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INVESTIGATION OF REDUCED TEL CONTENT IN COMMERCIAL100LL AVGAS

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COORDINATING RESEARCH COUNCIL, INC.
3650 MANSELL ROAD·SUITE 140·ALPHARETTA, GA 30022

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COORDINATING RESEARCH COUNCIL, INC.
3650 MANSELL ROAD, SUITE 140
ALPHARETTA, GA 30022
TEL: 678/795-0506 FAX: 678/795-0509
WWW.CRCAO.ORG

INVESTIGATION OF REDUCED TEL CONTENT IN COMMERCIAL 100LL AVGAS

(CRC Project No. CA-67-2010)

Prepared by

R. E. Wilkinson

for the CRC UL AVGAS Development Group

OCTOBER 14, 2010

CRC Aviation Fuel, Lubricant & Equipment Research Committee
of the
Coordinating Research Council, Inc.

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LIST OF ABBREVIATIONS & SYMBOLS

AFETF	Aviation Fuels & Engine Test Facility (FAA Williams J Hughes Technical Center)
AOPA	Aircraft Owners & Pilots Association
API	American Petroleum Institute
ASTM	American Society for Testing and Materials (ASTM International)
AVGAS	Aviation Gasoline
BHP	Brake Horsepower (also equates to IHP X mechanical efficiency)
BMEP	Brake Mean Effective Pressure = [792,000 X BHP]/ [CID X RPM]
BSFC	Brake Specific Fuel Consumption (lbs/hr/BHP)
°C	Degrees Centigrade
CAR	Civil Air Regulations
CFR	Code of Federal Regulations
CHT	Cylinder Head Temperature
CID	Cubic Inch Displacement
CofA	Certificate of Analysis
CR	Compression Ratio
EAA	Experimental Aircraft Association
EGT	Exhaust Gas Temperature
EXP	Experimental
°F	Degrees Fahrenheit
FAA	Federal Aviation Administration
F/A	Fuel/Air Ratio
FAR	Federal Aviation Regulation
FR	Full Rich mixture setting
FBO	Fixed Base Operator
GA	General Aviation
GAMA	General Aviation Manufacturers Association
gPb/L	Grams lead per liter
inHg	Inches of mercury
IHP	Indicated Horsepower = brake horsepower + frictional losses
IMEP	Indicated Mean Effective Pressure = [792,000 X IHP]/ [CID X RPM]
ISFC	Indicated Specific Fuel Consumption
JASC	Joint Aircraft System/Component Code (FAA)

LOP	Lean of Peak [Refers to fuel flow setting lean of peak EGT]
MAP	Manifold Pressure, typically inches Hg absolute
mL/gal	Milliliters per gallon
mmHg	Millimeters of mercury
MON	Motor Octane Number (ASTM D 2700)
NAAQS	National Ambient Air Quality Standard
NACA	National Advisory Committee for Aeronautics
NATA	National Air Transportation Association
OEM	Original Equipment Manufacturer
PN	Performance Number (ASTM D 909)
POH	Pilot Operating Handbook
PRF	Primary Reference Fuel
PSIG	Pounds per square inch gage
RPM	Revolutions Per Minute
RGL	Regulatory and Guidance Library (FAA)
ROP	Rich of Peak [Refers to fuel flow setting rich of peak EGT]
RVP	Reid Vapor Pressure
SAE	Society Automotive Engineering (SAE International)
SC	Supercharge Rating (ASTM D 909)
SDR	Service Difficulty Report (FAA)
TCDS	Type Certificate Data Sheet (FAA)
TDC	Top Dead Center (piston position)
TEL	Tetraethyl Lead
UL	Unleaded
ULL	Ultra Low Lead
VLL	Very Low Lead
WOT	Wide Open Throttle (same as full throttle)
100LL	100 Octane Low Lead AVGAS

FOREWORD

The source for the 100LL AVGAS survey data presented within this CRC report is a technical report prepared under contract by Crown Consulting Inc for the FAA William J Hughes Technical Center. The contents of this CRC report are intended to document the results of the survey of TEL content in commercial AVGAS as commissioned by the FAA Technical Center working as a member of the CRC Unleaded AVGAS Development Group and the CRC VLL Task Group, and to provide additional supporting technical data, analysis, and discussion where applicable.

The work product of CRC research is technical data which is made available to industry as a means of enabling the industry decision process. It is not the intent of this report to provide a recommendation for a specific reduction in TEL content, but rather the objective is to provide technical data and analysis sufficient to enable and facilitate industry's decision making process regarding a reduction in 100LL AVGAS lead emissions.

Where applicable throughout this report, the source of information or data is identified as a numbered reference. A numerical listing of these references is included at the end of this report. The author of this report has attempted to objectively document results in a summary manner using the FAA survey results and engine test results; there are no changes to data or conclusions.

The objective of the CRC UL AVGAS Dev Group is to conduct research and testing that will facilitate development of the next generation aviation gasoline with the goal of ensuring the availability of the required technical information for the development of an unleaded aviation gasoline that meets the requirements of both the existing and future general aviation fleet. Working as a subcommittee of the CRC UL AVGAS Dev Group is the CRC VLL AVGAS Task Group which was tasked by industry to conduct research into options for reducing the lead emissions of 100LL AVGAS.

A future technical report to be published by the FAA Technical Center will document the details of the engine testing conducted on a group of candidate reduced TEL AVGAS blends furnished by the fuel producers.

Note that although the term ULL (ultra low lead) had been previously used to describe a reduced TEL content AVGAS, the descriptor VLL (very low lead) has been recommended as the preferred suffix ie 100VLL, and is the term of reference applied within this report for a reduced TEL content AVGAS. This also avoids confusion with unleaded AVGAS development where the suffix "UL" has been proposed for unleaded grades.

1. INTRODUCTION

Aviation gasoline is produced pursuant to ASTM D 910 Standard Specification for Aviation Gasolines and DEF STAN 91-90 (British Ministry of Defense), where the maximum allowable tetraethyl lead (TEL) content for Grade 100/130LL (hereafter referred to as Grade 100LL in this report) is restricted to a maximum level of 0.56 gPb/L (0.53 mL TEL/L, 2.00 mL TEL/gal). Grade 100LL was introduced during the 1970's as a reduced TEL content AVGAS replacing the previous Grade 100/130 which was limited to 0.84 gPb/L (0.8 mL TEL/L, 3.00 mL TEL/gal); Grade 100LL offered a significant reduction in TEL content from the prior Grade 100/130.(1) Although ASTM D 910 includes provisions for AVGAS Grades 80/87, 91/98, and 100/130, the 100LL AVGAS product is the predominant AVGAS produced world-wide and used by the general aviation piston fleet. The octane quality and associated knock resistance of aviation grade gasoline has relied almost exclusively on the octane enhancing additive TEL which has been used as a knock suppressant in aviation gasoline since the late 1920's. The compound TEL is the primary fuel additive enabling the high octane quality fuel required by high performance high compression ratio aviation engines. As domestic environmental measures have continued to reduce the use of lead in manufactured products, aviation gasoline today remains the only domestically produced gasoline containing TEL. The general aviation industry has accordingly committed to pursue options for unleaded aviation gasoline including both near term and long term strategies for reduction of TEL content.

The AVGAS Stakeholder Group is a broad based coalition which represents the general aviation industry today relative to future unleaded aviation gasoline. The Stakeholder Group is working collaboratively with the industry manufacturers, the FAA, and the EPA to formulate and implement plans providing for reductions in lead emissions as associated with the 100LL AVGAS product. A major tenant of the Stakeholder's Group near term plan includes research into options for a reduced TEL content 100LL AVGAS. In August 2009, the AVGAS Stakeholder Group petitioned the CRC Unleaded AVGAS Development Group to investigate and conduct research into options for a reduced TEL content AVGAS. Since that time, the CRC VLL Task Group working as a subset of the CRC Unleaded AVGAS Development Group has conducted test and evaluation of reduced TEL content AVGAS, and has provided input and support to the FAA Technical Center's investigations into TEL production levels for commercial FBO AVGAS.

Working as a member of the CRC VLL AVGAS Task Group, the FAA William J. Hughes Technical Center has completed a survey of FBO 100LL AVGAS for TEL content and associated ASTM D 910 properties for the specific purpose of documenting TEL content for commercial 100LL AVGAS as used by the active fleet. Complementing the TEL study, a review of FAA Service Difficulty Reports (SDR) was performed for the purpose of searching for reports of detonation related service incidents for the piston powered fleet.

The objective of this report is to document the findings and observations associated with the survey of FBO AVGAS TEL content and associated properties, including search results of the FAA SDR database for detonation incidents. Also documented within the survey report are 100LL AVGAS production TEL levels for a major AVGAS producer and the TEL content for AVGAS used in official FAA certification testing by the OEM engine manufacturers. Test results for a series of full scale engine tests performed with a group of partially leaded fuels to assess the "lead response" of a representative high output worst case conventional reciprocating engine are included as complementary data.

It is not the intent of this report to provide a recommendation for a specific reduction in TEL content, but rather the objective is to provide technical data and analysis sufficient to enable industry's decision making process regarding a reduction in TEL content.

2. BACKGROUND

2.1. GENERAL AVIATION LEAD REDUCTION INITIATIVE

The National Ambient Air Quality Standards (NAAQS) were updated by the EPA in 2008 to reduce allowable levels of lead by 90%. The revised standard requires measurement of lead levels in the vicinity of general aviation airports. For each location found to be in a non-attainment status with the NAAQS, the State must develop a plan approved by the EPA to reduce lead emissions to bring these areas into attainment by 2017. As a result of this regulatory action, there is an urgent emphasis on addressing measures for reducing lead emissions from general aviation aircraft.

The Aircraft Owners and Pilots Association (AOPA), the Experimental Aircraft Association (EAA), the General Aviation Manufacturers Association (GAMA), the National Air Transportation Association (NATA), the National Business Aviation Association (NBAA), the American Petroleum Institute (API), and the National Petrochemical and Refiners Association (NPRA) comprise the AVGAS Stakeholders Group which represents the General Aviation aircraft owners, operators, and manufacturers and the oil and natural gas industry producers, refiners, and distributors of aviation grade gasoline (AVGAS). This AVGAS Stakeholder Group is actively engaged in working with the manufacturers, the FAA, and the EPA to achieve significant reductions in lead emissions for the General Aviation piston powered fleet which requires a minimum grade 100LL AVGAS.[(2)] The stated purpose of this Group is to collaborate, coordinate, and provide leadership leading to the development and implementation of the process by which an unleaded AVGAS solution will be identified.[(3)]

The AVGAS Stakeholder Group has identified both near term and long term strategies leading to the eventual transition to an unleaded AVGAS which are extracted from reference (3) as follows.[(3)] The Stakeholder Group Near Term Strategy provides for a near-term reduction of lead emissions from General Aviation aircraft based upon the following criteria. Note that the suffix VLL is used within this report to indicate a reduced TEL content AVGAS; the final determination and selection of a suitable suffix may well differ from the modifier VLL; the suffix ULL had previously been used to indicate a reduced TEL content AVGAS.

AVGAS STAKEHOLDER GROUP NEAR TERM STRATEGY [(3)]

- A drop-in 100VLL as a replacement for 100LL
- Requires no action from manufacturers or operators
- No impact on engine or aircraft FAA certification
- The use of 100VLL lowers total lead emissions in airport areas where monitoring may determine the current NAAQS standard is not being met

Although not the subject of this report, the AVGAS Stakeholder Long Term Strategy is structured around five major phases which are extracted from reference (3) and repeated as follows.

AVGAS STAKEHOLDER GROUP LONG TERM STRATEGY [3]

- Phase I – Establish FAA-led public-private partnership
  - Develop and implement an integrated FAA program to provide the information necessary for the marketplace to identify the best unleaded solution which is technically feasible

- Phase II – Identify viable unleaded AVGAS specification
  - Evaluate current D910 fuel specification to determine which parameters can be adjusted
  - Identify and support research needs for development of an unleaded AVGAS specification
  - Define all criteria for a viable unleaded AVGAS
  - Develop engine and aircraft certification processes to transition existing fleet to a new fuel

- Phase III – Develop and approve an ASTM fuel specification

- Phase IV – Certify new production aircraft to new fuel specification
  - Only affects new production engines and aircraft
  - Would require dual certification for unleaded and 100LL AVGAS

- Phase V – EPA/FAA regulate transition to unleaded AVGAS (includes FAA approvals & certifications necessary for safety)
  - Transition timeline dependent upon level of impact
    - ✓ FAA approvals & certifications necessary for safety
    - ✓ AVGAS production & distribution infrastructure
  - Regulation may need to consider special provisions if there are portions of the fleet that cannot transition within the timeframe

2.2. ASTM D 910 SPECFICATION

"ASTM D 910 Standard Specification for Aviation Gasoline and DEF STAN 91/90 (British Ministry of Defense) are recognized throughout the world as primary specifications for the production and quality control of AVGAS."[1] ASTM D 910 which was first introduced in 1947 currently provides for four different aviation grade gasolines. Current aviation grade gasolines are summarized in Table 1 of ASTM D 910 which is repeated below as Table 1.0 for the purpose of identifying TEL limits and associated octane ratings. As shown, the maximum allowable TEL content for Grade 100LL is 0.56 gPb/L (0.53 mL/L) which is equivalent to 2.00 mL/gal. There is no minimum limit specified for current TEL content. Aviation grade 100LL has gradually become the predominant fuel used by the general aviation piston fleet, both domestically and globally where the 100LL AVGAS is approved for use on those aircraft and engines originally certified for lower grades 80/87 and 91/98. For information on international specifications by country of origin for aviation gasoline, refer to reference (1).

Table 1.0
Detailed Requirements for Aviation Gasolines [4]
Extracted from ASTM D 910-04a Specification

		Grade 80	Grade 91	Grade 100LL	Grade 100	ASTM Test Method
Knock Value, lean mixture						
Octane Number	Min	80.0	91.0	99.5	99.5	D 2700
Knock Value, rich mixture						
Octane Number	Min	87.0	98.0			D 909
Performance No.	Min			130.0	130.0	D 909
Tetraethyl lead,						
mL TEL/L	Max	0.13	0.53	0.53	1.06	D 3341 or D 5059
gPb/L	Max	0.14	0.56	0.56	1.12	
Color		red	brown	blue	green	D 2392

2.3. AVGAS HISTORICAL TEL CONTENT

Historically, the TEL content in aviation gasoline has continued a downward trend from the high levels of 4.60 mL/gal (max) allowed in the early Grade 115/145 aviation gasoline to the current 2.00 mL/gal (max) specified for the Grade 100LL AVGAS. Grade 100/130 which was the predecessor to 100LL had a maximum TEL content of 3.00 mL/gal; Grade 100 is listed today as containing a maximum 4.00 mL/gal TEL, although Grade 100 is not currently a production fuel. As precipitated by a growing environmental awareness in the 1970's, Grade 100LL AVGAS was introduced during the 1970's which provided a significant reduction in TEL content and associated lead emissions. Grade 100LL AVGAS gradually became the predominant global aviation gasoline for piston powered aircraft.

Table 2.0 which is extracted from a 1951 document, reference (5), provides further insight into historical aviation gasoline grades and their associated critical properties including TEL content. Reference 5 indicates the MIL-F-5572 specification allowed a higher TEL content for the 91/96 and 100/130 grades than specified in the D910-48T specification.

