STATE OF NEW MEXICO
BEFORE THE ENVIRONMENTAL IMPROVEMENT BOARD

IN THE MATTER OF:

PROPOSED NEW REGULATION
20.2.50 Oil and Gas Sector — Ozone Precursor Pollutants **No. EIB 21-27(R)**

PRE-FILED TECHNICAL TESTIMONY OF MR. VIC L. SHELDON, A WITNESS ON BEHALF OF THE GAS COMPRESSOR ASSOCIATION

I. Introduction to My Testimony

My name is Vic L. Sheldon. I am testifying as a technical witness on behalf of The Gas Compressor Association (The GCA) in this proceeding. My testimony supports The GCA's proposed amendments to the New Mexico Environment Department's (Department) proposed regulation set out as 20.2.50.113.B(3) NMAC in the Department's proposed rule, 20.2.50 NMAC (Proposed Rule), specifically the emissions standards for engines. The GCA's proposed amendments to the Department's Proposed Rule are set forth in redline in GCA Exhibit 1. This testimony begins with an overview of my credentials. I will then go on to discuss the Department's proposed engine emissions standards, as set forth in the Department's Proposed Rule at 20.2.50.113.B(3) NMAC and The GCA's proposed amendments thereto.

As set forth in detail herein, natural gas original equipment manufacturers (OEMs), upstream and midstream end-users acknowledge and support employing the Best Available Technology (BAT) for emissions control from their engines, controls, packages, and installations. Natural gas OEMs, upstream and midstream end-users support lower oxides of nitrogen as this aids reduction of precursor compounds which result in ozone formation. The Gas Compression Packaging OEMs and end-users employ BAT products in order to gather, process and transport natural gas. The Department's Proposed Rule at 20.2.50.113.B(3) NMAC applies a 0.3g NOx per bhp-hr rating to new lean-burn combustion engines above 1000 bhp. The NOx emission standard in the Proposed Rule is lower than achievable in some spark ignited natural gas lean-burn combustion engines at the 1000 bhp power level. Currently available lean-burn engines with power ratings of 1000 to 1875 bhp are rated “Not to Exceed” (NTE) 0.5g NOx/bhp-hr. NTE emissions rating means the engine will operate below and up to 0.5g NOx per bhp-hr, but are not capable of operating at and below 0.3g NOx per bhp-hr on a NTE basis. Therefore, as set forth in The GCA’s proposed amendments to 20.2.50.113.B(3), the 1000 bhp power level provided in the regulation should be raised to 1875 bhp to reflect emissions the BAT provide in newly manufactured lean-burn engines.

My testimony provides an overview of today’s BAT in some lean-burn spark-ignited natural gas engines above the 1000 bhp power level, which I will explain cannot achieve the 0.3g NOx per bhp-hr in the Proposed Rule. I will explain in detail why raising the power threshold from 1000 bhp to 1875 bhp for such engines is necessary to align with the Department’s proposed definition of larger engines capable of employing pre-combustion chambers for effective combustion ignition of extremely lean fuel mixtures which can achieve the 0.3 g NOx per bhp-hr emissions. Larger lean-burn engines rated 1875 bhp and greater are currently rated NTE 0.3g NOx per bhp-hr.

I will also discuss how the emissions standards in Department’s Proposed Rule at 20.2.50.113.B(3) NMAC will effectively eliminate certain large lean-burn engines from operating in New Mexico. It is not technically feasible to further apply Low Emissions Combustion (LEC) technologies to those engines – specifically, those lean-burn engines rated between 1000 and 1875 bhp. The available LEC technologies have already been applied to lean-burn engines presently on the market from engine manufacturers. Efficient, low-emitting engines of that size are essential for gas gathering operations in New Mexico, and the Department must avoid regulating them out of existence based on an attempt to apply a NOx emission standard that is technically infeasible.

Finally, I will testify regarding why the Department's proposed emissions limits are unnecessarily more stringent than the federal standards for large lean-burn engines.

II. Statement of My Qualifications and Relevant Experience.

My resume is attached as GCA Exhibit 10. I received a Bachelor of Science in Mechanical Engineering from Purdue University. I also hold a Masters of Business Administration from Indiana Wesleyan University. I am a registered Professional Engineer in the State of Illinois.

Caterpillar is the company I chose to work for in 1978 after resigning my Regular Army Commission. Over thirty-seven years of my career has been dedicated to engine engineering design, test and development, field validation, manufacturing, product support, education and training, marketing, and managing engine designers and developers. I first worked in development of Caterpillar Natural Gas Engines as a test and development engineer from 1985-1990, developing the first-known air/fuel ratio control specifically for rapidly changing fuel quality at a natural gas plant early in that time. I next worked as a manufacturing liaison engineer for natural gas engines in Lafayette, Indiana, for Gas Engine Engineering in Illinois from 1990-1992. I then worked as a Senior Product Quality Engineer and then as an Application and Design Engineer for gas engines.

In 2001, I became a Market Development Consultant working in Kiel and Rostock, Germany for Caterpillar Rail & Petroleum Power Products, working with gas engine products. In 2003, I started work at Caterpillar Oil & Gas Group, Marine & Petroleum Products Division, where I served as a Market Development Consultant, a Market Professional and a Senior Marketing Professional until 2013. From 2013 to 2015, I served as an Engineering Manager for Caterpillar

Inc.- Large Power Systems Development, developing customer-driven G3500 engine products. Caterpillar G3500 engines are one of the primary categories of engines that are subject to the Proposed Rule.

I am currently the General Manager of VSheldon JEvertt Decisions, LLC where I have been a member since 2016. My current responsibilities include assisting end-users, OEMs, and dealers of diesel and natural gas engine power systems to identify the right engine and related equipment for a particular use or application. I help my clients identify the appropriate engine for the job that they need to accomplish, and knowing how these engines operate, from an emissions performance and other perspectives, is a key part of my role. That experience has allowed me to serve as a testifying expert related to G3500 natural gas engines in other proceedings.

I have extensive experience in the marketing and development of electric and mechanical power employing natural gas and diesel engines. This includes initiating and managing the development of new product introduction programs, including emissions upgrade kits for stranded end-user G3516 gas compression engines that lowered those engines' 2g NOx per bhp-hr emissions to 0.5g NOx per bhp-hr. I also launched a New Product Introduction program to design, develop, and manufacture new G3500 gas compression engines for US EPA NSPS 2nd stage, reducing NOx emissions seventy-five percent, increasing power at altitude, improving fuel tolerance, and reducing fuel consumption. For over 30 years, I have been working on the design and optimization of the types of engines used by oil and gas operators and compression service providers that are subject to regulation under the Proposed Rule.

III. Brief Overview of Caterpillar Engines

As useful background and context for the Department's Proposed Rule for engine emissions standards, it is helpful to understand more about the types of engines that are subject to regulation under the Proposed Rule. In this respect, it is useful to learn more about Caterpillar engines, as Caterpillar engines have been chosen by many natural gas compression OEMs and end-users. Caterpillar represents the highest-volume of lean-burn spark-ignited natural gas engines chosen by gas compression packaging OEMs and natural gas gathering and processing companies in North America.

There are several reasons my presentation of spark-ignited natural gas lean-burn gas compression engines is focused on the Caterpillar branded engine products. First, Caterpillar has the broadest offering of spark-ignited natural gas compression engines in the industry. Within this offering is the broadest range of spark ignited lean-burn engines employed as gas compression drivers. For purposes of my testimony, when I refer to “lean-burn” engines, I am referring to engine combustion with excess air to greatly reduce the formation of oxides of nitrogen during combustion. When I refer to “rich-burn” engines, I am referring to engine combustion with the correct or stoichiometric mixture of fuel and air with no excess air, resulting in NOx formation of greater than 10 g per bhp-hr requiring non-selective catalytic reduction (NSCR) after-treatment to further reduce NOx.

The Department references Low Emissions Combustion (LEC) technology as retrofit technology and references an EPA Technical Support Document that states, “*LEC are described as retrofits that allow engines to operate on extremely lean fuel mixtures to minimize NOx emissions. (CSAPR TSD, p. 5-3).” See* GCA Exhibit 11 at p. 5-3. As described in greater detail below, the referenced document then identifies the different LEC technologies that are available. The Proposed Rule establishes a NOx emissions standard that cannot be met by certain sizes of new, lean-burn engines, despite the incorporation of the available LEC technology.

