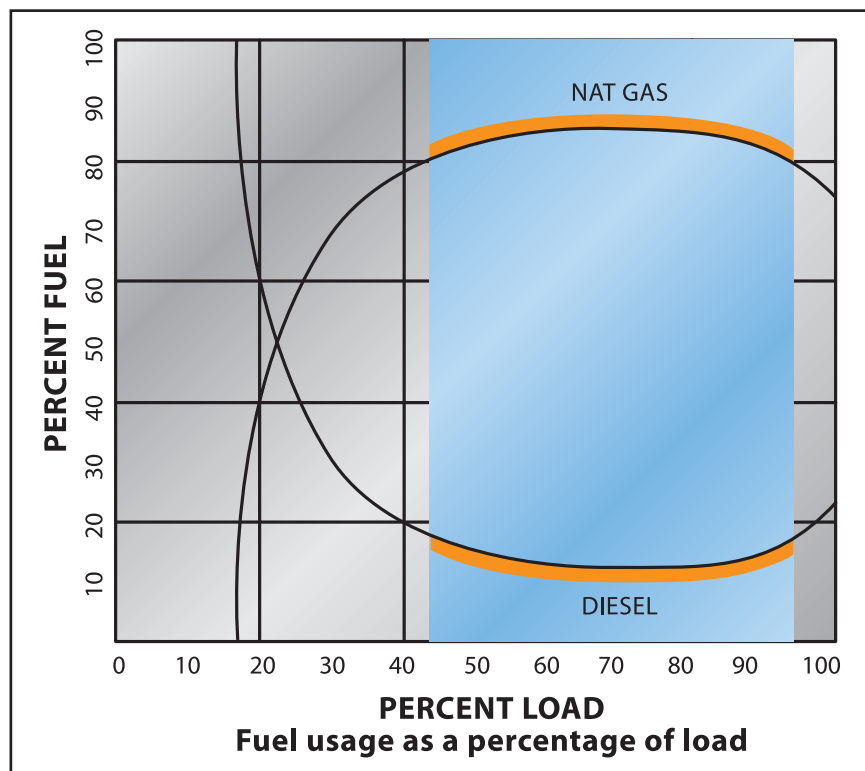


Figure 2

Note that our bi-fuel generators can operate on 100% diesel fuel in the event natural gas supply is interrupted. The control system automatically switches between bi-fuel and straight diesel modes as conditions dictate. Transition is seamless and transparent to the end user. In addition, there is no power derate for bi-fuel operation versus straight diesel mode, or during mode transitions. Generator load response and stability remain the same while operating in either mode.

### ADVANTAGES OF GENERAC'S BI-FUEL SOLUTION

Generac's bi-fuel engine generators offer a distinct cost advantage over more complex LPING or HPING engines, both in terms of initial capital investment and replacement part costs. When compared to other after-market systems using combustion air gas integration, Generac provides several distinct advantages:

- Designs are optimized for specific engines in our diesel generator product line
  - Engine characteristics have been carefully and comprehensively mapped
  - Gas deliveries have been established for all combinations of load and temperature
  - The result is maximum bi-fuel performance with safe, reliable operation
- Pre-ignition sensors immediately detect condition transients for corrective action, prior to knock ever occurring

- Dynamic gas control provides instantaneous adjustments for engine protection
- No performance compromises are required
- Generac's PowerManager® Digital Control Platform integrates control of bi-fuel operation with all other generator control functions into a single microprocessor. Benefits include fast system response, minimized interconnect wiring, easy system monitoring and advanced diagnostic capabilities
- The entire system has been factory prototype tested
- All systems are factory installed and the complete bi-fuel generator is factory load tested to verify performance and reliability
- Factory warranty and service support are included as part of entire generator

## **ACTIVE KNOCK PREVENTION — A KEY TO SUCCESS**

With its comprehensive fuel ratio mapping, the Generac bi-fuel control system safely operates the engine at all conditions of load and temperature. However, unexpected transients, such as temporary variations in fuel content, can result in pre-ignition, or "knock", if proper safeguards are not in place. A key to the success of Generac's bi-fuel solution is to detect when engine conditions are approaching pre-ignition and take corrective action prior to its occurrence. This safeguard system is not required during normal operation, but is available when needed to ensure reliable engine operation under all conditions.