Reference (12) provides additional insight and data on the development and characteristics of aviation gasoline.

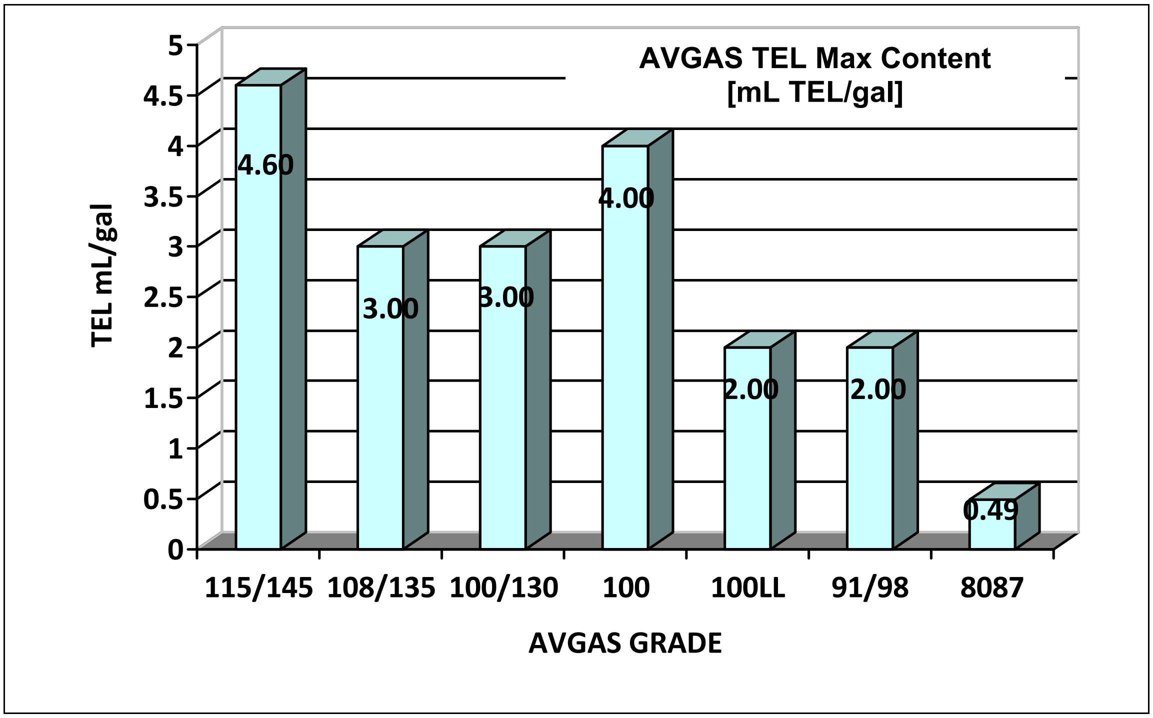

Figure 1.0
Historical AVGAS TEL Content, Ref ASTM D 910

Table 2.0
Summary of 1951 Military & Commercial Aircraft Gasoline Specifications (5)
NAVAER 06-5-501, USAF T.O. 06-5-4

	MIL-F-5572				**ASTM D910-48T**				
	80	91/96	100/130	115/145	80/87	91/98	100/130	108/135	115/145
At least 10% Evaporated @ °F	167	167	167	167	158	158	158	158	158
At least 40% Evaporated @ °F	167	167	167	167	-	-	-	-	-
At least 50% Evaporated @ °F	221	221	221	221	221	221	221	221	221
At least 90% Evaporated @ °F	275	275	275	275	257	257	257	257	257
Sum of10%+50%temp, min°F	307	307	307	307	307	307	307	307	307
End point max °F	338	338	338	338	338	338	338	338	338
Lead ml/U.S. gal max	0.5	4.6	4.6	4.6	0.5	2.0	3.0	3.0	4.6
Color	Red	Blue	Green	Purple	Red	Blue	Green	Brown	Purple
Freezing Point max °F	-76	-76	-76	-76	-76	-76	-76	-76	-76
Octane number lean min	80	91	100	-	80	91	100	-	-
Performance no. lean min	(58.3)	(76)	100	115	(58.3)	(76)	100	108	115
Octane no. rich min	-	96	-	-	87	98	-	-	-
Performance no. rich min	-	(87.5)	130	145	(68)	(87.5)	130	135	145
Heat value Btu per lb. min	18700	18700	18700	18700	18700	18700	18700	18800	18800
Reid vapor press Psi max	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
Reid vapor press Psi min	5.5	5.5	5.5	5.5	-	-	-	-	-

3. TEL EFFECT ON ENGINE PERFORMANCE

The compound tetraethyl lead (TEL) has a powerful effect on engine performance, specifically as an anti-knock agent, when used as an additive in aviation grade gasoline. The fuel octane rating needed to ensure that an engine will operate knock free is considered to be a first order requirement for an aviation spark ignition piston engine fuel. Refiners add TEL to meet the octane requirements for AVGAS. As documented in reference (11), the CRC Unleaded AVGAS Development Group determined that engine octane requirement is the most demanding and challenging criteria for an unleaded AVGAS. Accordingly, research into options for unleaded AVGAS and reduced lead content AVGAS has been driven by engine octane requirements.

As background considerations for a reduced TEL content AVGAS, it is important to recognize those AVGAS components which influence and establish the MON quality of the resulting 100LL product. The addition of TEL certainly has a significant impact on knock response and resulting fuel MON quality, but the base alkylate and aromatic content are other significant contributing variables. Refiners balance these three components (base alkylate, aromatics, and TEL) to achieve the desired MON rating of the fuel. There is a limit to which the effect of reduction in TEL may be offset by adjustment to the aromatic content while maintaining MON performance.

The following indicates the significance of the effect of TEL on engine knock performance using both historical data for a typical high output radial engine and recent data generated as part of a CRC-FAA Technical Center research program to evaluate effect of TEL in conventional horizontally opposed high output worst case reciprocating aircraft engine. The following provides insight into the sensitivity of engine knock performance to TEL content in the range of 1.0 – 2.0 mL/gal.

3.1. LEAD RESPONSE RADIAL AIRCRAFT ENGINE

The effect of TEL on aircraft engine performance has been the subject of extensive research since the early days of aviation. Research conducted on radial spark ignition reciprocating engines during the height of radial engine production years probed the “lead response” of engine operation using leaded aviation gasoline. A number of technical reports in the NACA archives document research results for explorations into leaded aviation gasoline in addition to investigations into other octane and performance enhancing additives.

NACA Report No. E4I28 was found to include test results described as “Lead Response” for a typical radial engine power section. The results are included within this report as an indication of effect of TEL on radial engine knock performance. The following Figure 2.0 which is extracted from NACA Report No. E4I28 indicates the “lead response” for a Pratt & Whitney R2800 radial engine (based upon single cylinder tests) in terms of knock limited IMEP for fuel/air ratios of 0.075 and 0.100. The test fuel was an S-3 Aviation Reference fuel with TEL content varied from 0.00 to 6.00 mL/gal. [6]

Figure 2.0 provides an indication of the sensitivity of knock limited IMEP to TEL content for the configuration and test conditions documented in E4I28.

- Based upon the actual data points within the range of 1.5-2.2 mL/gal, a change of 0.4 mL/gal results in a 4.9-3.7% impact on knock limited IMEP for a fuel/air ratio of .075 F/A. The sensitivity may also be expressed as 0.1 mL/gal is equivalent to 1.2 - .9% impact on knock limited IMEP.

- Based upon the actual data points within the range of 1.06 – 2.00 mL/gal, a change of 0.4 mL/gal results in a 4.1% impact on knock limited IMEP for a fuel/air ratio of .100 F/A which indicates sensitivity of 1% change in knock limited IMEP per 0.1 mL/gal TEL.

- Figure 2.0 further indicates that for the configuration and test conditions documented in E4I28, a change in TEL content from 3.0 mL/gal to 2.0 mL/gal resulted in an impact of approximately 9.6% on knock limited IMEP.

Inspection of Figure 2.0 indicates an inflection or shift in the lead response curve in the area of 1.0 to 1.5 mL/gal TEL. The NACA researchers noted this observation with the following comment – "*The results plotted in figure 18(b) show that a distinct irregularity in the susceptability curve exists in the region of 0.8 to 1.4 ml tetraethyl lead per gallon. It is also questionable whether this characteristic would be found under all test conditions and , if it should, whether this irregularity would always appear at the same tetraethyl-lead concentrations and would be of the same magnitude.*" [(6)]

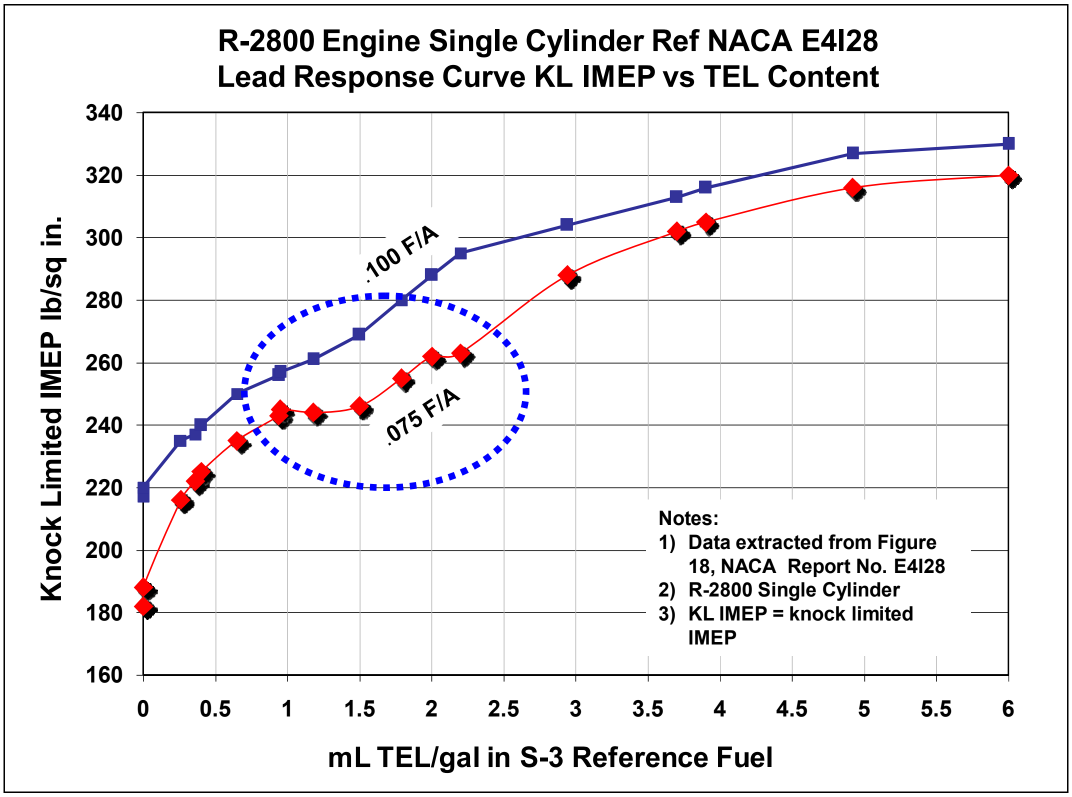

Figure 2.0
"Lead Response" Curve P&W R-2800, NACA E4I28[(6)]

3.2. LEAD RESPONSE CONVENTIONAL AIRCRAFT ENGINE

Aviation industry research into unleaded avgas alternatives during the last 15 years has essentially followed in the footsteps of yesterday's engine engineers and fuel chemists; however, the objectives and focus of research has shifted to alternatives for reducing and ultimately eliminating lead emissions as associated with aviation gasoline. In consideration of the Aviation Stakeholder Group's near term strategy to pursue a reduction in lead emissions using a "drop in" replacement reduced lead content 100 min grade AVGAS, the Aviation Stakeholder Group requested the CRC Unleaded AVGAS Development Group working in conjunction with the FAA Technical Center to investigate and conduct research into options for a reduced TEL content AVGAS. In response to the Stakeholder request, dual initiatives were launched by the CRC and FAA including full scale engine testing of manufacturer's reduced

TEL content AVGAS blends in addition to an effort to assess and identify typical TEL content in 100LL AVGAS consumed by the fleet.

The CRC VLL Task Group working as a subset of the CRC Unleaded AVGAS Development Group has conducted test and evaluation of reduced TEL content AVGAS samples and has provided support and input to the FAA Technical Center's investigation into TEL production levels for commercial FBO AVGAS. The following describes the preliminary results of CRC research investigations into full scale engine tests of a group of partially leaded fuels. The following data are provided in advance of a formal FAA Technical Center report which will document the full scale engine tests of a group of manufacturer's reduced lead content fuels.

3.3. CRC-FAA AFETF ROUND I VLL TESTS

In response to the Stakeholder request, the CRC VLL Task Group defined and implemented a research program during early 2010 which provided for full scale engine testing of a group of reduced TEL content AVGAS blends furnished by the fuel producers. Although the requirement was that the test blends meet D 910 specification, one of the fuel groups consisted of batch of 5 blends which were prepared using a production AVGAS; the TEL content was varied from 0 to 64% of max allowable TEL with toluene content maintained at approximately 11%. EM1 was a D 910 compliant fuel. This latter group of reduced TEL content fuel blends which are summarized in Table 3.0 offered the opportunity to investigate the lead response of similar fuels with varying TEL content in a full scale engine. The 100LL fuel noted in Table 3.0 represented a baseline FBO AVGAS with TEL content at 94.3% of D 910 limits. See Figures 6.0 and 7.0 for test fuel MON and Supercharge Rich trends.

Table 3.0 [7]
CRC FAA Tech Center VLL Fuels Matrix
Round I Tests 2010

ULL Blend	TEL (mL/L)	TEL (mL/gal)	% Max TEL D 910	Toluene (v/v%)	MON (D2700)	SC Rich (D909)
100LL	0.50	1.89	0.9434	<0.5	103.9	131.5
EM1	0.34	1.287	0.6415	11.8	102.4	135
EM2	0.26	0.98	0.4906	11.6	101.6	129
EM3	0.17	0.64	0.3208	11.5	100.2	117
EM4	0.08	0.30	0.1509	11.3	99.5	107
EM5	0.00	0.00	0.0000	11.1	94.4	97

A Textron Lycoming model IO-540-K engine, which was the primary test engine used for prior CRC Unleaded AVGAS research projects,[11] was also used for the test investigations into the lead response of the fuels identified in Table 3.0. The IO-540-K engine is rated at 300 BHP at 2700 RPM and features a 5.125 inch bore with 8.7:1 CR; the engine is six cylinder, air-cooled, horizontally opposed, fuel injected engine, and has been determined to be one of the worst case naturally aspirated engines relative to octane requirement.[11] The IO-540-K is representative of the large bore six cylinder naturally aspirated engines rated on minimum grade 100LL AVGAS which power a large segment of the general aviation fleet. The combination of large cylinder bore, high compression ratio, and high output are primary design features contributing to the high octane requirement.

Full scale engine detonation testing of the reduced TEL fuels shown in Table 3.0 was completed in June 2010 at the FAA Technical Center's Aviation Fuels and Engine Test Facility (AFETF) located in Atlantic City, New Jersey. Engine detonation test procedure consisted of conducting mixture lean out curves at power settings of 100% [2700 RPM WOT], 85% [2600 RPM], 75% [2450 RPM], and 65% [2350 RPM]. Each of the six cylinders was monitored continuously for indications of detonation as indicated by combustion pressure using the instrumented cylinder head concept described in reference (11).