The technologies presented or identified as LEC retrofit options are already incorporated in today's Caterpillar lean-burn engines that are subject to the Department's proposed rule. A closer look at the various technologies Caterpillar lean-burn engines employ today will follow, but first a view of the general size comparisons of spark ignited lean-burn natural gas engines above 1000 bhp level may be assisted by reviewing Image 1, *Range of Caterpillar Power Options for Oil & Gas Applications*, presented as an attachment to my testimony.

Image 1 presents the range of Caterpillar power options employed by natural gas engine OEMs, and natural gas end-users in upstream gas gathering, in midstream gas processing plants, and in midstream pipeline transmission. Of the Caterpillar engine models shown, the G3500, G3600 and the GCM34 products are spark ignited lean-burn combustion engines, while the smaller G3300 and CG137 spark-ignited natural gas engine products are rich-burn combustion engines.

Engine bore size matters when integrating LEC technologies. The G3500J LE family of engines and the G3600 A4 LE family of engines are spark ignited lean-burn combustion engines developed to meet lower emissions standards than the federal New Source Performance Standards (NSPS). These engines have improved capabilities beyond their predecessors over a wide range of gas compression site conditions including altitude, fuel quality, and ambient temperature. The smaller G3500J LE engine driven gas compression packages typically gather gases from wells. The larger G3600 A4 LE engine driven packages then move gas from the gas gathering systems to the gas plants which remove natural gas liquids. Please note the smaller G3500J LE 0.5g NOx per bhp-hr engines and the larger G3600 A4 LE engines already incorporate LEC technologies for extremely lean mixtures. The following technologies already incorporated in these two engine families include redesigned cylinder-heads, pistons, camshafts, exhaust systems which deliver high temperature exhaust to improved larger more efficient turbochargers, two-stage intercooling, electronically controlled gas flow for precise combustion gas metering, electronically controlled air/fuel ratio controls, and electronic ignition delivering high energy voltage to spark plugs. These technologies for LEC referenced by Department as LEC technologies are in place on both engine families, with the exception of pre-combustion chambers. The much larger G3600A4 LE engine began its manufacture in 1991 with an integrated pre-combustion chamber. The much smaller bore diameter of the G3500J LE engines prevents integration of a pre-combustion chamber.

IV. The Department's Proposed Engine Emission Standards

The Department's Proposed Rule sets forth engines emissions standards for new natural gas-fired spark-ignition engines constructed, reconstructed, or installed after the effective date of the rule. *See* Proposed Rule at 20.2.50.113.B(3) NMAC. The rule sets forth emission limits by specifying engine type, the rated bhp, and then presents standards for NOx, CO and NMNEHC. *See* Proposed Rule20.2.50.113.B(3), Table 2, NMAC. As explained in detail below and for the reasons set forth herein, the Department's proposed 1000 bhp threshold for more-stringent NOx emissions standards from new lean-burn engines should be changed; the more-stringent NOx standards for new lean-burn engines should apply only to engines equal to or greater than 1875 bhp.

(i) The Proposed Engine Emission Standards Fail to Consider Existing BAT and LEC Technologies

Table 1 below, Engine Family NOx Capability Ratings and Cylinder Data, presents engine models with NOx emissions capability, rating, and various engine cylinder characteristics of the G3500J LE engine family & G3600 A4 LE engine family from 1000 to 2500 horsepower. Please note the G3500J LE lean-burn engine ratings provide a not to exceed (NTE) site 0.5g NOx per bhp-hr emissions capability, whereas the much larger bore diameter G3600 A4 LE lean-burn family of engines have two NTE site emissions capabilities: 0.3g NOx per bhp-hr and 0.5g NOx per bhp-hr. The much larger cylinder-bore area of the G3600 A4 LE engine is three times (3X) the cylinder-bore area of the G3500J LE engines. This lower 0.3g NOx per bhp-hr emissions rating is possible for the larger-bore G3600 A4 LE engines primarily because of the enhanced ignition characteristics provided by the pre-combustion chamber. The pre-combustion chamber produces multiple burning plasma jets into and across the extremely lean main combustion chamber. This enables the extremely lean mixture in the main cylinder to be leaner than an engine that does not have pre-combustion chamber ignition. Without the enhanced pre-combustion chamber ignition, the extremely lean mixture in the main cylinder would not reliably combust. The Department's Proposed Rule at 20.2.50.113.B(3) NMAC as currently drafted, with the threshold for 0.3gNOx per bhp-hr for new lean-burn spark ignited engines beginning at the 1000 bhp power level, needs to be adjusted upward to capture only "larger" engines 1875 bhp and above. This raised power level more accurately reflects the larger lean-burn engines' design capability to achieve BAT of 0.3g NOx per bhp-hr on a not to exceed (NTE) basis.

TABLE 1, Engine Family NOx Capability Ratings and per Cylinder Data

Engine Family NOx Capability Ratings and per Cylinder Data	Not To Exceed NOx/bhp-hr	Engine Rating bhp	Rating per Cylinder bhp	Cylinder Bore Area sq in	1 Cylinder Displacment cu. in	1 Cylinder Torque lb-ft
G3500J LE Engine Family	0.5 g NOx		86.25	35.3	264	324
G3512J LE	0.5 g NOx	1035	86.25	35.3	264	324
G3516J LE	0.5 g NOx	1380	86.25	35.3	264	324
G3520J LE	0.5 g NOx	1725	86.25	35.3	264	324
G3600 A4 LE Engine Family	0.3 & 0.5 g NOx		312.5	109.4	1290	1641
G3606 A4 LE	0.3 & 0.5 g NOx	1875	312.5	109.4	1290	1641
G3608 A4 LE	0.3 & 0.5 g NOx	2500	312.5	109.4	1290	1641

The Department's proposed regulation set forth at 20.2.50.113.B(3), Table 2, NMAC of 0.3g NOx per bhp-hr for 1000 bhp rated engines does not reflect the actual BAT or LEC technologies existing on the most commonly employed lean-burn engines in the 1000 bhp to 1725 bhp rating range that are available on the market today. Adoption of the 0.3 gper bhp-hr NOx standard for engines in the 1000-1875 bhp range would effectively eliminate this category of lean-burn engines for natural gas gathering in New Mexico to meet the Department's proposed NOx standard. Adjusting the power level threshold upward from 1000 bhp to engines beginning at 1875 bhp would reflect the existing BAT more appropriately of "larger" G3600 A4 LE lean-burn engines at 0.3g NOx/bhp-hr NTE emissions, and enables use of the BAT G3500J LE lean-burn engines at their NTE emissions rating of 0.5g NOx per bhp-hr. Pre-combustion chamber technology for the G3500J LE lean-burn compression application does not exist.

The Department's proposed NOx emission standard at 20.2.50.113.B(3) NMAC of 0.3g NOx per bhp-hr for engines rated at 1000 bhp or greater may inadvertently eliminate gas gathering powered by lean burn engine in these 1000 bhp to 1725 bhp power nodes. Use of oversized, larger natural gas engines attempting to operate at too low a load have significant operation and maintenance issues which reduce product life and are not economically feasible. Emissions tests for inappropriately lowly loaded larger engines would not be possible at their data plate rating since there is not enough compression available to fully load the engines. Forcing the de-rated operation of oversized engines in these installations will not benefit emissions performance or air quality.

LEC technologies are integrated in lean-burn engines rated above 1000 bhp. The Department acknowledges and references LEC technology as retrofit technology, referencing a 2015 U.S. EPA Technical Support Document that states "*LEC are described as retrofits that allow engines to operate on extremely lean fuel mixtures to minimize NOx emissions. The LEC retrofit may include: (1) redesign of cylinder head and pistons to improve mixing (on smaller engines),* *(2) **Pre-combustion chamber (on larger engines)**, (3) Turbocharger, (4) High energy ignition system, (5) Aftercooler, and (6) Air-to-fuel ratio controller." See* GCA Exhibit 11 (EPA CSAPR TSD) at p. 5-3 to 5-4 (emphasis added). As described in Appendix A-1, *Low Emissions Combustion (LEC) Technologies are integrated in lean-burn engines*, attached, all of the LEC technology is incorporated into these lean-burn engines with the exception of the pre-combustion chamber on the smaller G3500J LE 0.5g NOx per bhp-hr family of spark ignited lean-burn engine.

The greatest technology differentiator between the G3500J LE lean-burn family of engines and the G3600 A4 LE family of lean-burn engines is the G3600 A4 LE family of engine's improved charge air/fuel mixture ignition capabilities. This is due to the G3600 A4 LE's use of a pre-combustion chamber design made possible by the engine's significantly larger cylinder bore diameter.