As stated earlier, pre-ignition can be very harmful to an engine. It is an inherent problem in Otto cycle and bi-fuel engines, since they compress a mixture of air and fuel in the cylinder prior to ignition. Pre-ignition occurs when a portion of the air / fuel mixture spontaneously ignites during the compression stroke but prior to the desired moment of ignition. This results in a "collision" of three pressure waves:

- 1) The flame front from the spontaneously ignited fuel
- 2) The flame front created by the normal ignition source
- 3) The piston compressing the air / fuel mixture

This collision causes a violent shock within the cylinder. When strong enough, the shock wave creates a knocking sound that can be heard outside the engine (thus the common term "knock"). Worse, however, is that the shock wave can actually erode the materials comprising combustion chamber components, including the pistons, valves and valve seats. Component damage may occur even prior to "knock" being audible. Another effect is higher cylinder temperatures<sup>2</sup>, which further aggravate conditions. If left unchecked, the repeated pounding can quickly destroy an engine.

In a bi-fuel engine, pre-ignition results from an air / fuel mixture that is too rich for given conditions of load, temperature and fuel quality. One approach used by others to avoid problems is running lower percentages of natural gas, but the consequence is that less of the bi-fuel benefits are realized. Generac uses advanced automotive sensor and control technologies to achieve the best combination of performance and reliability.

Generac bi-fuel engines are equipped with piezoelectric accelerometers adjacent to each cylinder. These sensors electrically send vibration signals back to the bi-fuel controller. Knowing engine position and speed, the controller "pays attention" to this signal during the compression stroke of each cylinder. Through extensive testing, Generac has determined the signature vibration signal created by conditions approaching, but prior to, pre-ignition. Sensing such conditions, the bi-fuel controller immediately initiates a reduction of natural gas supply to lean out the air / fuel ratio. This is accomplished via a motorized gas control valve located in the natural gas supply line.

A closed loop control system between the accelerometers, bi-fuel controller and gas control valve ensure that proper adjustments are made. System response is fast enough that corrective action can be taken prior to knock ever occurring. Diesel fuel injection is immediately increased as needed to maintain power requirements during safeguard adjustments.

## **GENERAC BI-FUEL BENEFITS**

- **Extended run times.** The reduced consumption of diesel fuel by the engine under bi-fuel operation means that run times per tank of fuel are significantly extended. This provides longer backup coverage during extended electrical power outages. Figure 3 shows a typical comparison of run times on a single tank of fuel for bi-fuel versus straight diesel operation. As illustrated, run times with bi-fuel operation can be measured in days rather than hours. This can be very important, since replenishment supplies may be difficult to obtain during widespread extended power outages associated with blackouts or major weather events.

**Comparison of Diesel vs. Bi-fuel Run Times per Tank Fill  
300 kW Genset at 80% Load, 240 kW Output**

**Diesel: 20.5 gallons/hour consumption**  
**Bi-fuel: 2.4 gallons/hour consumption**

Diesel Tank Size	Diesel Run Time	Bi-fuel Run Time
12"/183 gallons	8.9 hours	76.2 hours (3.2days)
24"/438 gallons	24.1 hours	182.5 hours (7.6 days)
36"/693 gallons	33.8 hours	288.8 hours (12.0 days)

Note: Fuel consumption rates and run times are approximate. Actual results may vary depending on fuel and operation conditions.

Figure 3

- **Reduced diesel fuel storage.** Because natural gas is the predominant fuel, smaller diesel tanks are a viable option, with added benefits:
  - less fuel is stored on site; permits may be easier to obtain
  - indoor installations with capacity limits per NFPA or local codes may become feasible
  - fuel heating in cold climates is more manageable
  - fuel treatment or replacement to prevent spoilage is less costly
- **Lower capital cost.** The cost of a midrange to large diesel engine generator is approximately two-thirds that of a spark-ignited gaseous engine generator of equivalent output. With Generac's bi-fuel design, we can offer primarily natural gas fueled gensets at nearly the cost of a diesel-powered unit. In addition, with higher thermal efficiency, less heat is rejected, so indoor applications can use smaller, less costly air handling systems.
- **Built-in fuel redundancy.** If the natural gas supply is interrupted for any reason, or if there is a fault in the bi-fuel system, the controls will automatically direct the unit back to 100% diesel without interruption of operation. Obviously, this is not possible with a spark-ignited natural gas engine.
- **Reduced maintenance costs.** Maintenance costs are reduced due to the clean burning characteristics of natural gas. Testing has shown that bi-fuel engine oil remains cleaner compared to engines running straight diesel. This presents opportunities for enhanced engine life and extended maintenance cycles<sup>3</sup>. In addition, there are no ignition system maintenance items (spark plugs, wires, distributor, etc.) as with natural gas engines.
- **Less fuel costs.** On an equivalent energy basis, natural gas fuel costs have traditionally been lower than diesel fuel. Bi-fuel systems allow lower fuel costs, yet provide the flexibility to resort to diesel fuel if price conditions dictate.
- **Lower exhaust emissions than diesel engines.** The introduction of natural gas in bi-fuel operation significantly reduces oxides of nitrogen (NOx) and particulate matter (PM) emissions compared to straight diesel combustion. Generac testing has demonstrated a 30% reduction in NOx and a more than 50% reduction in PM when operating in bi-fuel compared to straight diesel mode.