Results of the FAA AFETF detonation tests using the Table 3.0 fuels are shown graphically in Figure 3.0(7). The diagonal lines which intersect the BHP curves for each power setting indicate the fuel flow corresponding to onset of combustion knock for each of the fuel blends shown. The RPM indications correspond to the power settings of 100%, 85%, 75%, and 65%. Although Figure 3.0 illustrates the relative knock performance of the Table 3.0 fuels; it does not establish a quantifiable relationship between TEL content and engine knock, but rather only indicates those fuels with higher TEL provide an increasingly positive effect on engine knock performance.

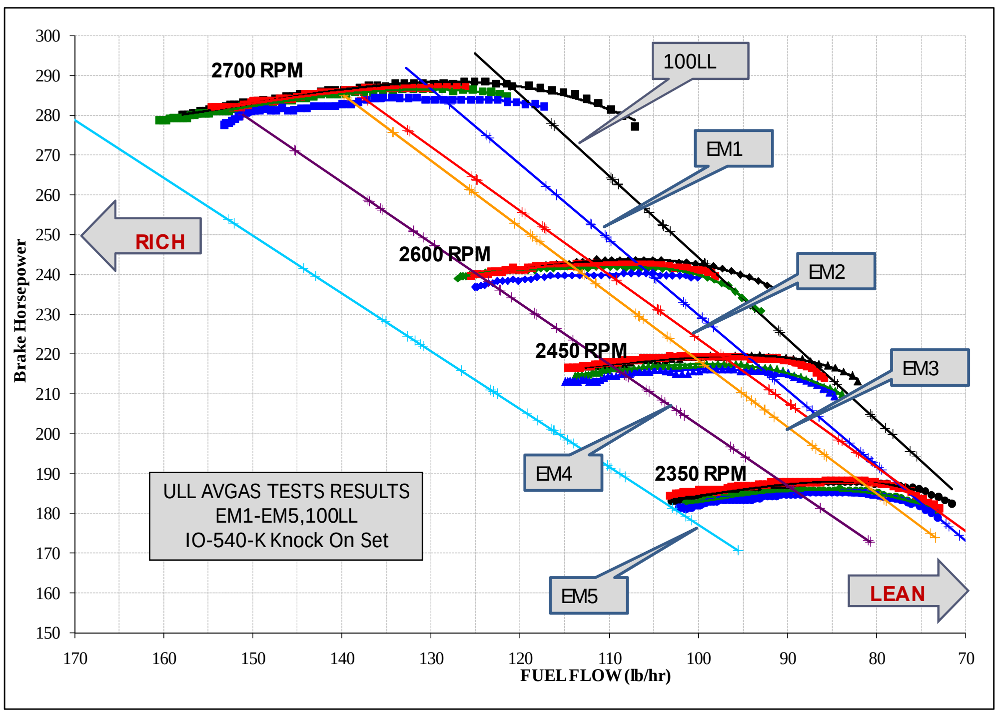

Figure 3.0
Knock Limited Fuel Flow, ULL Test Matrix, IO-540-K(7)

With the objective of quantifying the relationship between TEL content and engine knock performance, Figures 4.0 and 5.0 are derived from the Figure 3.0 data by plotting knock limited fuel flow as a function of TEL content for lines of constant BHP. The resulting data sets provide an indication of the effect of change in TEL content on engine knock performance as manifested by knock limited fuel flow. The MON rating for each test fuel is noted for reference since there was a gradual reduction in MON as TEL content was reduced with the drop in MON becoming more aggressive beginning at 0.30 mL/gal TEL as shown in Figure 6.0. Figure 7.0 shows the supercharge rich ratings for the Table 3.0 test fuels where the difference in the rich rating between EM1 and 100LL is likely the result of the difference in toluene content.

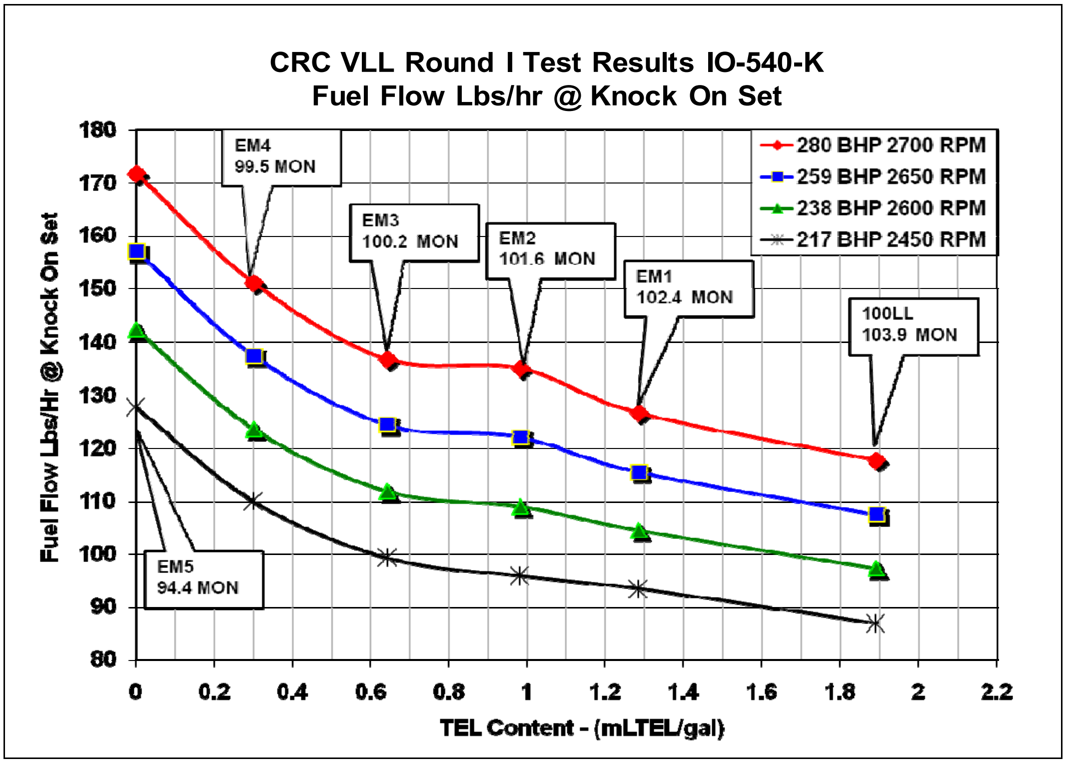

Figure 4.0
"Lead Response" TEL (mL/gal) Curve IO-540-K

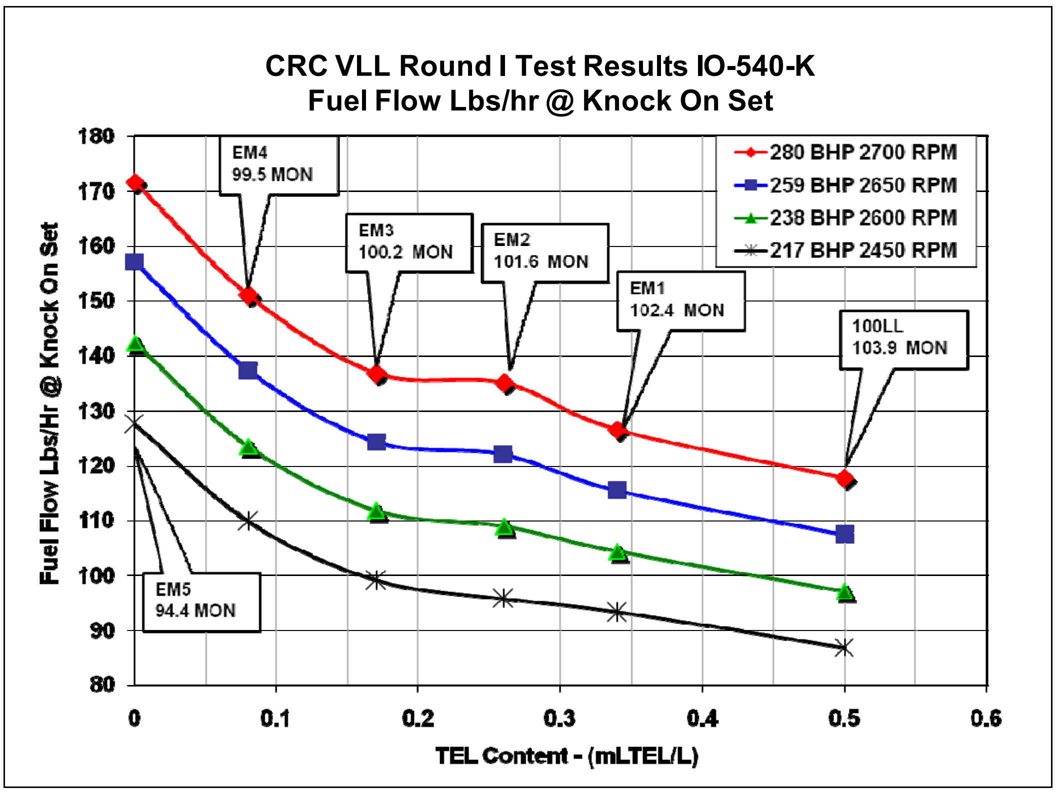

Figure 5.0
"Lead Response" TEL (mL/L) Curve IO-540-K

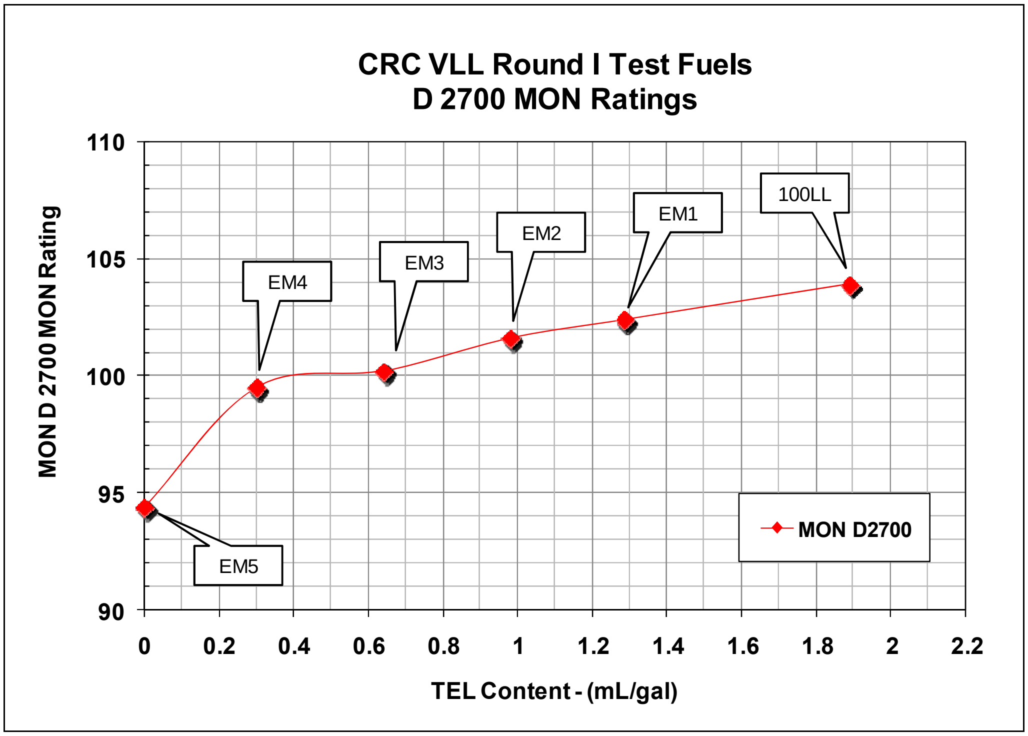

Figure 6.0
D 2700 MON Ratings, CRC VLL Round I Test Fuels

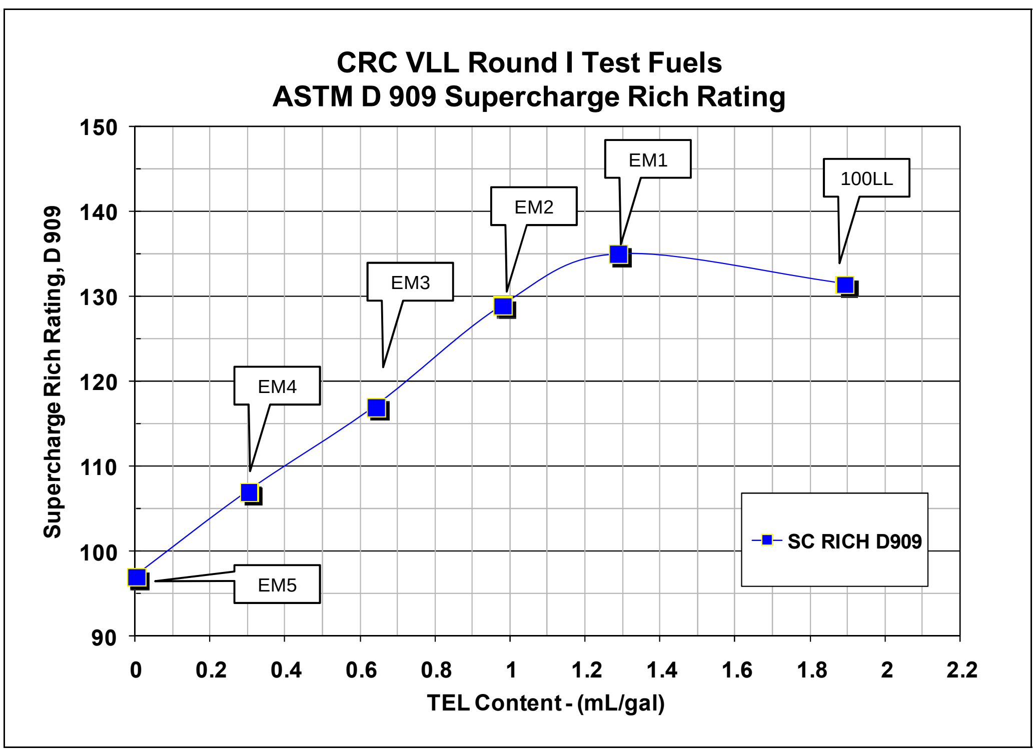

Figure 7.0
D 909 Supercharge Ratings, CRC VLL Round I Test Fuels

3.4. CONCLUSIONS ROUND I VLL TESTS

Figures 4.0 and 5.0 indicate the "lead response" for the IO-540-K test engine using the fuels described in Table 3.0. The data indicates the "lead response" in terms of knock limited fuel flow for TEL content in the 1.50 to 2.00 mL/gal range is linear. There is a "knee" in the curve around 0.60 mL/gal below which the "lead response" becomes non-linear as the TEL content approaches zero.

The utility of Figures 4.0 and 5.0 is that they indicate the relative change in engine knock limited fuel flow as a function of TEL content in the 1.50 – 2.0 mL/gal range of interest and beyond which provides for correlation with the fleet service experience with AVGAS at TEL values ranging from 1.22 – 2.00 mL/gal as discussed in Section 5 of this report.

Figures 4.0 and 5.0 provide an indication of the sensitivity of knock limited fuel flow to TEL content for the conventional IO-540-K engine configuration and test conditions documented.