The G3500J LE family of lean-burn engines with open chamber spark ignition emits NOx at levels that are half the federal New Source Performance Standard emissions requirement by providing NTE 0.5g NOx per bhp-hr site emissions. As shown in the Image 2, G3500 LE Open Chamber Spark Ignition Design, attached to this testimony, the spark plug is centrally located between the intake and exhaust ports and valves. There is not much room for the required engine coolant cooling passages to cool the exhaust seats, valves, ports and the spark plug. The spark plug gap provides the start of ignition which initiates a spherical flame front across the piston crown cup and later in the stroke across the entire piston diameter.

The G3600 A4 LE lean-burn pre-combustion chamber ignition of the extremely lean mixture in the main engine cylinder combustion chambers achieves both 0.5g and 0.3g NOx per bhp-hr on a site NTE basis. As shown in Image 3, G3600 A4 LE Lean-Burn Pre-Combustion Chamber Ignition, attached to this testimony, the additional space available in the much larger bore area of the G3600 A4 LE engine (three times (3X) the bore area of the G3500J LE engines) enables integration of the pre-combustion chamber and associated enhanced ignition of extremely lean main chamber mixtures. The process the pre-combustion chamber uses to provide ignition to the engine cylinders is as follows: the main chamber fuel is admitted into the engine cylinder intake port as the combustion air valve is open and admission ends before the intake engine valve is closed. A separate fuel supply to the pre-combustion chamber permits a small volume of gas into the pre-combustion chamber. The source of the air for the correct air/fuel ratio of the pre-combustion chamber is forced into the pre-combustion chamber during the compression stroke of the piston from the engine cylinder. A side-mounted spark plug in a lower position of the pre-combustion chamber ignites the not so lean pre-combustion chamber air/fuel mixture which initiates a flame front that reflects off the top of the pre-combustion chamber. The rapid spherical expansion of the flame front then jets out from each of the ports of the pre-combustion chamber across the engine cylinder piston crown. These burning plasma jets ignite the extremely lean air/fuel mixture in the main chamber. This combustion process provides a much faster, more complete, cooler combustion of the main chamber with a leaner air/fuel mixture than is possible with open chamber combustion.

The significantly larger family of G3600 A4 LE engines provide much more power per cylinder than the smaller G3500J LE family of engines. This large difference in power capability is made possible in part by several engine characteristics including larger bore diameter, bore area, longer stroke, larger cylinder displacement, higher torque per cylinder and greater Brake Mean Effective Pressure (BMEP) per cylinder. These differences in the space claims for BAT are more fully described in the attached Appendix A-2 to my testimony, and the differences in power related to engine size are more fully described in the attached Appendix A-3.

The significantly larger G3600 A4 LE engines provide more power than the G3500J LE engines. Table 2, Engine Model with NOx Capability Ratings, Torques, BMEP, presents the engine rating power, and torque (employing 54DegC or 130DegF separate circuit air coolant temperature ratings). This table reflects the greater engine displacement and BMEP of the G3600 A4 LE engine.

TABLE 2: Engine Model with NOx Capability Ratings, Torques, BMEP

Engine Model with NOx Capability Ratings, Torques, BMEP	Not To Exceed Emissions NOx/bhp-hr	Engine Rating bhp	Engine Torque lb-ft	Engine Displace-ment cu. in	BMEP psi
G3500J LE Engine Family	0.5 g NOx				185.3
G3512J LE	0.5 g NOx	1035	3,884	3,158	185.3
G3516J LE	0.5 g NOx	1380	5,177	4,211	185.4
G3520J LE	0.5 g NOx	1725	6,470	5,263	185.4
G3600 A4 LE Engine Family	0.3 & 0.5 g NOx				191.2
G3606 A4 LE	0.3 & 0.5 g NOx	1875	9,846	7,762	191.2
G3608 A4 LE	0.3 & 0.5 g NOx	2500	13,129	10,350	191.2

As shown in Table 3, Engine Family NOx Capability Ratings and Per-Cylinder Data, below, the smaller G3500J LE 0.5g NOper bhp-hr family of engines shown each have ratings greater than 1000 bhp, yet produce significantly lower engine torque than the G3600 A4 LE 0.3 & 0.5g NOx per bhp-hr family of engines. The larger G3600 A4 LE family of engines rating per cylinder is over 3.5 times that of the smaller G3500J LE 0.5g NOx per bhp-hr family of engines. The G3606 A4 LE engine is capable of 90% greater torque over the G3516J LE and greater than 50% greater torque over the G3520J LE engine. Torque at rated speed is what drives compressors, delivering needed gas flows at pressure. G3500J LE 0.5g NOx per bhp-hr engine displacements present a good indication the larger G3600 A4 LE engines are a significantly larger engine class providing greater efficiencies and lower emissions.

TABLE 3, Engine Family NOx Capability Ratings and Per-Cylinder Data

Engine Family NOx Capability Ratings and per Cylinder Data	Not To Exceed NOx/bhp-hr	Engine Rating bhp	Rating per Cylinder bhp	Cylinder Bore Area sq in	1 Cylinder Displacment cu. in	1 Cylinder Torque lb-ft
G3500J LE Engine Family	0.5 g NOx		86.25	35.3	264	324
G3512J LE	0.5 g NOx	1035	86.25	35.3	264	324
G3516J LE	0.5 g NOx	1380	86.25	35.3	264	324
G3520J LE	0.5 g NOx	1725	86.25	35.3	264	324
G3600 A4 LE Engine Family	0.3 & 0.5 g NOx		312.5	109.4	1290	1641
G3606 A4 LE	0.3 & 0.5 g NOx	1875	312.5	109.4	1290	1641
G3608 A4 LE	0.3 & 0.5 g NOx	2500	312.5	109.4	1290	1641

The external sizes and mass of the G3500J LE 0.5g NOx per bhp-hr family of engines and G3600 A4 LE 0.3g & 0.5g NOx per bhp-hr family of engines show the larger G3600 A4 LE class engines are significantly larger and heavier. As shown in Table 4, Engine Model with NOx Capability, below, the cubic volume of the G3606 A4 LE engine is 49% greater than the G3516J LE and 29% greater than the G3520J LE engine. Similarly, the mass of the G3606 A4 LE engine is 71% greater than the G3516J LE and 45% greater than the G3520J LE engine. Although this larger engine size is generally more efficient, it also requires significant additional investments in the package and site installation to provide adequate air, coolant and fuel cooling to enable these greater capabilities and result in the lower 0.3g NOx per bhp-hr exhaust emission rating. The heat rejection on a brake specific basis is lower on the larger G3600 A4 LE family of engines than the smaller G3500J LE family of engine. The smaller G3500J LE engine-driven gas compression packages perform a critical role in gas gathering, moving gas to larger gas compression packages to gas processing plants.

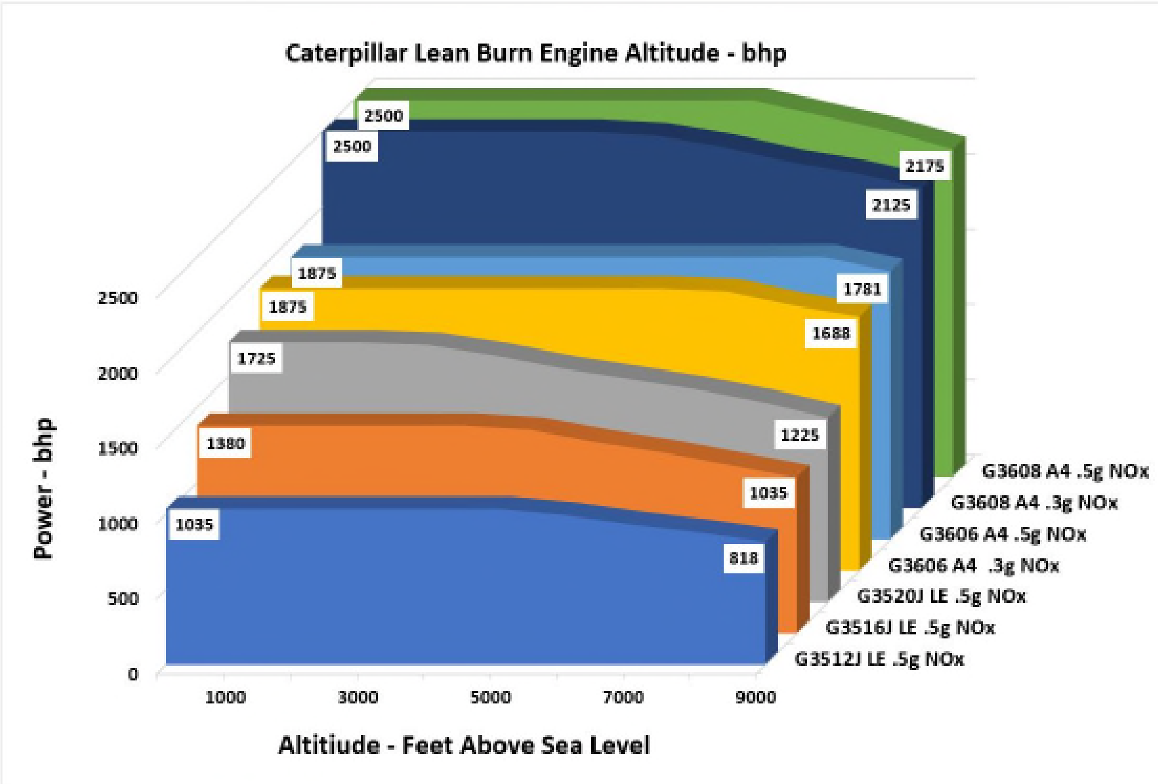
TABLE 4, Engine Model with NOx Capability[2]