In California, bi-fuel engines used for standby generators are classified as compression ignition engines. Generac bi-fuel engines meet emissions requirements established by the South Coast Air Quality Management District (SCAQMD), the regulatory agency for a large portion of southern California, including Los Angeles. Certified Equipment Permit (CEP) numbers have been issued to Generac by SCAQMD in recognition of emissions compliance (CEP #407661 for the 300 kW engine and CEP #414037 for the 375 kW engine — see below for more product details).

Air quality management districts in other portions of California have similar emissions requirements as SCAQMD. However, many of these districts have tightened permissible levels of PM emissions. Generac bi-fuel engines also comply with these low-PM requirements (0.1 gram/HP-hour limit).

While California has long been a forerunner in regulating engine exhaust emissions, other metropolitan areas in the United States are also adopting or considering emissions regulations for standby generators. Also, more companies are adopting environmentally conscious or "green" operating philosophies in response to increased awareness of the need to protect our environment. Both consumers and businesses are providing influence in this movement. One example is the increased adoption of ISO 14000, Standards for Environmental Management. The automotive manufacturing industry is a leading proponent of this standard, and is extending requirements for its suppliers to incorporate an ISO 14000 Environmental Management System. The reduced emissions output of Generac bi-fuel generators may prove to be a solution when such requirements are encountered.

## GENERAC'S BI-FUEL PRODUCT OFFERINGS

Generac produces bi-fuel engine powered generators with electrical outputs of 300 kW and 375 kW. For both units, the base prime mover is a turbocharged and after-cooled 12.0 liter diesel truck engine that has provided many years of reliable service in diesel generator use. This engine is factory equipped with our bi-fuel system that has been fully developed and tested by Generac. The 300 kW unit has a direct drive 1800 RPM engine while a Generac gear reduction system allows engine operation at 2300 RPM (within the engine's peak power band) to produce the higher power output for the 375 kW unit.

These units are available in various configurations for standby power applications:

- Single stand-alone gensets – SB300 and SB375
- Modular Power Systems units – MB300 and MB375
- Gemini® Twin Pack gensets – MB600-GEM and MB750-GEM

The latter two versions utilize Generac's Modular Power System technology to cost-effectively parallel multiple gensets for larger power requirements up to 3750 kW.

All bi-fuel system components are fully covered under the prevailing generator warranty. Our generators carry a standard two-year warranty, with optional two-year comprehensive, five-year basic and five-year comprehensive warranties available.

All Generac bi-fuel units also use our PowerManager® Digital Control Platform, which incorporates digital control of bi-fuel operation along with the balance of generator control functions into a single, powerful, microprocessor-based module. The result is a very reliable system that is also easy to service. For more information on any of these products, contact your Generac representative or visit [www.generac.com](http://www.generac.com).

<sup>1</sup> Sean H. Turner, Christopher S. Weaver, P.E., "Dual-Fuel Natural Gas / Diesel Engines: Technology, Performance and Emissions", Chicago, IL, Gas Research Institute (GRI) Engine Technology Group, 1994, 19,44.

<sup>2</sup> Turner, op. Cit., 7.

<sup>3</sup> Paul J. Beck, Bruce A. Hamilton, Robert Shepherd, Richard A. Cemenska and Louis A. Lautman, "Performance Engine Durability and Oil Life Analysis of Pilot Ignition Natural Gas Engines", 6 - 8 August, 1997, Society of Automotive Engineers, International Future Transportation Technology Conference (SAE Technical Paper Series 972664), 5.