- Assuming a linear response in the 1.3 – 2.0 mL/gal range, the data indicate a change of 0.4 mL/gal results in a 4.9% impact on knock limited fuel flow for the BHP shown in Figures 4.0 and 5.0

- Alternately a change of 0.5 mL/gal results in a 6% impact on knock limited fuel flow for the BHP shown in Figures 4.0 and 5.0

- A change in TEL content from 2.00 mL/gal to 1.22 mL/gal (39% reduction) is equivalent to a 9.4% change in knock limited fuel flow, reference Figures 4.0 and 5.0

- Based upon Figures 4.0 and 5.0, the sensitivity of engine knock to TEL content may be expressed as 0.1 mL/gal is equivalent to 1.2% impact on knock limited fuel flow. Note that this is in agreement with the radial engine lead response at .075 F/A discussed in Section 3.1. Although the metrics are expressed in different terms, knock limited IMEP for a radial engine and knock limited fuel flow for a conventional engine, they are complementary and indicate the relative change in knock on-set as a function of TEL.

4. GENERAL AVIATION PISTON POWERED FLEET

Of interest relative to the use of 100LL AVGAS and the associated TEL content is the size of the general aviation piston powered fleet which requires use of a minimum grade 100LL AVGAS. Based upon the results of a recent study which researched the FAA Registry for registered piston powered aircraft and the associated FAA TCDS for a listing of approved fuels, the total U.S. GA fleet in 2010 consists of 228,078 aircraft with the piston powered fleet portion comprising 83% of the total.[8] The U.S. piston fleet in YR2010 consists of 189,453 aircraft which is estimated to be 60% - 70% of the total worldwide piston fleet. General Aviation is defined as all aviation other than military and commercial airlines according to the General Aviation Manufacturers Association.[11]

Piston powered GA aircraft (less than 12,000 lbs gross weight) are almost exclusively powered by horizontally opposed spark ignition reciprocating engines configured in 4, 6, and 8 cylinder arrangements manufactured by original equipment manufacturers (OEM) Teledyne Continental Motors and Textron Lycoming as FAA approved products conforming to either CAR 13 Civil Air Regulations or 14 CFR 33 Federal Aviation regulations.

Many older GA engine models are approved to operate with a minimum grade 80/87 AVGAS but are also approved to operate with the more readily available higher grade 100LL AVGAS. A small percentage of the fleet is approved to operate on an older minimum grade 91/96 AVGAS with a few aircraft listing 91/98 as the approved fuel. GA engine models produced since the mid 1970's are mostly high output, high performance, high compression ratio (8.5 – 8.7CR) engines which require a minimum grade 100LL AVGAS for adequate knock protection. The minimum grade fuel approved for operation with an aircraft/engine is specified in the engine FAA TCDS, the aircraft FAA TCDS, and the aircraft POH (Pilot Operating Handbook).

The FAA approved GA engines are both naturally aspirated and turbocharged with ratings from 100 BHP to in excess of 400 BHP. Fuels approved for operation in GA engines are specified in the FAA approved OEM continuous airworthiness data and the associated FAA TCDS (type certificate data sheet which may be accessed at http://rgl.faa.gov). The approved fuel is typically specified in the FAA TCDS as aviation gasoline conforming to ASTM D 910 specification either minimum grade 80/87, 91/96, 91/98, 100LL, or 100/130. FAA certification of each engine model required that adequate detonation (knock) margins be demonstrated by test using a certified fuel of minimum quality while operating at worst case conditions for knock.

4.1. FLEET APPROVED MINIMUM GRADE FUEL

A study was recently commissioned by the FAA Technical Center's Aviation Fuels and Engine Test Facility (AFETF) to quantify the piston powered fleet composition based upon the approved minimum grade fuel as listed in the FAA TCDS for each aircraft.(8) The results of this study which are based upon data contained in the FAA Registry and the FAA TCDS establish a baseline data base for the active piston powered aircraft by make and model along with a listing of the approved minimum grade fuel.

Based upon the results of this study, reference (8), 43.3% of the GA fleet requires a minimum Grade 100LL AVGAS and is therefore dependent upon the leaded aviation grade 100LL gasoline for both performance and knock protection. Industry specialists believe it is this 43.3% of the fleet representing later model aircraft used for business and utility purposes which accounts for the majority of the general aviation flight time. Although there is a large segment of the general aviation fleet (84,429 aircraft representing 44.6% of fleet) rated on minimum grade 80, 87, 90 or 91 AVGAS, this group of aircraft is also approved to operate with the next higher grade 100LL. Engine manufacturer service bulletins specify that engines are approved to operate with the next higher grade AVGAS, but are not approved to operate with a lower grade. Therefore, 166,492 aircraft representing 87.9% of the fleet are eligible for operation with 100LL AVGAS. FAA TCDS data show 0.4% of the aircraft are approved for use with an unleaded min grade 91/96. In the absence of a domestic min Grade 91 production AVGAS and minimal availability of min Grade 80 AVGAS, min Grade 100LL is the predominantly available AVGAS today. A 91/96UL AVGAS is available within Europe.

Table 4.0 [8]
General Aviation Fleet Approved Min Fuel Grade
Based Upon FAA Registry & TCDS

Fuel Grade①	Number of Aircraft	Percent of 189,453 Aircraft
100LL Minimum	82,063	43.3%
80 Minimum	69,402	36.6%
Other Fuel ②	17,508	9.2%
91 Minimum	13,387	7.1%
Unknown	5,306	2.8%
Unleaded 91/96	825	0.4%
87 Minimum	802	0.4%
Jet A	147	0.1%
90 Minimum	13	0.0068%
Total Aircraft	189,453	100%

Notes:
① Minimum fuel grades extracted from FAA TCDS for aircraft.
② Category "other fuel" includes TCDS fuel designations of 65, 70, 73, 108/135, & 115/145.

5. SURVEY 100LL AVGAS TEL CONTENT

Whereas 100LL AVGAS is the predominantly available aviation gasoline today and in consideration of the AVGAS Stakeholder Group's near term strategy to pursue a reduction in lead emissions using a "drop in" replacement reduced lead content 100 min grade AVGAS, the AVGAS Stakeholder Group requested the CRC Unleaded AVGAS Development Group working in conjunction with the FAA Technical Center to explore options and viability for a reduced TEL content 100 min grade AVGAS. In response to the Stakeholder request, dual VLL initiatives were launched by the CRC and FAA including full scale engine testing of manufacturer's reduced TEL content AVGAS in addition to an effort to assess and identify typical TEL content in 100LL AVGAS consumed by the fleet. The following describes the results of the FAA Technical Center's survey to quantity FBO AVGAS TEL levels as dispensed to the fleet.

5.1. OBJECTIVES

ASTM D 910 specifies a maximum content for TEL in 100LL AVGAS but no minimum. With the recognition that there are normal production variances in TEL content of AVGAS as the result of process variables including basic alkylate and refining process, the FAA Technical Center's AFETF commissioned a study to investigate the actual variation of TEL content in 100LL AVGAS. The primary objective of this study was to quantify the normal variances in TEL content as encountered by the fleet at the FBO level with a secondary objective of documenting fleet operating exposure to variances in TEL content. The purpose of this study was to develop a data base that would support and contribute to the industry's study of options for reducing lead emissions. Prior to this study, there was limited to no information available in a summary format which documented normal TEL variances in 100LL AVGAS as delivered to the fleet.

5.2. METHODS

The production and quality control processes for aviation gasoline require the documentation of critical fuel properties by laboratory test at both the refinery level and as delivered by the fuel distributer to the FBO (Fixed Base Operator). Each batch of fuel is accompanied by a certificate of analysis which identifies the conformance of critical properties including TEL content, MON, SC rating, density, vapor pressure, net heat of combustion, and distillation properties in accordance with the applicable ASTM specification. Accordingly, the 100LL AVGAS delivered to the FBO infrastructure is well documented by the certificates of analysis (CofA).

Additional data on analysis of fuel properties is available through the ASTM NEG (National Exchange Group) wherein AVGAS samples are shared among various test laboratories for documentation of critical properties as part of a cross check of repeatability. The NEG data furnished for the purpose of this survey was in the format of average values and did not associate properties with a specific refinery. The FAA Technical Center's field TEL study focused on generating a data base of TEL content using certificates of analysis obtained at random from the FBO infrastructure. The resulting data base also included TEL data provided by one major fuel producer for several years of production. Certificates of analysis for fuel samples collected by the FAA and subjected to analysis by an independent laboratory were also included in the data base. Each data point was "blinded" for the purpose of confidentiality.

In recognition that the OEM engine manufacturers obtain and file certificates of analysis for 100LL AVGAS used in official FAA certification testing, a search was also conducted at the engine manufacturers for documentation of 100LL AVGAS properties used in FAA certification tests. The resulting data points complemented the FBO certificates of analysis. Data from the engine manufacturers was also "blinded" for confidentiality.

SURVEY DATA CAVEAT

Survey data consisting of CofA, NEG data, and engine manufacturer's reports were used without change or prejudice. CofA are accepted by the industry as a certificate of validation. Further investigation or verification of the accuracy of the reported data was determined to be outside the scope of the researcher's authority. It is noted that several data points indicated MON values higher than normal. Although MON is of interest, the primary objective of this survey was to explore and investigate TEL trends in production AVGAS.

5.3. RESULTS

The resulting survey data consisting of certificates of analysis, documentation furnished by the original engine manufacturers, NEG data, and refinery data were compiled and furnished by the FAA Technical Center to an independent consulting firm for review, analysis and compilation in a summary report. That report is included as Appendix A to this report. [(9)] While the presented sample set is small, it was observed that the addition of data (from 55 to 89) had little impact on the max and mean values of TEL. The summary of findings is extracted from Reference (9) and repeated as follows. The reader is referred to Appendix A for a detail accounting of the survey data and associated analysis.

Figure 8.0[(9)]
FAA FBO AVGAS Survey Results

- ✈ Samples = 89 CofA (representing 8 refineries)
- ✈ MON ratings
  - o Max = 108
  - o Mean = 103.7
  - o Min = 101.6
- ✈ Tetraethyl Lead content
  - o Max = 0.56 gPb/L (100% of D 910 limit)
  - o Mean = 0.47 gPb/L (84% of D 910 limit)
  - o Min = 0.34 gPb/L (61% of D 910 limit)

Figure 9.0[(9)]
Engine Manufacturer Certification AVGAS Survey Results

- ✈ Samples = 23 data points
- ✈ MON ratings
  - o Max = 107.6
  - o Mean = 103.8
  - o Min = 101.1
- ✈ Tetraethyl Lead content
  - o Max = 0.60 gPb/L (107% of D 910 limit)
  - o Mean = 0.40 gPb/L (71% of D 910 limit)
  - o Min = 0.08 gPb/L (14% of D 910 limit)*

(*may indicate typographical error in original source report)

Figure 10.0(9)
Segregation of Fuel Samples by % TEL Reduction

- ✈ 39% of the fuel samples described by CofA and industry laboratory reports could meet a 20% reduction in TEL
- ✈ 51% of the fuel samples described by CofA and industry laboratory reports could meet a 15% reduction in TEL
- ✈ 64% of the fuel samples described by CofA and industry laboratory reports could meet a 10% reduction in TEL
- ✈ 44% of the fuels used for FAA certification could meet a 20% reduction in TEL
- ✈ 67% of the fuels used for FAA certification could meet a 15% reduction in TEL

6. GA FLEET 100LL SERVICE EXPERIENCE

Results of the survey of TEL content in production 100LL AVGAS as distributed to the fleet through the general aviation FBO network indicate that the domestic piston powered fleet has been exposed to service experience with TEL content varying from a low of 61% of max allowable TEL to a mean of 84% of max allowable TEL while still meeting MON and other D 910 specification properties. As discussed in Section 3 of this report, the additive TEL is effective as a knock suppressant in AVGAS. As the content of TEL is reduced, there is a corresponding impact on engine knock response. A threshold of TEL reduction is ultimately reached where fuel octane quality is sufficiently degraded to the extent that engine knock margins are degraded. The latter is not the case with the current fleet as indicated by a study of related fleet service experience which indicates a neglible incident rate of knock with no indications of fuel related incidents. The successful service experience with varying levels of TEL speaks highly of the margins originally designed into the general aviation products.

Experience has shown that the effect of knock is usually manifested in burned pistons, eroded piston domes or edges, or burned holes in pistons with a resulting loss in engine power and a noticeable change in engine vibration. With the objective of evaluating fleet service experience based upon the premise that the fleet has been subjected to operation on 100LL AVGAS with TEL content as low as 61% - 84% of max allowable TEL, FAA Service Difficulty Reports (SDR) have been reviewed for indications of detonation incidents as might be indicated by reports of “burned pistons, eroded pistons, burned hole in piston, signs of detonation” with the results summarized as follows.

6.1. FAA SERVICE DIFFICULTY DATA BASE

The FAA maintains a data base for reports of service difficulties for aviation products which may be accessed at http://av-info.faa.gov/sdrx/. A reformatted version of the FAA SDR data base which is restructured to list only general aviation related reports less air carriers, commuters, and military may be accessed at www.landings.com/_landings/pages/search/search_sdr.html where SDR data is retrieved from the FAA ftp server on a weekly basis. The FAA SDR data base does not contain all reports of aviation difficulties but rather only those which are voluntarily submitted to the FAA where each is based upon the submitter's assessment of the service difficulty. However, the FAA SDR data base does provide useful information providing insight into specific service difficulties when viewed in the context that the reported difficulties provide an indication of relative incident rates as compared to other difficulty categories or the aggregate of all reports for a specified aircraft model, engine model, or groups of aircraft models or engine models. The entire FAA SDR data base reflecting all elements of aviation contains 1,500,000 entries 1975 to present, ref http://www.aviationdb.com .

6.2. SDR REPORTS DETONATION INCIDENTS

A search of the FAA SDR data base for the general aviation fleet was performed for reports of detonation incidents by searching for reports of piston difficulties for the following aircraft series which represent the manufacturers of those aircraft powered by high performance high compression ratio engines both naturally aspirated and turbocharged. Rather than searching all small aircraft manufacturers, the search targeted the following representative general aviation aircraft models which account for 154,825 aircraft or 81.7% of the total FAA registry of piston powered aircraft. The search was facilitated by searching under the FAA JASC code "8530"[10] and key word "piston". FAA JASC code 8530 is defined as "For reports of engine cylinders and associated parts…..typical parts are piston, piston pin, exhaust valve, intake valve, valve guide, rocker arm, valve cover, cylinder, pushrod….". Results of the SDR data search are summarized as follows. A copy of the SDR report for each of the 31 "burned piston" listings is on file and available upon request. The SDR reports surveyed covered a time period of 17 years, 1993 to present.