Engine Model with NOx Capability	Not To Exceed Emissions NOx/bhp-hr	Rating bhp	Length ft	Width ft	Height ft	Engine Space cu ft	Mass lb
G3500J LE Engine Family	0.5 g NOx						
G3512J LE	0.5 g NOx	1035	10	7.23	7.01	506.8	15611
G3516J LE	0.5 g NOx	1380	11.77	6.18	7.5	544.9	23777
G3520J LE	0.5 g NOx	1725	13.49	6.18	7.75	645.7	10785
G3600 A4 LE Engine Family	0.3 & 0.5 g NOx						
G3606 A4 LE	0.3 & 0.5 g NOx	1875	15.22	5.72	9.58	834	36638
G3608 A4 LE	0.3 & 0.5 g NOx	2500	18.5	7.42	9.58	1319	46500

(ii) The Proposed Engine Emission Standards are Lower Than the BAT of Today's Smaller G3500LE Spark Ignited Natural Gas Lean-burn Combustion Engines

The larger G3600 A4 LE spark ignited lean-burn natural gas engines have greater power and emissions capability than the G3500J LE engines. This is fundamentally because of greater flow of cooler combustion air. The greater intake air flow at cooler temperatures is possible through more effective on-engine technologies: exhaust driven turbochargers compress the charge air. It is then cooled through two stage intercooling. Although the G3500J LE engine has two-stage intercooling of the charge air, size constraints prevent it from being as efficient as on the larger class engine. The more efficient G3600 A4 LE engine turbochargers and two stage intercooler permit greater cooled air mass flow, which permits more fuel at the correct air/fuel mixture, and improves the engine's ability to develop power at altitude while cooling the air fuel mixture for combustion.

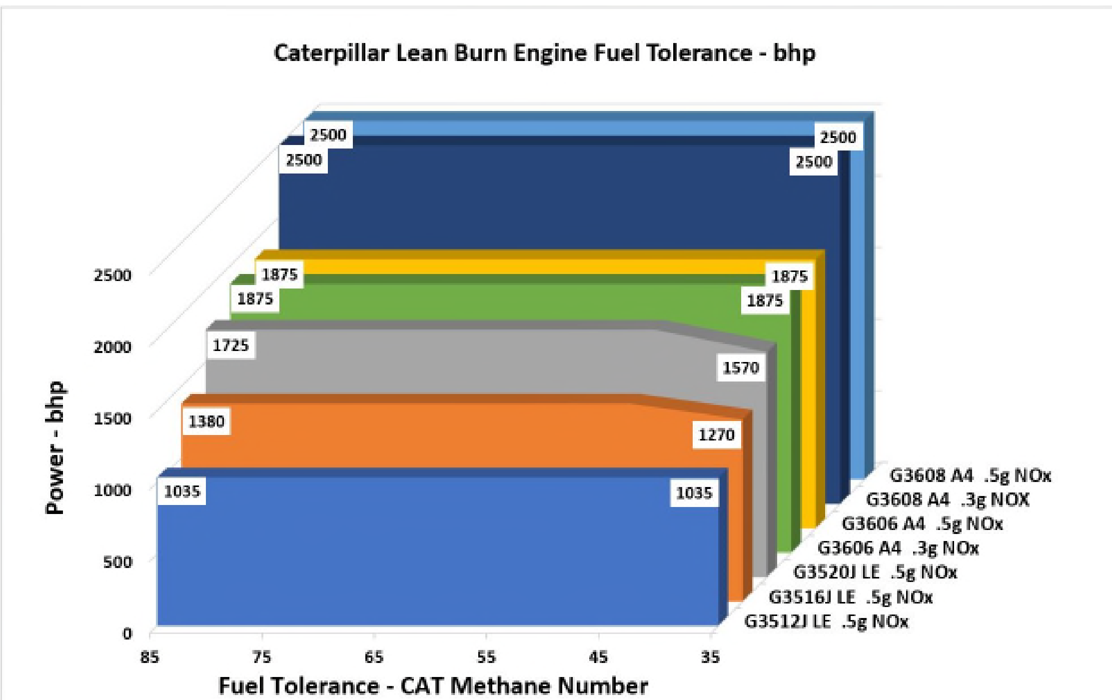
The chart below titled "Caterpillar Lean-burn Engine Altitude – bhp" presents the site power capability for each of the subject engines.



Site possible power is on the vertical axis and site altitude is on the horizontal axis. The three G3500J LE 0.5g NOx per bhp-hr engines are in the foreground whereas the four G3600 A4 LE 0.3g & 0.5g NOx per bhp-hr engine emissions ratings are the background objects. Note the G3606 A4 LE and G3608 A4 LE engines have two NTE emissions ratings (0.3g & 0.5g NOx) while the G3500J LE family of engines emissions is limited to one NTE 0.5g NOx per bhp-hr setting. The site power available for these ratings at higher elevations reflect the additional mass flow of cooled air required for the NTE emissions settings has been matched with additional fuel for very lean air/fuel combustion mixtures.

More combustion air at cooler temperatures aid in providing greater power with lower fuel quality. The larger class G3600 A4 LE engines have greater ability to provide cooler charge air in excess quantities than the smaller G3500J LE engines. This benefit is shown on the chart

"Caterpillar Lean-Burn Engine Fuel Tolerance – bhp." The application of the BAT to both the G3500J LE and G3600 A4 LE engines have resulted in much greater fuel tolerance than their predecessors. Note the larger more efficient G3600 A4 LE lean-burn engines do not have a derate even with hotter field gas fuels with a Caterpillar Methane Number of 35. (The Caterpillar Methane Number quantifies the combustion knock characteristics of a gaseous fuel mixture. The lower the CAT Methane Number the hotter the fuel, the more likely to cause combustion knock.) The G3516J LE and G3520J LE lean-burn engines do not begin their power derations until CAT Methane Number 45 with further derate when consuming fuels down to a Methane Number of 35.