Table 5.0
FAA SDR Reports for Burned Pistons [10]
Representative Manufacturers – General Aviation Fleet

Aircraft Series	FAA Registry 2010 Fleet Size	FAA SDR Reports			
		Code 8530 Cylinder	Code 8530 Piston	Burned Piston	Incident Rate Burned Piston
Beech	17,209	299	15	4	0.023%
Cessna	74,258	1304	54	17	0.023%
Cirrus	3,383	11	0	0	0.000%
Mooney	6,764	45	2	0	0.000%
Piper	46,030	496	15	10	0.022%
Robinson	2,249	23	1	0	0.000%
Enstrom	283	11	0	0	0.000%
Bellanca	2,501	4	0	0	0.000%
Maule	1,005	3	0	0	0.000%
Diamond	1143	21	0	0	0.000%
TOTAL	154,825	2216	87	31	0.020%

It is concluded based upon the review of SDR reports for detonation incidents for the fleet portion indicated that the occurrence of detonation in the fleet is rare with the total number of detonation incidents at 0.02% of the fleet surveyed. None of the SDR reports corresponding to the above 31 reports of "burned pistons" indicated fuel was a factor. For some of the 31 reports, it was not totally certain that detonation was the contributing event; for the majority of the reports the cause of detonation was not identified. Likely causes of detonation incidents include mis-adjusted ignition timing, magneto failures, blocked fuel injector nozzle, and operation at high power with lean mixture. Those reports which indicated structural failure of the piston rather than thermal failure were not included in the 31 reports which contained failure descriptions consistent with "burned pistons, eroded pistons, burned hole in piston, signs of detonation". Piston structural failures typically have unique signatures which are distinctly different from a detonation induced event which results in excessive piston temperature.

The engine models listed in the 31 reports are summarized in Table 6.0 relative to model designation and configuration - naturally aspirated, turbocharged, carbureted, fuel injected, compression ratio and approved min grade fuel. Turbocharged engines represented 48% of the engines identified as possibly having encountered a detonation event. No conclusions are drawn based upon engine models and/or turbocharged versus naturally aspirated. On the contrary, the documented detonation events appear to be evenly distributed across the naturally aspirated and turbocharged models; however, the naturally aspirated fleet represents a larger population than turbocharged models.

Table 6.0 [10]
Engine Models Listed in FAA SDR
Reports of Burned Piston, Detonation

Engine Model	Configuration	Compression Ratio	Min Grade AVGAS
O-235-L2C (4ea)	NA, Carb	8.5	100/100LL
O-320-D2J	NA, Carb	8.5	91/96
O-320-D3G	NA, Carb	8.5	91/96
O-470-R	NA, Carb	7.0	80/87
IO-360-C1C	NA, FI	8.7	100/100LL
IO-360-G	NA, FI	8.5	100/100LL
IO-470-L (2)	NA, FI	8.6	100/100LL
IO-520-CB	NA, FI	8.5	100/100LL
IO-520-D	NA, FI	8.5	100/100LL
IO-520-F	NA, FI	8.5	100/100LL
IO-540-K1J5	NA, FI	8.7	100/100LL
IO-540-S1A5	NA, FI	8.7	100/100LL
GTSIO-520-L	Turbo, FI	7.5	100/100LL
GTSIO-520-M	Turbo, FI	7.5	100/100LL
GTSIO-520-N (2ea)	Turbo, FI	7.5	100/100LL
LTSIO-360-E	Turbo, FI	7.5	100/100LL
TSIO-360-KB	Turbo, FI	7.5	100/100LL

TSIO-520-(Unkn)	Turbo, FI	7.5	100/100LL
TSIO-520-NB (2ea)	Turbo, FI	7.5	100/100LL
TSIO-520-R (2ea)	Turbo, FI	7.5	100/100LL
TSIO-520-VB	Turbo, FI	7.5	100/100LL
TSIO-520-WB	Turbo, FI	7.5	100/100LL
TIO-540-J2BD (2)	Turbo, FI	7.3	100/100LL

Notes:

1) NA = naturally aspirated, Turbo = turbocharged, Carb = carbureted, FI = fuel injected

7. CONCLUSIONS

The purpose of the CRC research documented within this report was not to specify or recommend a specific reduced TEL level for AVGAS, but rather to conduct research and investigations with the objective of generating technical data which would enable and facilitate the industry's decision process for a reduced TEL AVGAS. The results of the tests and investigations documented within this report fulfill this objective. Significant findings and observations are summarized as follows.

7.1. TEST RESULTS ENGINE LEAD RESPONSE

Figures 4.0 and 5.0 provide an indication of the sensitivity of knock limited fuel flow to TEL content for the conventional IO-540-K engine configuration and the test conditions documented. The following observations and conclusions are based upon the 1.5 – 2.0 mL/gal TEL range of interest unless noted otherwise.

- Test results indicates a change of 0.4 mL/gal (20% reduction in TEL) results in a 4.9% impact on knock limited fuel flow
- Alternately a change of 0.5 mL/gal (25% reduction in TEL) results in a 6% impact on knock limited fuel flow.
- A change in TEL content from 2.00 mL/gal to 1.22 mL/gal (39% reduction in TEL) is equivalent to a 9.4% change in knock limited fuel flow. Note that the survey results indicate minimum field FBO fuel TEL content was documented as being 1.22 mL/gal.
- The sensitivity may also be expressed as 0.1 mL/gal is equivalent to 1.2% impact on knock limited fuel flow over the 1.5 – 2.0 mL/gal range of interest.
- Analysis indicates the conventional engine lead response is in agreement with the radial engine lead response of 1.0 -1.2% change in knock limited IMEP per 0.1 mL/gal TEL as discussed in Section 3.1. Although the knock metrics are expressed in different terms, knock limited IMEP for radial engine and knock limited fuel flow for conventional engine, these indices are complementary and indicate the relative change in knock on-set as a function of TEL.

7.2. SURVEY RESULTS FBO 100LL AVGAS

Figures 8.0 through 10.0 present a summary of the findings and observations documented within the Appendix A report. Significant findings and observations are summarized as follows.

- Survey results of TEL content in FBO AVGAS (89 data points) indicate mean (average) TEL content in AVGAS is 84% of max TEL allowed by ASTM D 910 based upon the data examined.
- Survey results of TEL content in FBO AVGAS indicate the fleet has service experience with TEL content as low as 61% of the max TEL allowed by ASTM D 910 for fuels of 101.6 MON or higher.
- Mean MON for FBO AVGAS was observed to be 103.7 MON with minimum MON documented at 101.6 MON. The maximum MON for AVGAS as indicated by the CofA data was 108 MON.
- Examination of engine manufacturer certification data (23 data points) indicates 100LL AVGAS used for official FAA engine certification testing had TEL content varying from minimum of 14% of max allowable to a mean of 71% of max allowed. Associated minimum MON was 101.1 with mean MON being 103.8. The maximum MON for the 15 certification data samples was 107.6 MON. (Note that 14% may indicate a typographical error in the original source data.).
- 39% of the fuel samples described by CofA and industry laboratory reports could meet a 20% reduction in TEL.
- 51% of the fuel samples described by CofA and industry laboratory reports could meet a 15% reduction in TEL.
- 64% of the fuel samples described by CofA and industry laboratory reports could meet a 10% reduction in TEL.
- 44% of the fuels used for FAA certification could meet a 20% reduction in TEL.
- 67% of the fuels used for FAA certification could meet a 15% reduction in TEL.

7.3. FLEET SERVICE EXPERIENCE

With the objective of evaluating fleet service experience based upon the premise that the fleet has been subjected to operation on 100LL AVGAS with TEL content as low as 61% - 84% of maximum allowable TEL as documented by the Appendix A survey results, FAA Service Difficulty Reports (SDR) were reviewed for indications of detonation incidents as might be indicated by reports of “burned pistons, eroded pistons, burned hole in piston, signs of detonation”. Significant findings and observations are summarized as follows.

- It is concluded based upon the review of FAA SDR reports for detonation incidents that the occurrence of detonation in the fleet is rare with the total number of detonation incidents at 0.02% of the fleet surveyed. None of the SDR reports indicated fuel was a factor. Qualifications regarding SDR reports are discussed in Section 6.1.
- Analysis of survey results and engine lead response data indicates the fleet service experience with TEL content at 61% - 84% of max allowable TEL is equivalent to a 9.4% -3.8% variance in engine knock margin respectively from the baseline 2.0 mL/gal TEL level. The latter speaks highly of the margins originally designed into the general aviation powerplants in consideration that service experience indicates knock is a rare occurrence within the fleet.

8. RECOMMENDATIONS

The test results and findings documented within this report indicate the general aviation fleet has successful service experience with a TEL content of 1.22 – 2.00 mL TEL/gal (100LL AVGAS) having a MON of 101.6 or greater. Technical considerations for specifying a maximum lead content less than 2.00 mL/gal should obviously be guided by the fleet service experience documented within this report.

Although a reduced TEL content within the range of experience documented within this report is technically feasible, there are other non-technical considerations which must be addressed by the aviation industry which are outside the jurisdiction of CRC research.

In the advent of implementation of a reduced TEL AVGAS, it is recommended that the FAA and the general aviation industry give consideration to ensuring aircraft owners, pilots, and maintenance personnel are provided with the necessary informational training.

9. REFERENCES

(1) The History, Specification, Production, Use and Evaluation of Unleaded Aviation Gasoline, Report by the D 910 Task Force of D02.J.02.

(2) Letter, AVGAS Stakeholder Group to EPA, dated June 10, 2010.

(3) Presentation, GA AVGAS Coalition Briefing, EAA AirVenture 2010, July 27, 2010.

(4) ASTM D 910, “Standard Specification for Aviation Gasolines”.

(5) Aviation Fuels and Their Effects on Engine Performance, NAVAER 06-5-501, USAF T.O. No. 06-5-4, dated 1951 by Ethyl Corporation

(6) NACA Report No. E4I28, “Experimental Studies of the Knock-Limited Blending Characteristics of Aviation Fuels”, N. D. Sanders, R V. Hensley, R Breitwieser, dated October 1944

(7) FAA Technical Center Test Results, Email dated July 25, 2010, D Atwood to R Wilkinson

(8) Herbert W. Schlickenmaier, Crown Consulting Inc., “Aviation Fuels Research Fleet Database Report”, dated October 13, 2010 (prepared by Crown Consulting Inc. under Purchase Order 7200006107 from Lockheed Martin NISC II Bridge Contract DTFAWA-08-C-00009 with the Federal Aviation Administration)

(9) Melanie Thom, Baere Aerospace Consulting Inc., “Review of Certificates of Analysis and Test Data of Aviation Gasoline for Current Ranges of Lead Additive”, dated Sept. 9, 2010 (prepared for Crown Consulting Inc. under Purchase Order 7200006107 from Lockheed Martin NISC II Bridge Contract DTFAWA-08-C-00009 with the Federal Aviation Administration)

(10) FAA Flight Standards Service, Aviation Data Systems Branch, AFS-620, “Federal Aviation Administration Joint Aircraft System/Component Code Table and Definitions”, October 27, 2008

(11) CRC Report AV-7-07, “Research Results Unleaded High Octane Aviation Gasoline”, June 17, 2010

(12) Alisdair Q. Clark BSc PhD, “Aviation Gasoline History and Future”, IASH 2007, October 2007.

10. ACKNOWLEDGEMENTS

The information contained within this report reflects the participation and commitment of industry specialists representing a broad segment of general aviation including fuel producers, test laboratories, FBO, fuel distributors, aviation engine and aircraft manufacturers, aviation trade organizations, fuel trade organizations, specialized consulting firms, the FAA, and the CRC executive office. The successful completion of the survey of AVGAS properties followed by the compilation and analysis of survey data as complemented by engine testing to investigate engine lead response were made possible in no small part by the actions of those committed to the future of general aviation.

The leadership and guidance provided by the Aviation Stakeholders was instrumental in establishing goals and objectives. Typical of previous CRC aviation gasoline research projects, the participation and contribution of the FAA Technical Center's Aviation Fuels and Engine Test Facility was crucial to the outcome. Most importantly, it was the foresight of the FAA AFETF which launched the project to survey FBO AVGAS with the goal of better understanding the variance of TEL in commercial AVGAS.

Lastly, the author would like to express his humble appreciation to the CRC Unleaded AVGAS Development Group for the opportunity to compile this report on their behalf.

- END OF TEXT –

APPENDIX A

"REVIEW OF CERTIFICATES OF ANALYSIS AND TEST DATA OF AVIATION GASOLINE FOR CURRENT RANGES OF LEAD ADDITIVE"

VER. 6.0 DATED SEPTEMBER 9, 2010

Review of Certificates of Analysis and Test Data of Aviation Gasoline For Current Ranges of Lead Additive

Assessing the Viability of Lowering Lead Levels in Current Aviation Gasoline Production

In an attempt to demonstrate a commitment to the global community by the aviation gasoline user community, it is desirous to reduce the amount of lead added to current aviation gasoline. This endeavor was to evaluate on a very small sample set the current lead additive levels in fuels currently meeting the ASTM D-910 specification to assess the industry's current ability to produce lower lead containing fuels. This was done by reviewing the Certificates of Analysis procured for contemporary loads of aviation fuels from a variety of FBO's, and test labs, as well as fuels used by engine manufacturers for engine certification. The result was a sample set of 89 individual data points, which were reviewed for the lead content all converted to grams of lead per liter of fuel. The samples were also segregated by regions using time zones of the manufacturer location, and by refinery (blinded for this report) in an attempt to identify, if any, relationships of lead usage by region or by refiner. This report used the data as provided by the manufacturers whose sole responsibility it is to the correctness of the data. No assessment of the MON "cushion" or evaluation of formulation should be made from this data.

Prepared by: Melanie Thom

9/9/2010

Report Prepared for Crown Consulting

REVIEW OF CERTIFICATES OF ANALYSIS AND TEST DATA OF AVIATION GASOLINE FOR CURRENT RANGES OF LEAD ADDITIVE

Assessing the Viability of Lowering Lead Levels in Current Aviation Gasoline Production

NOTE: Survey data consisting of CoA, NEG data and engine manufacturer's reports was used without change or prejudice. CoA's are accepted by the industry as a certificate of validation. Further investigation or verification of the accuracy of the reported data was determined to be outside the scope of the researcher's authority. It is noted that several data points indicated MON values higher than normal. Although MON is of interest, the primary objective of this survey was to explore and investigate TEL trends in production AvGas.

As such no conclusions regarding the relationship between formulas, MON cushion or how the lead reduction will affect the MON values can be made. This analysis should *only* be used to evaluate the existence of fuels currently meeting ASTM D910 with less than maximum allowable lead content. Furthermore, the production of VLL 100 requires more than just the reduction in lead. The data in this report is only demonstration of the *ability* of refiners to produce a lower lead fuel, **not** an analysis of *how* to produce fuel with lower lead. Significant research and development will be required by refiners to develop formulations that still meet all the specification requirements.

Summary

1. The sample set, excluding the ULL study included 89 individual data points. While this is a small sample set, analysis of this data suggests that it is representative of the East Coast and Midwest. There are no obvious indications that it is not representative of Central and West Coasts.

2. An additional set of Certificates for fuel used during engine certifications was also supplied and reviewed. This data set included 23 individual entries for which 21 had a motor octane value entry and 9 had a lead content. Of the 23 samples, 6 were blends prepared from 100LL and iso-octane and were not included in the analysis. This data was analyzed separate from the field sample entries.

3. After reviewing the data, it was determined that approximately 39% of the fuel described by the Certificates of Analysis (COA) and industry laboratory reports could meet a 20% reduction in the TEL additive, 51% could meet a 15% reduction in TEL, and 64% could meet a 10% reduction in TEL as indicated by current production lots.

    - Of the nine certification fuels with lead contents indicated, 44% could meet the 20% reduction and 67% could meet the 15% reduction. This is in line with the fielded data.

4. Sixteen (16%) of the data was from the National Exchange Group (NEG) database and all location and refinery information was previously purged for these samples.

5. When separated by refineries, 25% of the fuel in the sample set was provided by a single refinery, H. Another 22.4% was provided by refinery C. When the fuels from the individual refineries were analyzed, it was determined that refinery H only produced 5% that contained less than 20% TEL additive (1 of 19 samples). At a reduction of 15% and 10%, only 11% of the production would be in spec (same 2 fuels of the 19). This is far below the group percentages and indicates that this refinery would likely be unable to meet a lead reduction with current production.

6. A review of the data by region and by refinery showed no relationship with the amounts of lead used with the exception of refinery H.

7. While there was limited aromatic information available, there did not appear to be any relationship between the amount of lead used and the amount of aromatics used. Said another way, there did not appear to be high lead required with low aromatics or vice versa. This is likely due to the influence of the third component, the base alkylate for which there is no information.

8. The mean MON value was 103.7. The maximum was 108 and the minimum, excluding a sample set made for the ULL study, was 101.6.

    - Of the 15 certification fuel samples, the mean MON value was 103.8. The maximum value was 107.6 and the minimum was101.1.

    - A question was raised that 108 as an MON seemed unlikely. With this data point removed, the mean was still 103.7 and the new maximum was 107.6.

9. The mean elemental lead content was 0.47g/L and the median was 0.48g/L. The maximum was 0.56g/L and the minimum, excluding the ULL study set was 0.34 g/L.

    - Of the 15 certification samples, excluding the blended test samples, the mean elemental lead content was 0.40g/L and the median was 0.43. The maximum lead content was 0.60 g/L and the minimum was 0.08g/L.

10. The mean elemental lead content of all analyzed samples, excluding blend samples, was 0.46g/L. This value is 82% of the maximum lead level permitted (0.46 / 0.56).

11. Eighty-seven percent (87%) of the samples reviewed had a reported MON of greater than 102, sixty percent had an MON greater than 103 and thirty-two percent were greater than 104. Only five percent were higher than 105.

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Discussion

Background

In 2010, the EPA issued an advanced notice of proposed rulemaking and requested input on data gaps. As part of the Industry Stakeholders FAST plan to respond to the EPA, the possibility of reducing the amount of lead used in current, compliant fuel formulations was considered as a near-term means of responding. In the short time available, several options for evaluating this option were proposed; 1) having the refiners report on their current ability to reduce their lead additive levels and meet specification, 2) having refiners blend very low lead (VLL) fuel meeting specification and have it tested and 3) review current Certificates of Analysis available in the aviation community and assess the actual lead content of current compliant fuels.

The refiners seemed uncomfortable providing an assessment of their formulas and their current lead additive levels. Several of the refiners did agree to blend VLL formulas but there was discourse over time regarding whether the refiners should take current formulas and just add less lead and see what resulted; or whether they should adjust the rest of the formula to maintain all of the specified properties. The activity was further complicated by the length of time necessary to actually blend the fuel and then test it.

The third activity was a review of the CoA's for currently supplied fuel. The hypothesis was that this was fuel that was currently produced. If it had lower than maximum lead, it indicated the *ability* to produce fuel with lower than maximum lead. This collection was accomplished by representatives from the FAA Technical Center requesting and collecting CoA's from a random selection of Fixed Based Operations (FBO's). In some cases, fuel samples were collected from the FBO and specifically analyzed by an independent laboratory. In addition to the data collected from FBO fuels, the laboratory analyses from the certification fuels used by the engine manufacturers, and data from the NEG analyses were collected. This data was compiled and then analyzed and is the topic of this report.

Sample Handling

The certificates of analysis were collected as copies from the FBO's where fuel was purchased. The FBO's were selected randomly. The data from the certificates were entered into a spreadsheet. For those fuels collected from the FBO's, the laboratory data sheets were used as the source of the data. The data was entered as provided, no entries being made where data was not provided. The only exception was for the values of MON and lead content as indicated below. Each sample also had its refinery identity blinded such that the data could be sorted based on the refinery but so the refiners' identification was not included in the data set.

Region Identifier

Each refinery listed was given a regional I.D. by using the U.S. time zones based on the location of the refinery. In some cases the location of the refinery was overtly provided. In other cases, it was inferred based on the primary location of a company's refinery. For example, one company had two locations at which they produced aviation gasoline, both in the same time zone. Thus any sample from this company could reasonably be placed in a time zone. Each location was given a number based on the zones as shown in Figure 1. The small numbers of global aviation gasoline samples were just coded as "global".

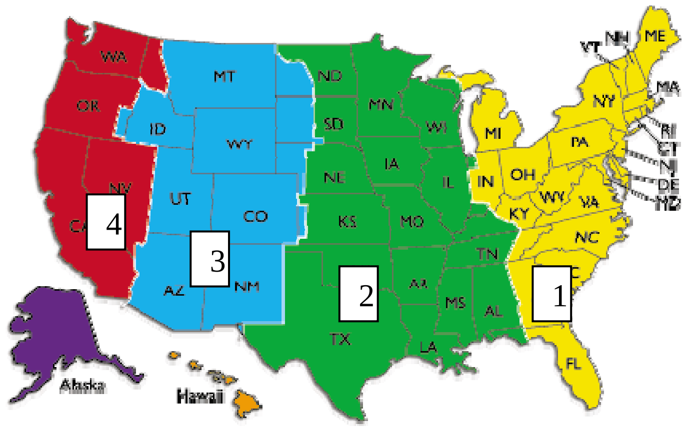

Figure 1 – U.S. Time Zones

MON Values from Aviation Lean Ratings

Some of the CoA's provided the octane performance as aviation lean ratings. These were converted to motor octane numbers (MON) using Table 9 found in ASTM D-2700-09, and reproduced in
Figure 2. The aviation lean rating was found on the table and the equivalent MON read off of the axes. Where necessary, the value was interpolated. An example is shown in
Figure 2 for a lean rating of 112.28 being converted to a MON of 104.2. Note that a MON of 100 is equivalent to a performance number of 101.7. A performance number of 100 results in a MON value of 99.8.

TABLE 9 Conversion of Motor O.N. to Aviation Method Rating[A,B,C]

Motor Octane Number	0.0	0.2	0.4	0.6	0.8
75	73.59	73.81	74.04	74.27	74.49
76	74.72	74.95	75.17	75.40	75.63
77	75.85	76.08	76.30	76.53	76.75
78	76.98	77.20	77.43	77.65	77.88
79	78.10	78.33	78.55	78.77	79.00
80	79.22	79.44	79.67	79.89	80.11
81	80.33	80.55	80.78	81.00	81.22
82	81.44	81.66	81.88	82.10	82.32
83	82.55	82.77	82.99	83.21	83.43
84	83.65	83.86	84.08	84.30	84.52
85	84.74	84.96	85.18	85.40	85.61
86	85.83	86.05	86.27	86.48	86.70
87	86.92	87.13	87.35	87.57	87.78
88	88.00	88.22	88.43	88.65	88.86
89	89.08	89.29	89.51	89.72	89.94
90	90.15	90.37	90.58	90.79	91.01
91	91.22	91.43	91.65	91.86	92.07
92	92.29	92.50	92.71	92.92	93.13
93	93.35	93.56	93.77	93.98	94.19
94	94.40	94.61	94.82	95.04	95.25
95	95.46	95.67	95.88	96.09	96.29
96	96.50	96.71	96.92	97.13	97.34
97	97.55	97.76	97.96	98.17	98.38
98	98.57	98.74	98.91	99.08	99.25
99	99.43	99.60	99.77	99.95	100.54
100	101.07	101.60	102.14	102.67	103.21
101	103.74	104.27	104.81	105.34	105.88
102	106.41	106.94	107.48	108.01	108.55
103	109.08	109.61	110.15	110.68	111.22
104	111.75	112.28	112.82	113.35	113.89
105	114.42	114.95	115.49	116.02	116.56
106	117.09	117.62	118.16	118.69	119.23
107	119.76	120.29	120.83	121.36	121.90
108	122.43	122.96	123.50	124.03	124.57
109	125.10	125.63	126.17	126.70	127.24
110	127.77	128.30	128.84	129.37	129.91

[A] This table converts Motor octane numbers to Aviation method ratings equivalent to those of now-discontinued Method D 614, Test for Knock Characteristics of Aviation Fuels by the Aviation Method.

Figure 2 – Table 9 from ASTM D-2700

Lead Content

For the purpose of analysis, all of the provided lead contents were converted to a uniform unit of grams of lead per liter (gPb/L). For lead contents provided as milliliters of TEL, the conversion factor of 1mL TEL = 1.0589 g Pb was used. For those provided as lead in gallons, these values were converted to liters, 1 US gallon = 3.785 liters.

Other Data Sources

In addition to the data from CoA's, data from the NEG data was included as a separate entry. These data are averaged values from a set of samples used to confirm inter-laboratory repeatability of specification testing. These data were provided as average values with the refinery information purged prior to receipt.

Data were also provided from engine manufacturers from their engine certification trials. These data included both generic fuel procured for the test and fuels blended specifically as test fuels. Only the actual aviation gasoline data were used for the analysis.

Development of Max Lead for Reduction Levels

In order to assess the maximum reduction level that might be achieved, the maximum lead content for each of three reduction levels was computed. The reductions considered were 20%, 15% and 10% reduction from current maximum lead content permitted by specification. This correlated to maximum elemental lead levels of 0.45 gPb/L, 0.48 and 0.51. For the analysis, the number of individual fuels that would have met the maximum levels was counted and reported. It was assumed that a) because these were fuels meeting specification, it was an indication that individual refiners could currently produce fuels with the indicated levels that met specification, and b) that the small sample set would replicate the larger population within an acceptable level.

Analysis

For the following evaluations, all of the charts are located in the Annex located at the end of the document. For charts indicating the lead reduction levels, the 20% reduction is indicated by a purple line and the 15% reduction indicated by an orange line.

Caveat on MON data

With respect to the MON values reported in this analysis, the analyst has only the values as provided by the Certificates of Analysis from which to perform the analysis. The sole purpose of this analysis was to determine whether there are currently fuels in the distribution network meeting minimum D910 specification with a lower than maximum permitted lead content. It is not intended to be an analysis of the "cushion" in MON.

The values used in this analysis, including MON are as provided. For MON the values are either directly reported as MON or have been converted from values provided as Aviation Number Ratings (lean ratings) to MON. The analyst has in good faith assumed the refiner providing the data via a CoA has provided correct data. The analyst is not in a position to second guess "correct" reporting from "incorrect" reporting. With respect to MON/performance number, if 108 is assumed to be wrong, what about 106? Or 105? Or 102? If part of the data is assumed to be incorrect then all of the data should be assumed to be incorrect.

Furthermore, because the values of MON and rating numbers converge around 100 and 100 MON is the baseline considered for compliance to specification, the conclusions in this report are not significantly impacted by using "incorrect" MON data around or above 100. The extent of the exceedance of MON to specification minimum is neither the purpose of this effort nor has any impact on the analysis towards the actual purpose, a survey of how much lead is being used in currently delivered 100LL. Reporting the MON serves only to confirm the fuels did meet specification independent of the amount of lead additive used and the MON data serves no other purpose in this analysis.

Therefore, while discussion may be warranted within the aviation gasoline producing industry regarding the accuracy of the CoA sheets, the actual status of the MON values has no substantive impact on the conclusions drawn for this report.

Readers are discouraged from using the results of this analysis to make any assessments regarding the formulation of aviation gasoline, the relationships between lead and MON, or the cushion in MON for production.

Combined Data

The first exercise after completion of the datasets, was to evaluate whether there was any observable correlation between the supercharge rating, the motor octane number and the lead content of the fuel, Figure 3 – Supercharge rating and Motor Octane Number vs. Lead content, Including Engine Cert. Figure 3 – Supercharge rating and Motor Octane Number vs. Lead content, Including Engine Cert contains all of the data from the CoA's, the NEG data and the engine certification data excluding blended experimental samples.

This analysis was done to see if there was any indication of a correlation between observable variations in the supercharge rating and the motor octane number with changes in lead content. No correlations were observed. All of the MON values were reasonably consistent while the lead values showed observable variations.

In addition to the data, lines indicating the 20% reduction (purple) and the 15% reduction (orange) in the maximum TEL level are included on the graph. This visually indicates the observation that was mathematically calculated that between 33 and 40% of the samples would meet the 20% reduction in maximum TEL content. About 50% of the samples would meet 15% reduction in maximum TEL and 64% would meet 10% reduction in maximum TEL. These values remained relatively constant as additional data was included in the dataset. This is **not** a weighted average as no data on the size of the individual batches of fuel is available.

Because it is known that refiners have basically three major building blocks with which to achieve the desired MON and supercharge rating; i.e. the alkylate, the lead, and the aromatic content, it was desirous to evaluate any relationships between the building blocks. No information was available for the alkylate type or quality, so the relationship between aromatic content and lead content was evaluated. This is shown graphically in Figure 4. Unfortunately, few of the datasheets included a value for aromatic content. For those samples that did, there appeared to be no correlation between the aromatic content and the amount of lead used. In some cases the lead and aromatic were relatively higher together as compared to other samples and in other cases samples with high lead had low aromatics. This was most likely due to differences in the type of alkylate used. No correlation could be drawn from these data.

By Region

In an attempt to determine if there were any trends based on the region of the country at which the fuel was produced, the data were separated by regions based on time zones and then sorted based on these regions. The data were again graphed to evaluate lead content versus aromatic content by region, excluding the engine certification data. Because of the method for procuring the data, the majority of the samples that could have a region attributed to them were from region one and two.

An attempt to identify whether aromatics were used more prevalently in a specific region was also made. The data was graphed comparing aromatic content to lead content by region and is shown in Figure 5. Again the analysis was hampered by a lack of aromatic content data. Those samples having aromatic content were primarily in data that could not be attributed to a region. The three global samples did show higher aromatic content, but these were fuel samples blended specifically to be ULL samples.

The MON vs. Lead was graphed and is shown in Figure 6. In general there was just as much variability in both the MON and the lead content in regions one, and two. Regions three and four had similar sample values, however with only two data points no conclusion can be reasonably drawn. The data not attributed to a specific region had similar variability in the data. The samples attributed to non-U.S. manufacturers "global" did have nearly exactly 100 MON values but this was due to being prepared specifically for an ULL test.

Again, no trends in the data by region for either the MON vs. Lead or the Aromatics vs. Lead were observed with one possible exception. There did appear to be slightly higher lead used in region two. This however is likely explained by a review of the data by refinery presented in the next section.

By Refinery

There is a concern that a decision to reduce the maximum lead content may result in single refineries being unable or unwilling to continue to produce aviation gasoline. Even if 40% of the refineries sampled are capable of producing spec fuel with lower lead, there is a concern that it is possible that one of the 60% that would not continue to produce fuel could account for the majority of the aviation gasoline produced. Unfortunately it is beyond the scope of the data and this report to comment on that risk. It was possible, however, to evaluate the currently produced fuel by the refiner of record on the CoA. This gives no information on the refiner's abilities to produce fuel of a lower lead content over time but it does give information on the existence of fuel produced by a refiner with lower lead contents at individual points in time. There is also no data available on the sizes of the individual batches meaning no assessment of the impact of losing one refinery would have on the overall fuel production levels.