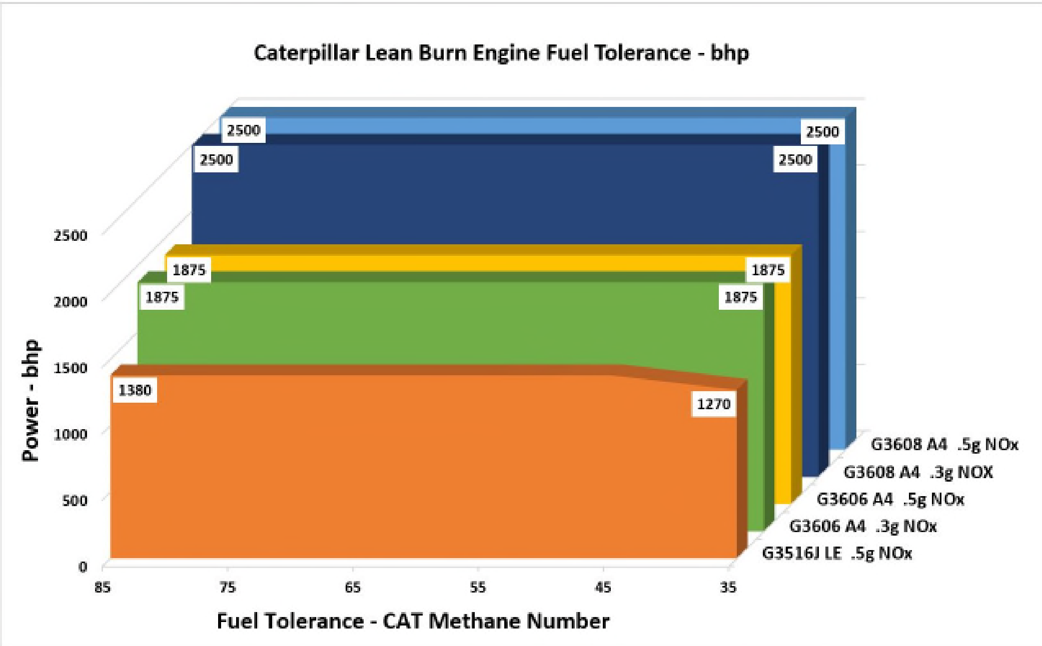
Of note, greater excess combustion air is required as the fuel mixture heating value increases (and the Caterpillar Methane number decreases). Natural gases hotter than methane CH_4 (911 BTUper cu ft) such as ethane C_2H_6 (1631 BTUper cu ft) and propane C_3H_8 (2353 BTUper cu ft) are associated gases in oil & gas reservoirs. Even small fractions of the associated field gases in the fuel mixture require additional excess air to maintain the needed lean air to fuel ratio to achieve 0.5 g NOx per bhp-hr. The G3500J LE lean-burn engines are only cabable of achieving 0.5 g NOx per bhp-hr for site Not to Exceed (NTE) emissions basis. The larger, more capable G3600 A4 LE lean-burn engines can provide more and cooler air for leaner combustion enabling it to achieve not only the 0.5g NOx per bhp-hr but also the lower 0.3g NOx per bhp-hr NTE emissions level rating.

Larger class engines require additional packaging for specific sites or ambient capabilities. A key to the package is the various cooling circuits have specific heat loads which must be dissipated to enable the engine to have the capability intended. John Dutton’s direct written technical testimony, GCA Exhibit 12, provides a more detailed discussion of the package design, manufacture, transportation, installation, and commissioning for a specific engine model at a site rating and site emissions.

As currently proposed, the emission requirement at the power threshold of the Department’s Proposed Rule at 20.2.50.113.B(3) NMAC is lower than the BAT for today’s spark ignited natural gas lean-burn combustion engines. The challenge is that the 0.3gNOx per bhp-hr standard is lower than the current BAT emission rate for spark ignited natural gas lean-burn combustion engines available for three smaller engine models which have at least a 1000 bhp power rating. The reality is the natural gas compression packaging OEMs, and end-users have chosen to employ spark ignited lean-burn engines at 1380 bhp at 1400 rpm for a large fraction of the gas gathering space. The BAT for these greater than 1000 bhp engines is not capable of meeting the proposed 0.3g NOx perbhp-hr emissions level.

As shown in my testimony, the key issue is G3500J LE engines do not have a bore size sufficient to include a pre-combustion chamber ignition system. Engine bore size matters and is a distinction in this conversation. "Larger lean-burn" spark ignited engines more correctly define the G3600 A4 LE engine family and not the G3500J LE engines. The larger G3600 A4 LE family of engines have cylinder diameters providing over three times the cylinder bore area of the smaller G3500J LE family of spark ignited engines.

The chart below provides the effectiveness of BAT for the G3516J LE and the G3600 A4 LE lean-burn spark ignited compression engines. The 1380 bhp G3516J LE 0.5g NOx per bhp-hr NTE engine is shown in the foreground. The G3606 A4 LE and G3608 A4 LE 0.3g NOx per bhp-hr NTE and 0.5g NOx per bhp-hr NTE ratings are shown in the background. The site power is presented as a function of fuel tolerance represented by CAT Methane Number. The larger G3600 A4 LE family of lean-burn engines shown on this chart reflect the benefits of greater engine size and it pre-combustion chamber ignition technology. The larger G3600 A4 LE family of lean-burn engines reflect the BAT for larger lean-burn natural gas engines and achieves 0.3 g NOx per bhp-hr NTE emissions. Of lean-burn engines, only engines greater than 1875 bhp can achieve the 0.3 gper bhp-hr NOx limit!



(iii) The Proposed Engine Emission Standards are Unjustifiably Lower than Federal Engine Emission Standards.

The Proposed Rule, which sets forth a limit of 0.3g NOx per bhp-hr emissions for 1000 bhp and greater rated engines, is not in line with the applicable federal standards that apply to new engines. “New” reflects date of engine manufacture, not date of manufacture of an engine-driven compression package, nor the date of installation at a given site. In fact, this limit is significantly lower than the emissions requirements in US EPA 40 CFR 60, Subpart JJJJ for new, non-emergency lean-burn engines greater than or equal 500 but less than 1350 bhp: 1.0 g NOx per bhp-hr, 2g COper bhp-hr and 0.7g VOCper bhp-hr. The federal New Source Performance Standards (NSPS) for individual engines is appropriate unless in established NAA (Non-attainment Areas) where individual site permitting processes by NMED based on total emissions is more appropriate to limit specific sites or areas.

(iv) Applicability of the Engine Emission Standards Should Be Based on Date of Manufacture or Reconstruction

As proposed, 20.2.50.113.B(2), Table 1 NMAC and 2.2.50.113.B(3), Table 2 NMAC currently determine applicability based on whether an engine is “constructed, reconstructed, or installed” either before (Table 1) or after (Table 2) the effective date of the rule. The Proposed Rule determines new or existing standard applicability in a way that is not consistent with how the EPA determines applicability for spark-ignition engines, and that does not make sense from a functional standpoint. EPA’s standards for spark-ignition engines in 40 CFR Part 60, Subpart JJJJ bases applicability on the “date of manufacture” – which is when an engine is originally produced, or when it is reconstructed. See 40 CFR § 60.4230 (basing applicability on manufacture date) and 40 CFR § 60.4248 (defining “date of manufacture”).

The language in the Proposed Rule would consider an engine to be "new" (and therefore subject to the new engine emission standards in Table 2 of 20.2.50.113.B(3) instead of the existing engine emission standards in Table 1 of 20.2.50.113.B(2)) if it is relocated. As discussed above, the technology to achieve a certain NOx level for lean-burn engines is built into the engine, and it can be cost prohibitive if not technically infeasible to retrofit older engines with technology that was not part of the original design. An engine should not be considered "new" just because the engine is moved and "installed" at a new location. Relocation of compressor packages is common, and nothing about the relocation should provide a basis for converting the engine in that package from an existing engine into a new engine subject to significantly more-stringent emission standards.

The GCA has proposed to change the applicability triggers for new and existing engine emission standards under the Proposed Rule to make them consistent with the applicable federal standards and to avoid a new-source trigger based on "installation" at a new location. "Installed" should not be a criteria for determining if an engine is "new" as opposed to "existing." Determining the applicability of emission standards for engines only makes sense if based on the date of manufacture or reconstruction. The recommended changes to the horsepower levels and NOx limits in 20.2.50.113.B(2) Table 1 NMAC and 20.2.50.113.B(3) Table 2 NMAC that The GCA has recommended are predicated on and dependent upon these changes to how applicability of the emission standards is determined.

V. Conclusion

The greatest technology differentiator between the smaller G3500J LE Lean-burn engine family and the larger G3600 A4 LE lean-burn engine family is the G3600 A4 LE engine's improved charge air/fuel mixture ignition capabilities. This is due to the G3600 A4 LE engine's use of a pre-combustion chamber design made possible by its larger cylinder bore. The Proposed Rule at 20.2.50.113.B(3) NMAC ignores the fact that newly manufactured lean-burn engines rated between 1000 bhp and 1875 bhp cannot achieve the proposed NOx emission standard, even though BAT is already employed. As currently drafted, the Department's regulation requires engine emissions levels that are not available for lean-burn engines from 1000 up to 1875 bhp. For the reasons set forth herein, GCA's amendments to 20.2.50.113.B(3), Table 2, NMAC should be adopted, specifically by requiring the 0.3g NOx per bhp-hr BAT emissions for larger natural gas lean-burn engines at equal to or greater than 1875 bhp power level.

This concludes my direct technical testimony in this matter.