A review of the aromatic content by refiner shown in Figure 7 again showed too little aromatic data to be of value drawing conclusions. However, a review of the MON vs. Lead data showed graphically in Figure 8 indicates there is a strong correlation in lead content for one of the blinded refineries. The refinery indicated by "H" showed the routine use of nearly maximum TEL. In only one instance was less than 0.45gPb/L used and that instance correlated to a lower MON content at the same time. For the dataset reviewed, this refinery accounted for nearly one quarter of the fuel samples considered. It is not known if this relationship is comparable to the industry position for the refinery.

Two of the refineries accounted for just under half of the samples reviewed. One was refinery "H" already discussed. The second was refinery "C" which could meet the 20% reduction 47% of the time, and a 15% reduction about 53% of the time. Further analysis of the use of lead by refinery indicated that two of the refineries with two and four samples respectively could meet the

0.45gPb/L limit with all their samples. These two refineries only accounted for 8% of the samples reviewed and accounted for only six samples. Refinery D with four samples could meet the 15% reduction with all the provided samples. The breakdown of the remaining refineries is shown below in Table 1.

Refinery	Number Samples	Number at 20% reduction	Number at 15% reduction	Number at 10% reduction	% with 20% TEL	% with 15% TEL	% with 10% TEL	Percent of Sample Set
C	17	8	9	10	47%	53%	59%	22.4%
D	5	1	3	5	20%	60%	100%	6.6%
H	19	1	2	2	5%	11%	11%	25.0%
L	2	2			100%	100%	100%	2.6%
M	4	3			75%	100%	100%	5.3%
P	13	3	4	7	23%	31%	54%	17.1%
S	4	4			100%	100%	100%	5.3%
X	9	2	3	6	22%	33%	67%	11.8%

Table 1 – Refinery versus ability to produce lower lead, in spec aviation gasoline

From Engine Certification Fuels

In addition to reviewing the fuels as an agglomeration, the fuels were also reviewed specific to the dataset provided on the fuels used for engine certifications. It was noted that not all of this data included any lead content data; however all of the data, including the blended test fuels provided MON values or Aviation Lean Rating values that were converted to MON. Of the 15 samples provided, 9 of them included a lead content. This data is provided graphically in Figure 9.

The maximum elemental lead content indicated for the engine certification fuels was 0.60g/L, which is out of specification high. The minimum value indicated was 0.08g/L. This may have been a typographical error, as it was reported to be 0.29gPb/**gal**, which would have been more in line with other data as 0.29gPb/**L**. As entered the mean lead content was 0.40gPb/L, which was slightly lower than the general data.

This dataset, like the industry dataset indicated a similar breakdown of approximately 40% being able to meet the 20% reduction, 67% meeting the 15% reduction and 67% meeting the 10% reduction.

Conclusions

Based on the review of the provided data five basic conclusions can be drawn:

1. Based on an agglomeration of the sample data, about 1/3 of the samples currently produced are below the maximum lead content at a 20% reduction over current specification lead levels. At a 15% reduction, approximately ½ would meet spec.

2. The primary supplier of fuel representing 24% of the dataset could not meet a 20% reduction of the maximum lead level. This supplier met the maximum lead level at a 15% reduction in 11% of the samples.

3. There does not appear to be a relationship between regions and lead content excluding the impact of the single refinery on the region data.

4. No obvious relationship can be drawn based on the lead and aromatics data due to the lack of lead data and no information on alkylates. There were instances of high lead with high aromatics and low lead with high aromatics.

    a. Similarly no relationship was found between the lead level and the motor octane number or the supercharge rating.

5. Of the samples reviewed over 87% had motor octane values higher than 102 and 60% were over 103. Only 5% were higher than 105.

Annex – Graphical Representations of the Data

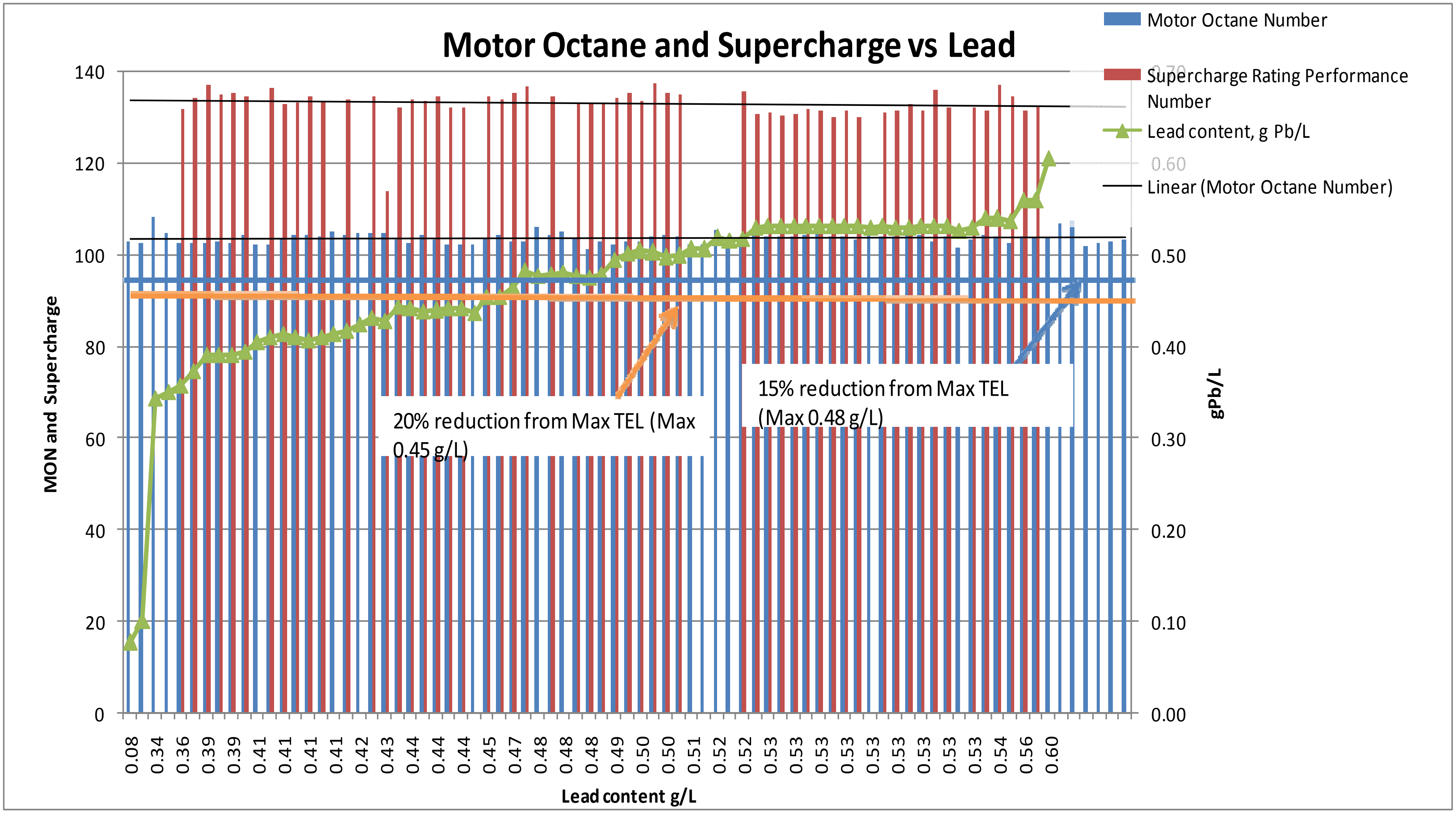

Figure 3 – Supercharge rating and Motor Octane Number vs. Lead content, Including Engine Cert

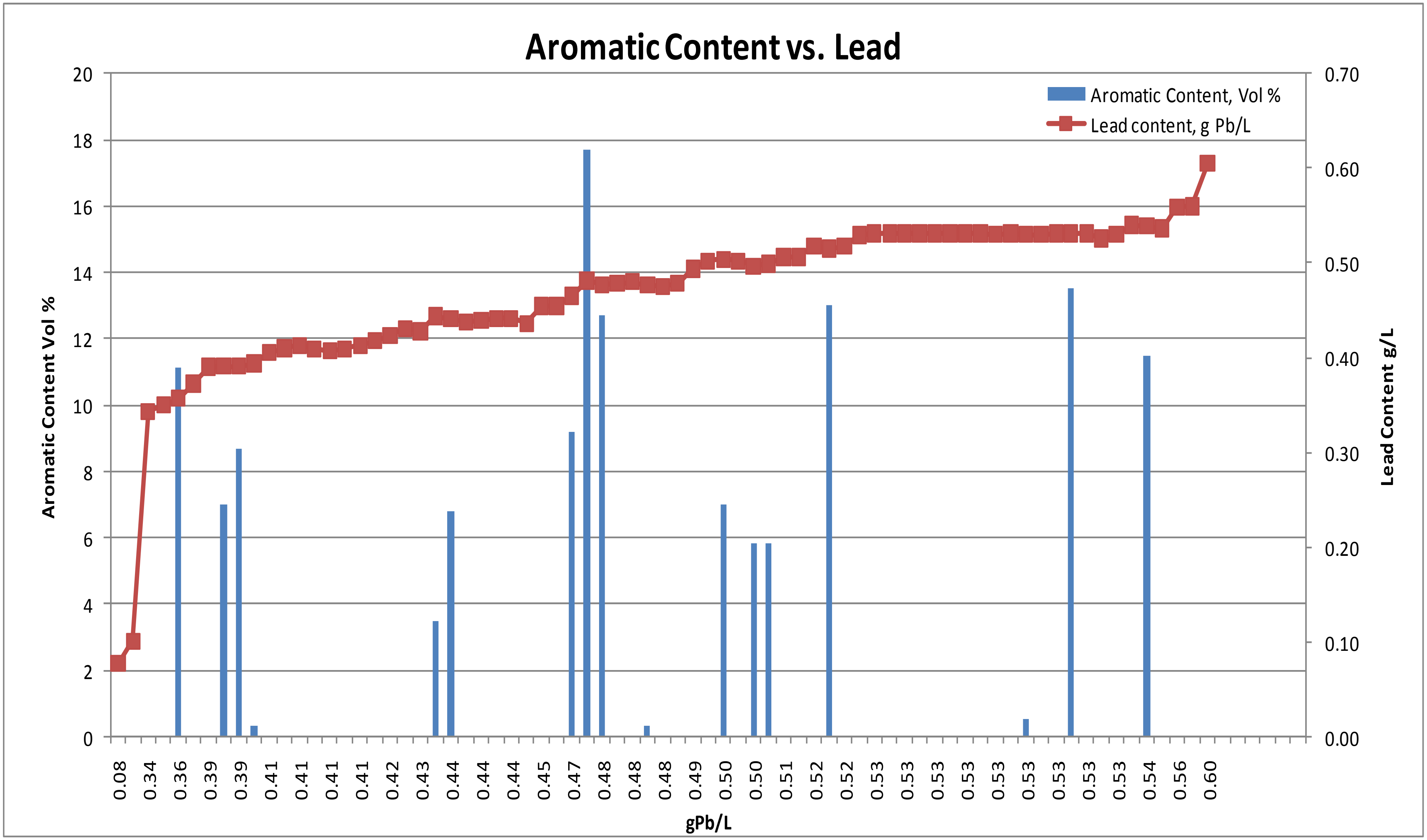

Figure 4 – Lead Content vs. Aromatic Content, Including Engine Cert

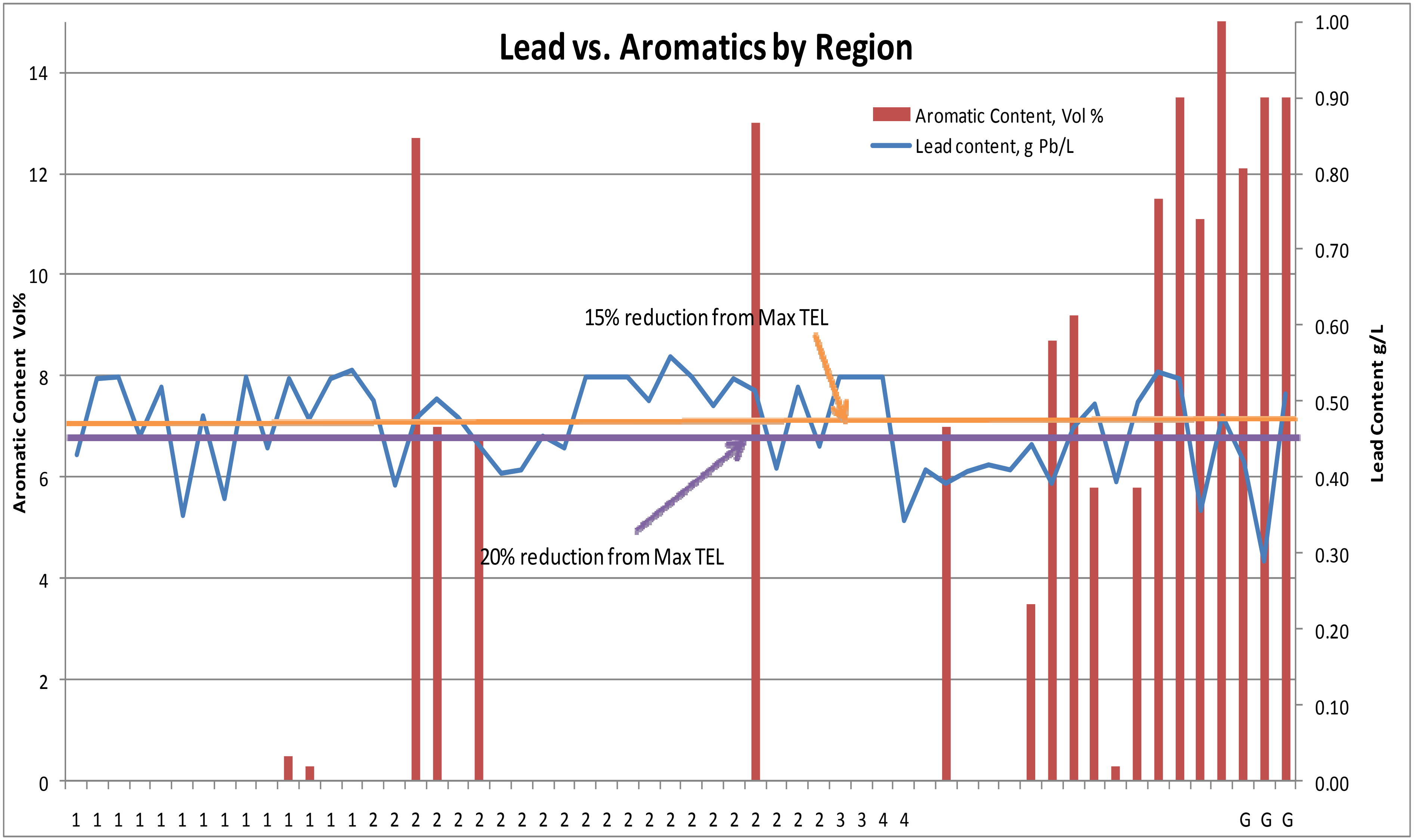

Figure 5 – Lead Content vs. Aromatic Content by Region for CoA's, Excluding Engine Cert Fuels

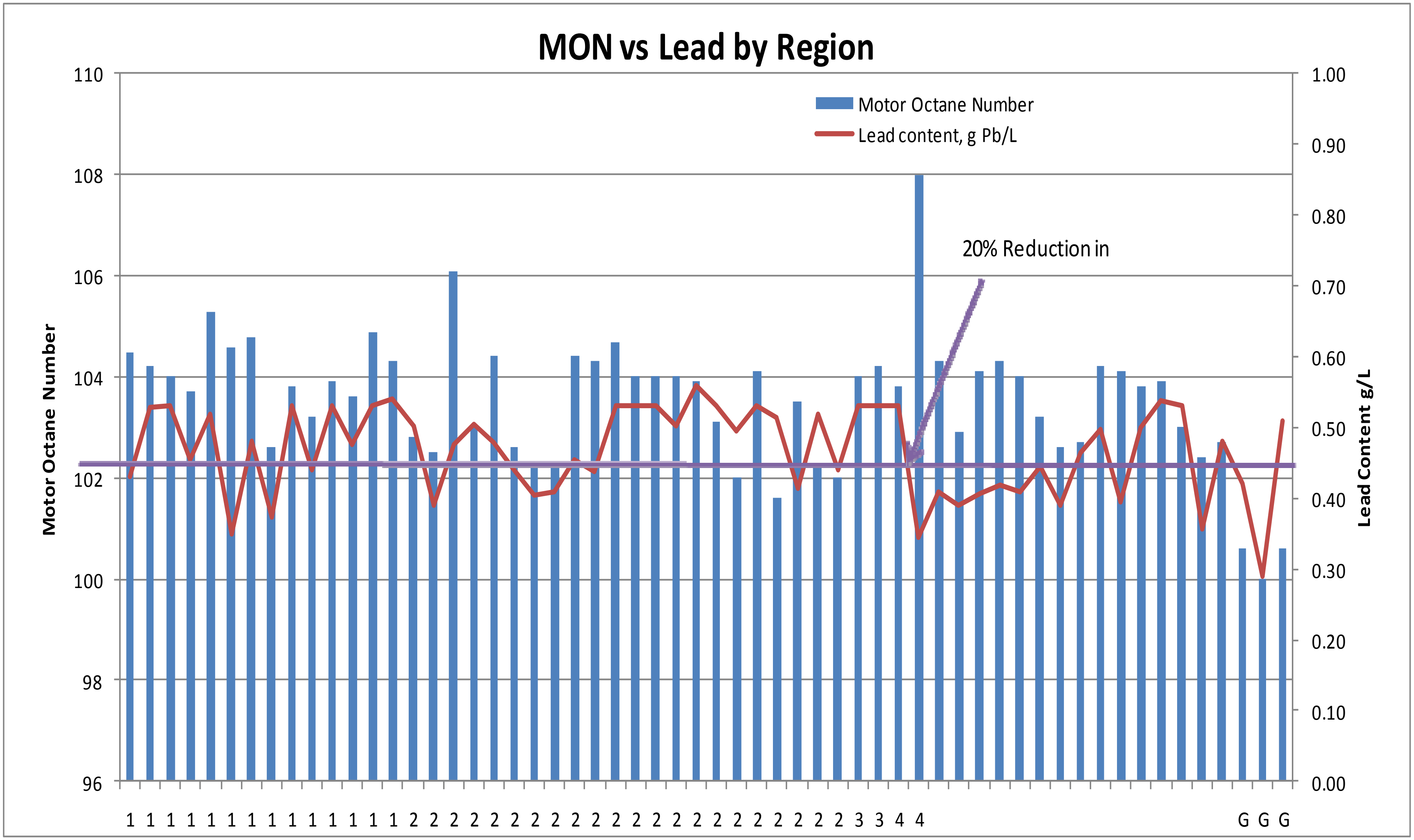

Figure 6 – Motor Octane Number vs. Lead Content by Region for CoA's, Excluding Engine Cert Fuels

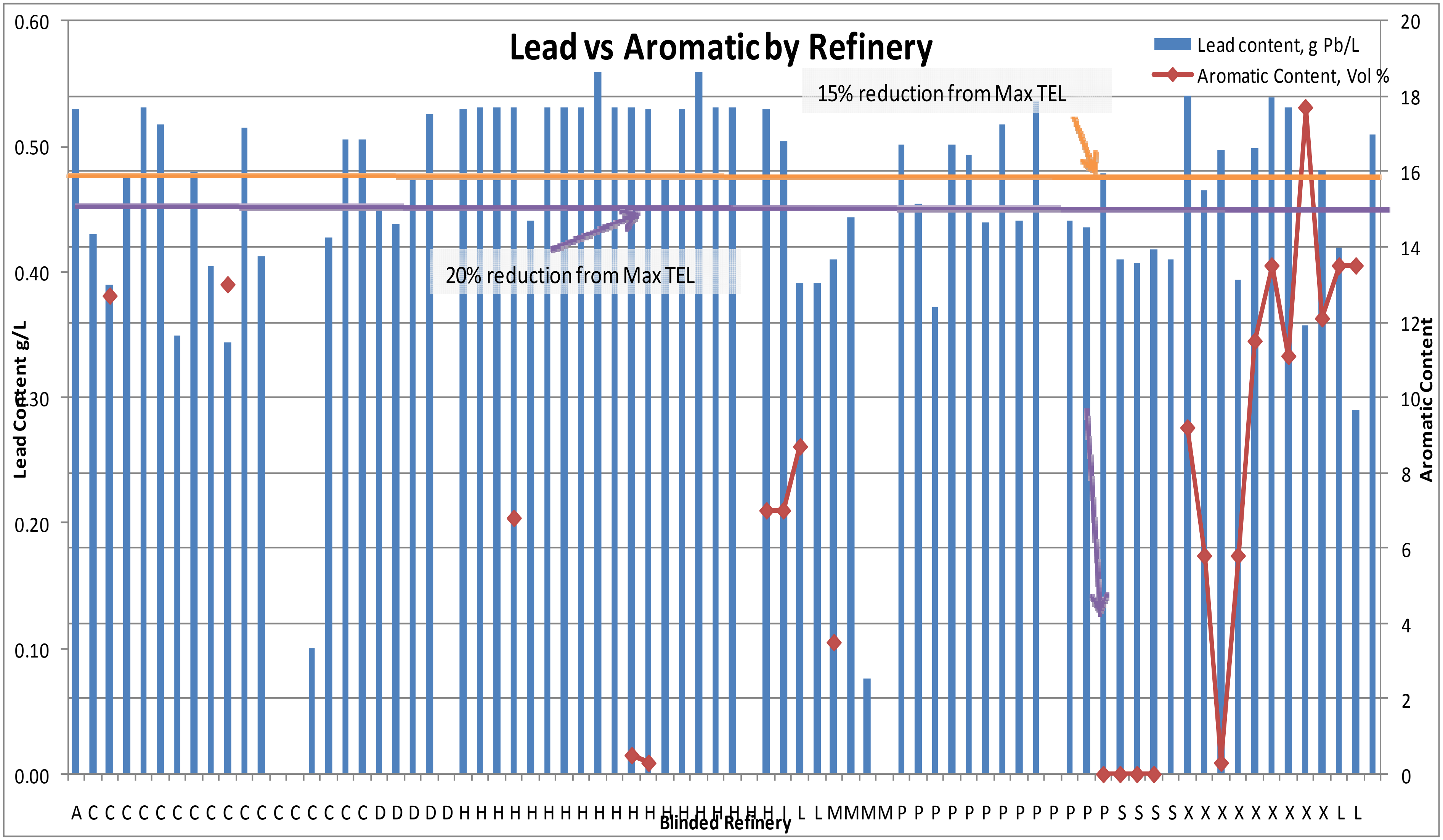

Figure 7 – Lead Content vs. Aromatic Content by Blinded Refinery, Including Engine Cert Data

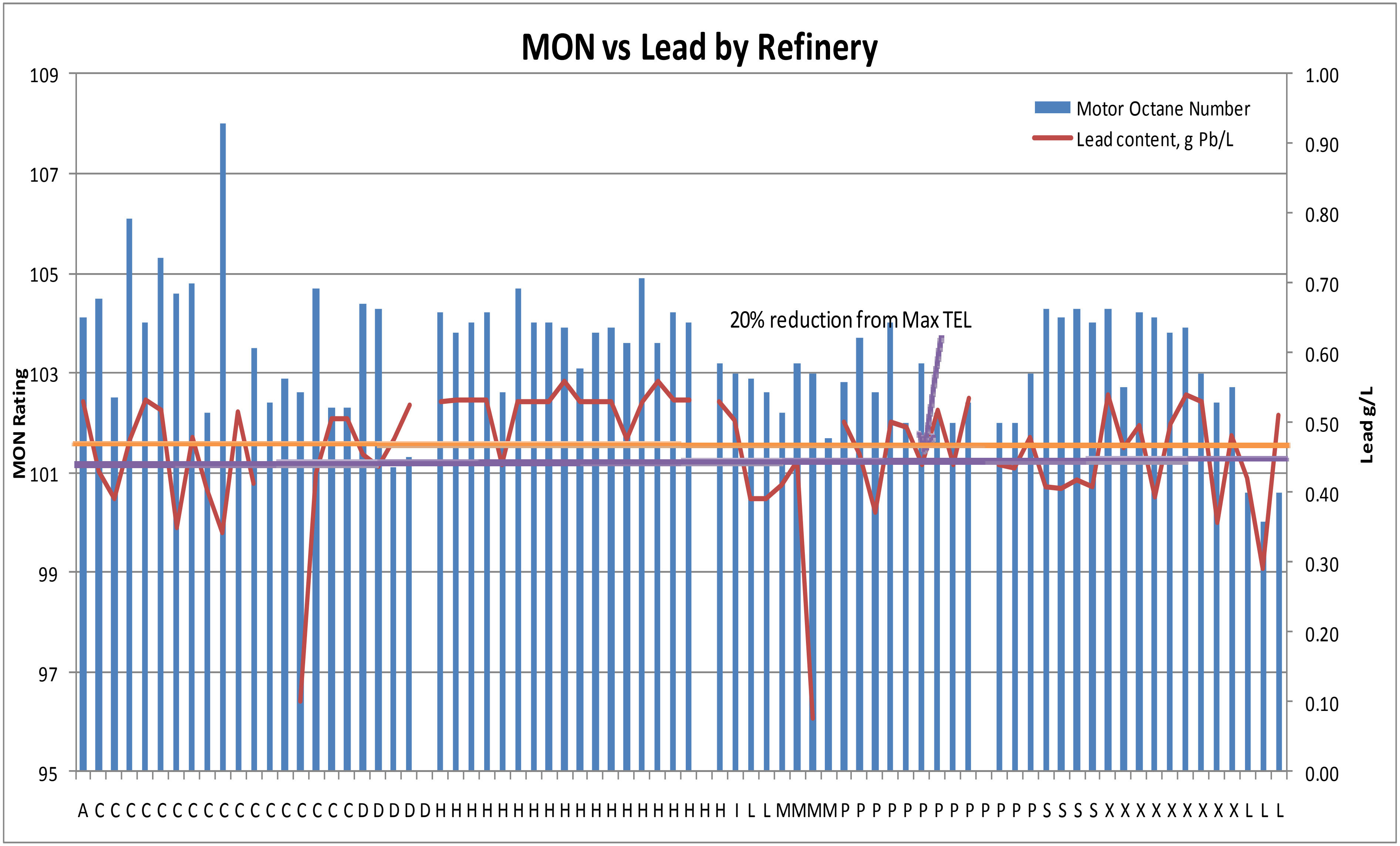

Figure 8 – Motor Octane Number vs. Lead Content by Refinery, Including Engine Cert

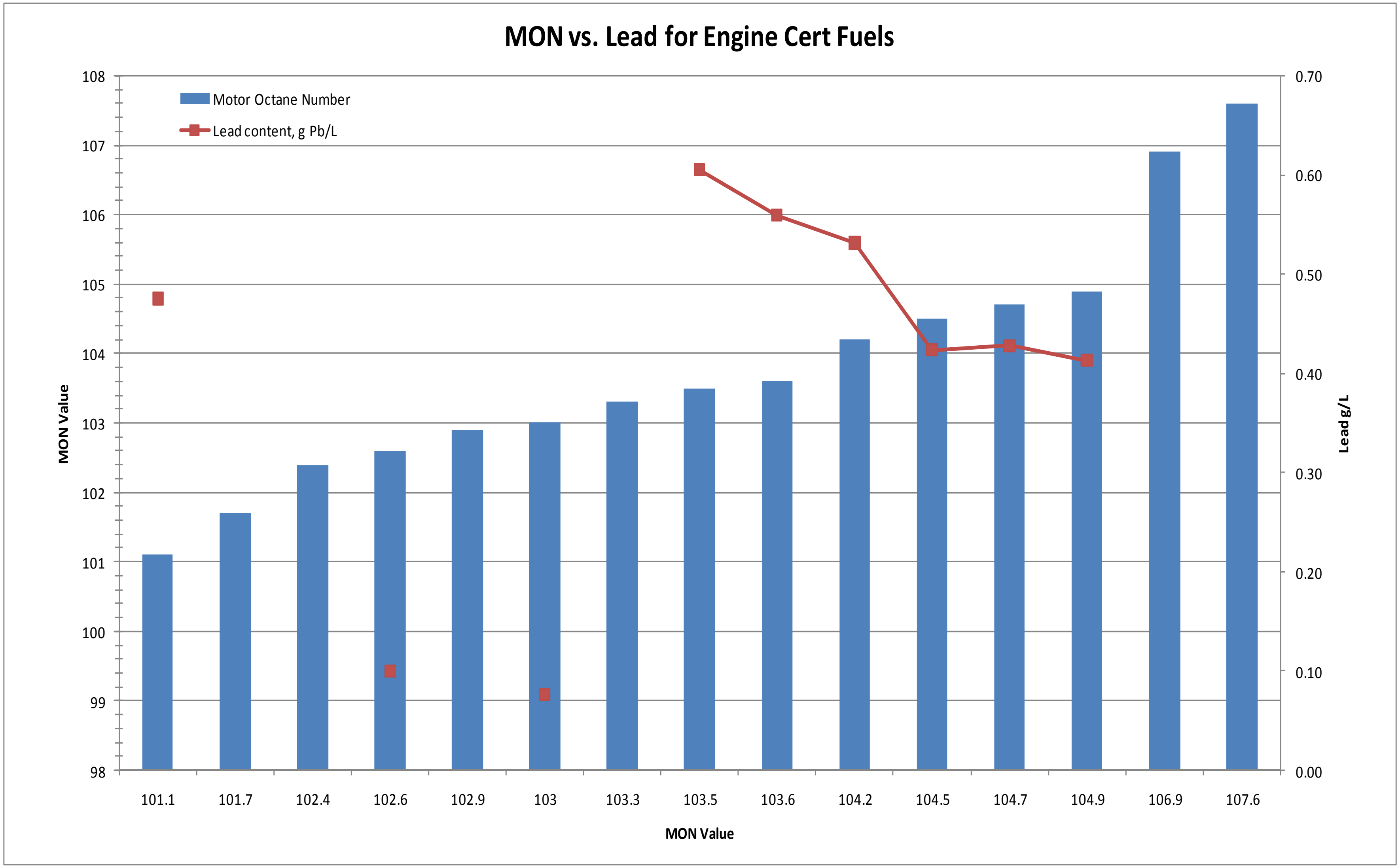

Figure 9 – Motor Octane Number vs. Lead Content Specific to the Engine Certification Fuel