IMAGES

Image 1: Range of Caterpillar Power Options for Oil & Gas Applications

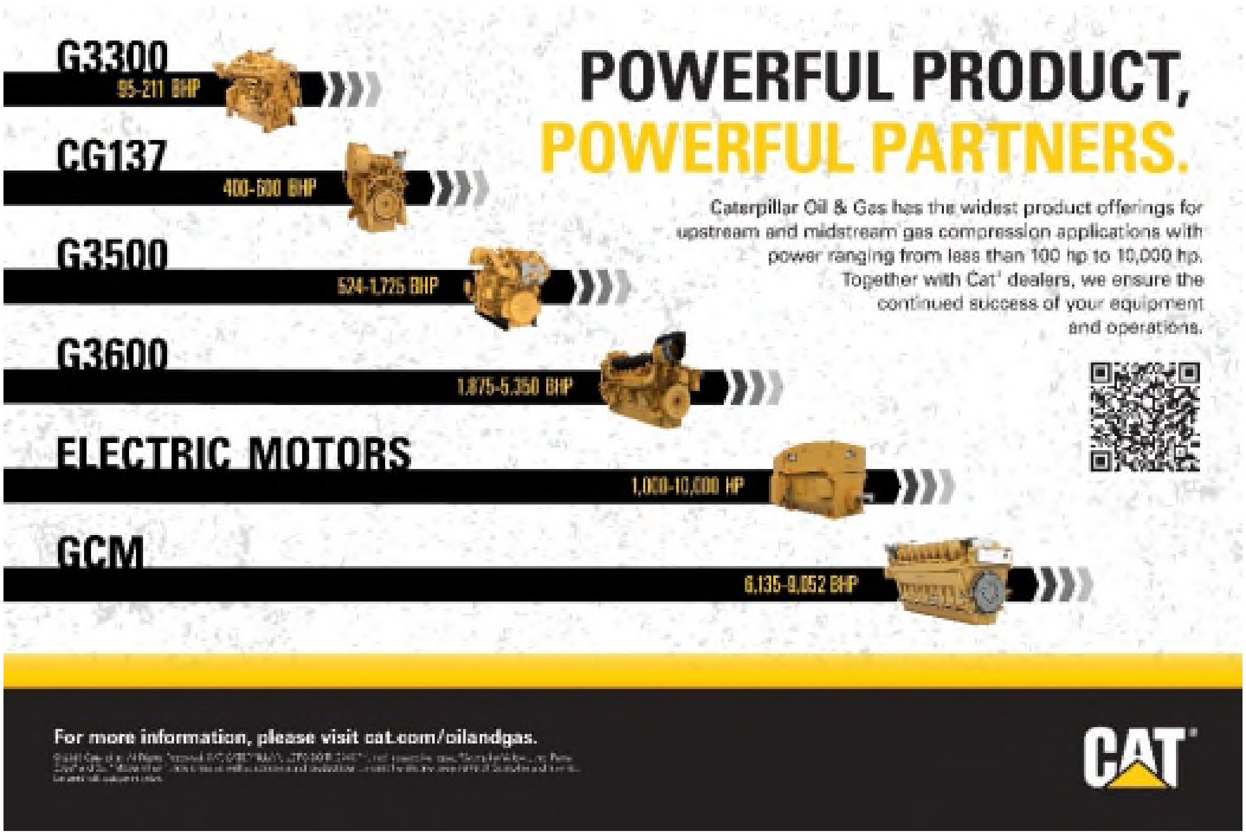


Image 2: G3500 LE Open Chamber Spark Ignition Design

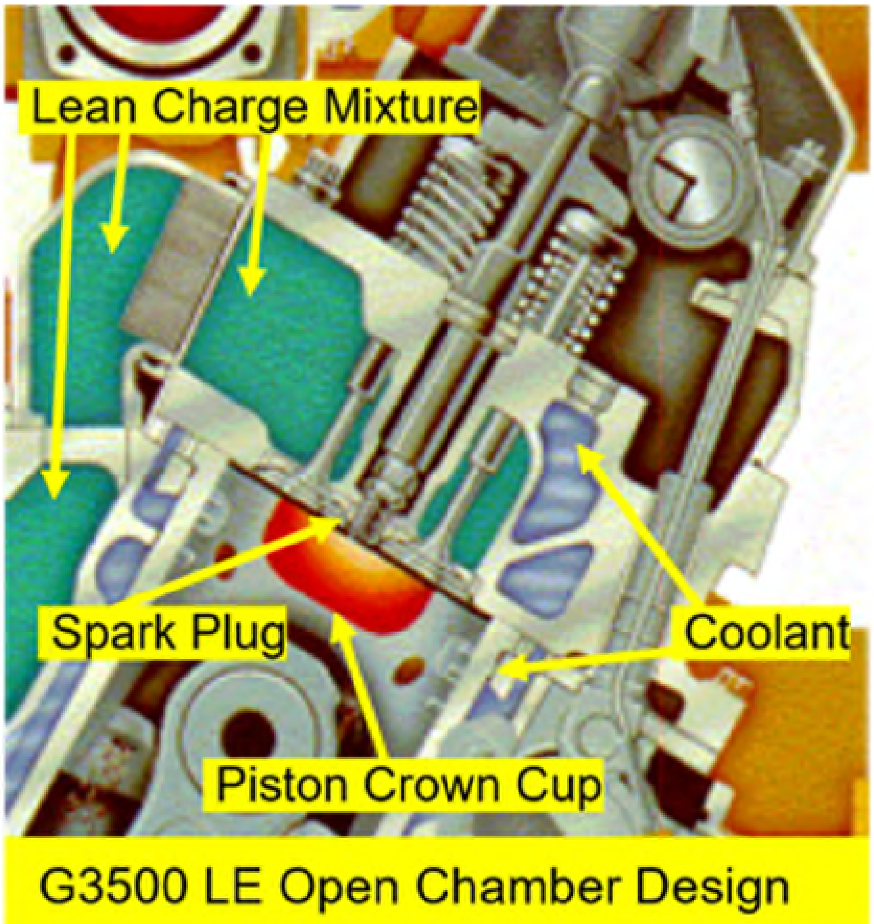
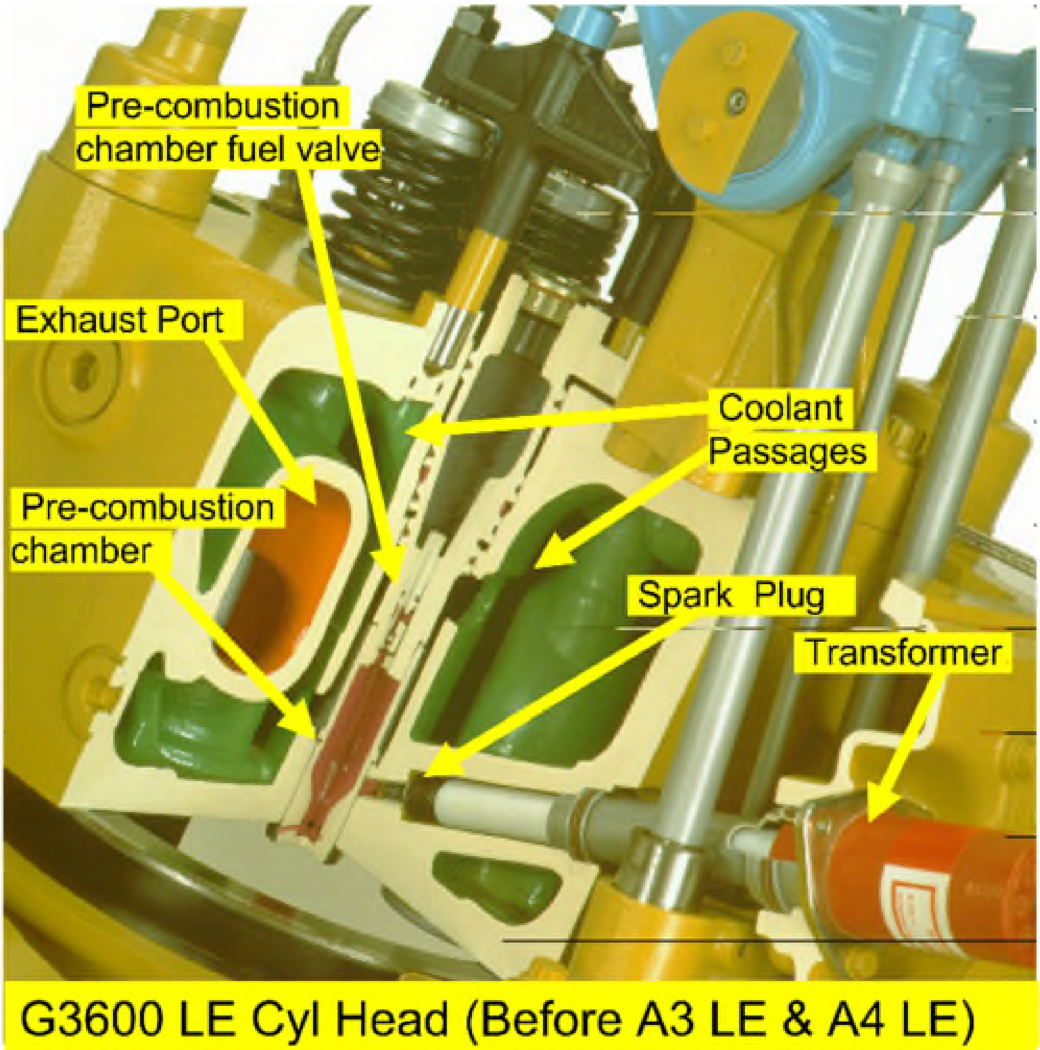


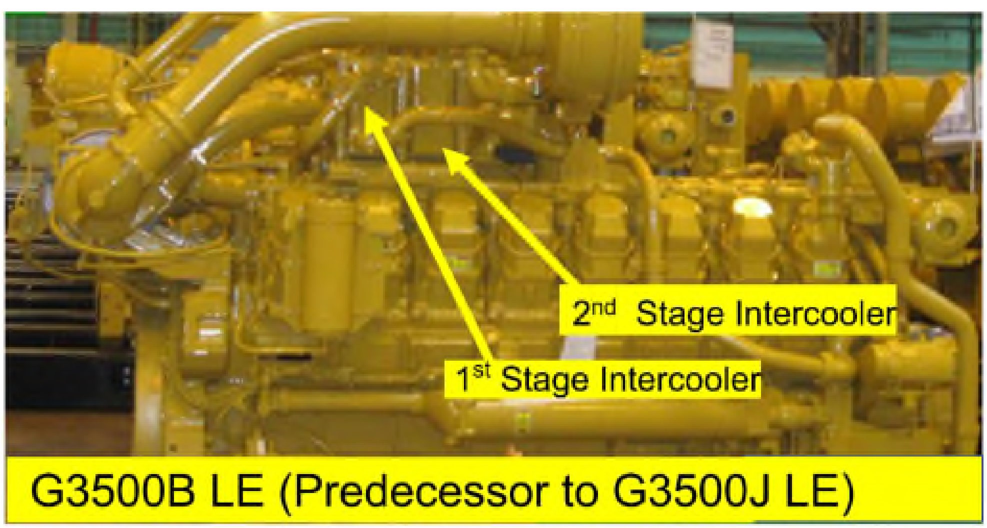
Image 3: G3600 A4 LE Lean-Burn Pre-Combustion Chamber Ignition



APPENDIX A-1:

Low Emissions Combustion (LEC) Technologies are integrated in lean-burn engines.

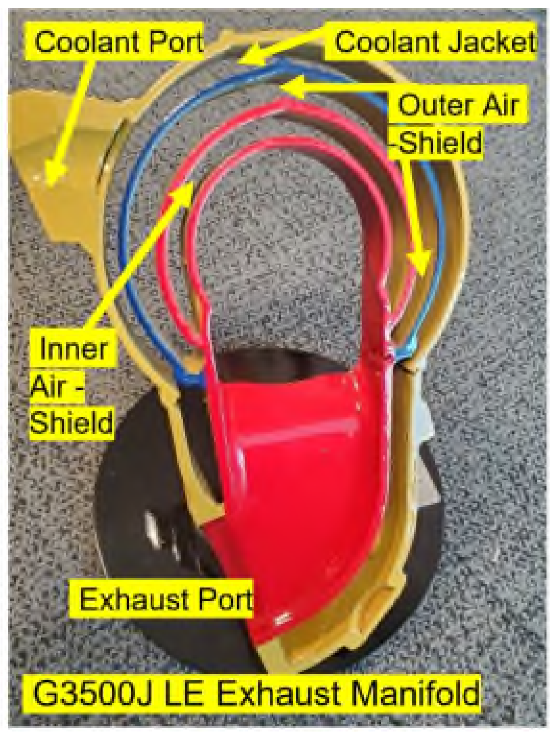
1. Low Emissions Combustion (LEC) Technologies are integrated in lean-burn engines rated above 1000 bhp. The Department references LEC technology as retrofit technology and cites a 2015 U.S. EPA document that states, "*LEC are described as retrofits that allow engines to operate on extremely lean fuel mixtures to minimize NOx emissions. The LEC retrofit may include: (1) redesign of cylinder head and pistons to improve mixing (on smaller engines), (2) **Pre-combustion chamber (on larger engines)**, (3) Turbocharger, (4) High energy ignition system, (5) Aftercooler, and (6) Air-to-fuel ratio controller.*" *See* GCA Exhibit 11 (EPA CSAPR TSD) at p. 5-3 to 5-4 (emphasis added). As described below, all of the LEC technology is incorporated into these lean-burn engines with the exception of the pre-combustion chamber on the smaller G3500J LE 0.5g NOx per bhp-hr lean-burn engine family.
   1. Two-stage intercooling: engine jacket first stage and cooler separate circuit second stage. In the image the first stage (Engine Jacket Coolant) is on the left and the second



stage (Separate Circuit Aftercooler Coolant) at a cooler temperature is on the right.

2. The G3500J LE and G3600 A4 LE engines have forged instead of cast, larger turbocharger compressor wheels, coolant-cooled center bearing housings, and dry exhaust turbine housings. This move from cast compressor wheels was made for greater structural strength and durability. The center bearing housings need cooling to prolong bearing life. The exhaust turbine housings have been left dry to aid in delivering as much heat energy to the exhaust turbine wheel as possible, enabling greater air mass flow compressed to higher pressures.

3. The G3500J LE and G3600 A4 LE engines each have exhaust manifolds which provide hot exhaust to the turbochargers. The G3500J LE engine has double air-shielded and engine coolant-jacketed exhaust manifolds. The two key features of the G3500J LE engines: 1) cooler outside skin temperatures provided by the engine coolant jacket and 2) two concentric separate air jackets maintain heat in the exhaust gases to the exhaust turbine wheel of the turbochargers. The much larger G3600 A4 LE engine has dry cylinder exhaust elbows to a dry exhaust manifold. These dry exhaust manifolds deliver hot exhaust to the turbocharger exhaust turbine for greater boost pressure and flow available for the combustion charge intake air. The cylinder elbows and exhaust manifold and turbocharger exhaust turbine housings have hard wrap insulation to maintain greater heat transfer to the turbocharger exhaust turbine wheel.



4. Actuated exhaust gas bypass valve controls exhaust energy to the turbocharger exhaust turbine. As more exhaust energy is required because of site altitude or ambient temperature and pressures, the bypass valve is electronically controlled instead of a simple spring backed diaphragm wastegate, which was manually set for a site. A wastegate routes unneeded exhaust flow to the engine exhaust outlet. Both the G3500J LE and G3600 A4 LE engines incorporate this technology for greater flexibility of the resulting charge air boost.
5. The G3500J LE employs Fuel Mass Flow Actuators to meter gas into the turbocharger compressor inlet air flow, assuring more complete in-cylinder air fuel mixture combustion. This means of metering more accurately delivers the needed quantities of fuel. The G3600 A4 LE engines similarly employ an electronic flow device to fuel the main cylinder chamber fuel manifold.
6. The G3500J LE family of engines and the G3612 A4 LE and G3616 A4 LE lean-burn engines use an actuated turbocharger compressor bypass valve. This turbocharger compressor bypass valve is not available on the G3606 A4 LE nor the G3608 A4 LE engines. This turbocharger compressor bypass valve system provides more flexibility for varying site ambient and load control requirements. More boost is available when needed and the cooled charge is recirculated into the turbocharger compressor inlet when not needed. This compressor bypass system enables effective use of larger, more efficient turbochargers which provide additional beneficial boost to support higher altitude and higher ambient temperature sites. This charge air management system expands the use of the turbocharger's available operating range. It also makes cooled charge air / fuel mixture readily available for effective load acceptance.

APPENDIX A-2:

Space claims for Best Available Technologies on G3500J LE and G3600 A4 LE engines.

Much of the Best Available Technology (BAT) presented earlier is common to today's gas compression spark-ignited lean-burn combustion engines. Both the G3500J LE 0.5g NOx Engines and G3600 A4 LE 0.3g NOx & 0.5g NOx engines employ two-stage intercooling. The space claim for two-stage charge air intercooling make for tight on-engine "packaging" for improved cooling of turbocharger compressor out air flow. Although there may be some limitations on the smaller class G3500J LE engines in terms of desired efficiency of air and coolant flow which effect heat transfer rate and efficiency, the larger G3600 A4 LE engines provide greater space to enable more efficient heat transfer.

1. Both the G3500J LE and G3600 A4 LE lean-burn engines employ improved larger, forged turbocharger compressor wheels. The needed space claim is not great.
2. The smaller sized family of G3500J LE engines make the manufacture of air-shielded, engine coolant cooled exhaust manifolds possible. The larger size and taller geometry of the G3600 A4 LE lean-burn engines may have remote mounted coolers for the natural gas, engine coolant, and charge air cooler sections. This may permit hard insulation wrapped dry cylinder exhaust elbows and manifolds acceptable while delivering exceptional charge air flows and pressures.
3. Both the G3500J LE and G3600 A4 LE lean-burn engines employ actuated exhaust bypass valves. Space or volume claim to include for this technology is not an issue.
4. Both the G3500J LE and G3600 AR lean-burn engines employ actuated fuel mass control devices. Space claim for this technology is not an issue.

5. Both the G3500J LE family of engines and G3612 A4 LE and G3616 A4 LE lean-burn engines use an actuated turbocharger compressor bypass valve. Space claim for this technology is not an issue.

6. The greatest difference in the technologies applied to the G3500J LE and the G3600 A4 LE lean-burn engines is use of a pre-combustion chamber in the G3600 A4 LE 0.3g & 0.5g NOx engines. The space claim required for this technology is met with the larger class G3600 A4 LE engine.

7. G3600 A4 LE family of engines' bore diameter is 176% of the G3500J LE engines: 11. 8 inches vs. 6.7 inches. This much larger bore diameter provides room for greater air and fuel flow than possible in the smaller bore G3500J LE engines. The G3600 A4 LE family of engines cylinder bore diameter of 300mm (11.8inch) provides more than three (3) times the cylinder bore area of the G3500J LE family of engines: This additional area enables greater intake air and exhaust flow areas for a much larger rating per cylinder and engine torque. The larger geometry of the G3600 A4 LE family of engines enable the use of pre-combustion chamber ignition of the extremely lean main chamber mixture.

G3500J LE vs G3600 A4 LE Bore and Bore Area	Not To Exceed Emissions NOx/bhp-hr	Bore mm	Bore in	Bore Area sq in
G3500J LE Engine Family	0.5 g NOx	170	6.7	35.3
G3600 A4 LE Engine Family	0.3 & 0.5 g NOx	300	11.8	109.4

APPENDIX A-3:

More power per cylinder of G3600 A4 LE family of engines as compared to the G3500J LE family of engines. The significantly larger family of G3600 A4 LE engines provide much more power per cylinder than the smaller G3500J LE family of engines. This large difference in power capability is made possible in part by several engine characteristics including larger bore diameter, bore area, longer stroke, larger cylinder displacement, higher torque per cylinder and greater BMEP per cylinder:

1. G3600 A4 LE engine bore diameter is 176% of the G3500J LE engines: 11. 8 inches vs. 6.7 inches. This much larger bore diameter provides room for greater air and fuel flow than possible in the smaller bore G3500J LE engines.
2. G3600 A4 LE engine bore area is 310% of G3500J LE engine bore area: 109.4 square inches vs. 35.3 square inches.
   i) This additional cylinder bore area enables much greater cylinder-head area and related geography above the cylinder-head gasket combustion fire ring enabling much larger intake air and exhaust port flow areas yielding much greater rating and torque per engine cylinder.
   ii) The additional area of the G3600 A4 LE cylinder bore provides room for much greater engine coolant flow areas to cool the cylinder-head fire deck, the two exhaust ports and the **centrally mounted pre-combustion chamber**. This cooling capacity for the pre-combustion chamber is perhaps the greatest differentiator of why the G3600 A4 LE engines have the 0.3g NOx per bhp-hr NTE Site capability and the G3500J LE engines are limited to the 0.5g NOx per bhp-hr.

(1) Caterpillar and other compression ignition engine manufacturers and their OEMs have found diesel engine cylinder-heads provide significant cooling by the excess diesel fuel passing through the diesel fuel injector body.)

(2) A key problem with pre-combustion chamber engines is the critical need to prevent the pre-combustion chamber from becoming too hot acting similar to a "glow plug" which could provide an unintended ignition source for the next engine compression cycle. This "glow plug" ignition source would initiate combustion prior to the needed spark plug ignition. This pre-ignition can cause engine damage.

(3) Over sixty years ago, Caterpillar developed an inertial welding capability to uniformly fabricate thin-walled diesel engine pre-combustion chambers to enable greater heat transfer to the cylinder-head jacket coolant preventing early cylinder ignition.

iii) Additional cylinder-head area provides greater space for more structural iron or ductile-iron for greater strength, resisting increased cylinder pressures at elevated cylinder temperatures.

iv) Generally, structural limitations create thinner walls or structures specifically in/near the lower surface of the engine cylinder-head reduce cooling effectiveness and strength to reliably withstand cylinder pressure.

v) If the area or volume of iron is too space limited the expansion / contraction due to engine combustion temperatures and pressures over time, may initiate fatigue cracking.

vi) Stronger structures provide increased strength, combined with more effective engine jacket coolant passages and flow, enabling greater engine cylinder-head life.

3. G3600 A4 LE engine stroke is 157% of the G3500J LE engines stroke: 11.8 inch vs. the 7.5 inch
    i. The approximate one & one-half longer cylinder piston stroke than the G3500J LE engine provides greater combustion efficiency through longer combustion expansion phase.
    ii. Longer cylinder piston stroke may require slower crankshaft speeds to keep the piston velocity within the piston/ring/liner design specifications for durability/reliability and for combustion gas obturation preventing combustion gas blowing by the piston rings, contaminating the engine crankcase lubrication oil prematurely.
    iii. Longer cylinder piston stroke with slower engine speed enables longer intake and exhaust valve durations allowing more air for combustion and longer combustion expansion.
4. G3600 A4 LE engine individual cylinder displacement is 488% of the G3500J LE engines: 1290 cu.in vs. the 264 cu.in.
    i. The almost five times greater individual cylinder displacement than the G3500J LE engines, significantly reduces the number of cylinders needed to carry the engine load but requires greater total engine coolant heat rejection capability in the package installation. This larger G3600 A4 LE engine's brake specific heat rejection is lower than the smaller G3500J LE engines.
    ii. Greater individual cylinder displacement is an indication of a larger class of engine which typically has greater combustion efficiency and more control of combustion and emissions.

5. G3600 A4 LE engine torque per cylinder is 507% of G3500J LE engines: 1641 lb-ft vs. the 324 lb-ft.
    i. The five times greater torque per cylinder of the larger class G3600 A4 LE engine results in a fewer total number of engine cylinders and reduces the total number of engine components.
    ii. The greater torque per cylinder of the larger class G3600 A4 LE engine requires larger stronger components to transfer the total engine torque through the flywheel to driven equipment.
6. G3600 A4 LE engine has 3% greater Brake Mean Effective Pressure than G3500J LE engines: 191.2 psi vs. 185.3 psi.
    i. Much larger components and stronger structures are required to contain the combustion pressures of the much larger engine. This enables the G3600 A4 LE family of engines to operate reliably at 3% greater Brake Mean Effective Pressure (BMEP) over the G3500J LE family of engines.

ii. Greater BMEP is a measure of a higher level of cylinder pressure of the entire four cycles of combustion. This greater mean effective pressure over the larger cylinder area develops greater torque on the crankshaft pin for each cylinder.

Engine Model with NOx Capability Ratings, Torques, BMEP	Not To Exceed Emissions NOx/bhp-hr	Engine Rating bhp	Engine Torque lb-ft	Engine Displace-ment cu. in	BMEP psi
G3500J LE Engine Family	0.5 g NOx				185.3
G3512J LE	0.5 g NOx	1035	3,884	3,158	185.3
G3516J LE	0.5 g NOx	1380	5,177	4,211	185.4
G3520J LE	0.5 g NOx	1725	6,470	5,263	185.4
G3600 A4 LE Engine Family	0.3 & 0.5 g NOx				191.2
G3606 A4 LE	0.3 & 0.5 g NOx	1875	9,846	7,762	191.2
G3608 A4 LE	0.3 & 0.5 g NOx	2500	13,129	10,350	191.2