LESSONS LEARNED DURING THE DEVELOPMENT OF UNLEADED AVGAS

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INTTRODUCTION

THIS PRESENTATION COMPLEMENTS THE PREVIOUS SAE SECTION MEETING PAPER TITLED *"The Prescription For The Unleaded Avgas Dilemma"* HELD ON THURSDAY, MARCH 8, 2013.

LESSONS LEARNED SINCE THE TRANSITION TO THE GRADE 100LL AVGAS REMAIN UNATTENDED AFTER 50 YEARS, AND A BROAD RANGE OF ADDITIONAL LESSONS MANIFESTED DURING THE DEVELOPMENT OF UNLEADED AVIATION GASOLINES HAVE ALSO BEEN DISMISSED FOR THE PAST 25 YEARS [REF 2].

GIVEN THE CURRENT UNLEADED AVIATION GASOLINES PROGRAM CONDITIONS, A FAIR AND OPEN-MINDED RE-EVALUATION OF THE LESSONS LEARNED COULD PROVE BENEFICIAL TO THE PROGRAM.

SUBSTANTIATION, AND DETAILED INFORMATION REFERENCES ON TOPICS COVERED BY THIS PRESENTATION, ARE LISTED AT THE CONCLUSION OF THIS PAPER.

LEAD IS KING

WE CANNOT HOLD A DISCUSSION OF THIS TOPIC WITHOUT ADDRESSING THE ROLE OF TETRAETHYL LEAD ON CURRENT HIGH OCTANE AVIATION GASOLINES.

LEAD IS KING IN THE CONTROL OF AVGAS DETONATION CHARACTERISTICS, AS IS WELL ILLUSTRATED IN FIGURE 1 [REF1, SEC9].

The Influence of Motor Octane, Supercharge and TEL on Full Size Engine BMEP at Light Knock

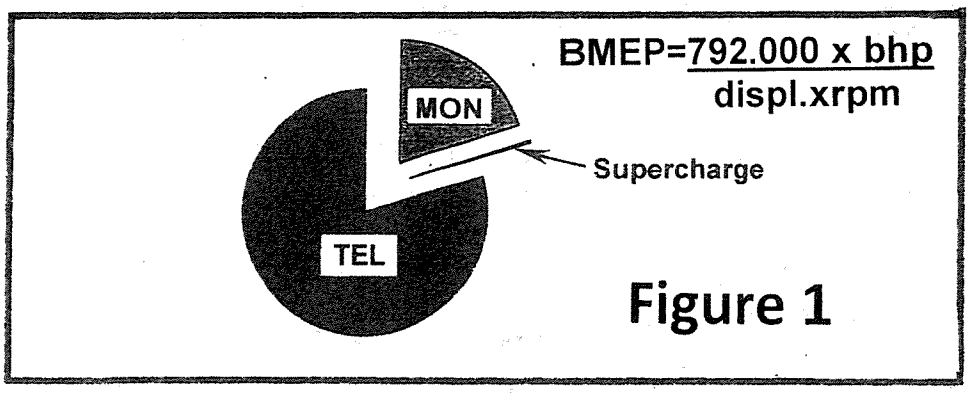


Figure 1

KNOCK LIMITED POWER IS PRIMARILY INFLUENCED BY THE FUEL TETRAETHYL LEAD (TEL) CONTENT.

KNOCK LIMITED POWER IS INFLUENCED TO SOME EXTENT BY FUEL MOTOR OCTANE QUALITY.

KNOCK LIMITED POWER IS NOT INFLUENCED BY THE FUEL SUPERCHARGE QUALITY.

THE CURRENT ASTM D910 AVGAS SPECIFICATION DOES NOT REFLECT THE STRONG INFLUENCE OF TEL ON AVGAS KNOCK SUPRESSION CHARACTERISTICS.

ASTM D910 SPECIFICATION REVISIONS

REVISIONS TO TABLE 1 OF DETAILED REQUIREMENTS FOR AVIATION GASOLINES, ADJUST MOTOR OCTANE AND TEL LIMITS IN CONCERT WITH A POLINOMIAL CURVE DEVELOPED FROM CRC DATA AND THE ORIGINAL D910 SPECIFICATION [REF 2].

CONSIDERATION SHOULD BE GIVEN TO THE DELETION OF ALL REFERENCES TO GRADE 100VLL (VERY LOW LEAD AVGAS), DUE TO POTENTIAL SERVICE RISKS AND QUESTIONABLE MERITS.

REVISIONS TO TABLE 1 ARE ESSENTIAL TO THE DEVELOPMENT AND PRODUCTION OF HIGH OCTANE TEST REFERENCE OR BASELINE FUELS.

REVISIONS TO TABLE1 RESTORE THE 12% DETONATION FUEL FLOW SAFETY MARGINS OF MANY ENGINE INSTALLATIONS. SAID MARGINS WERE REDUCED AND EVEN ELIMINATED WITH THE TRANSITION TO GRADE 100LL AVGAS 50 YEARS AGO.

TABLE 1 NOTE STATING *"...Historically, market survey and test engine data..."* AND CONCLUDING *"....while meeting the lean and rich mixture limits specified in Table1..."*,MUST BE DELETED. THIS NOTE PROMOTES THE REDUCTION OF TEL CONCENTRATIONS TO CRITICAL LEVELS.

REVISIONS TO TABLE 1

REVISED LIMITS ARE UNDERLINED

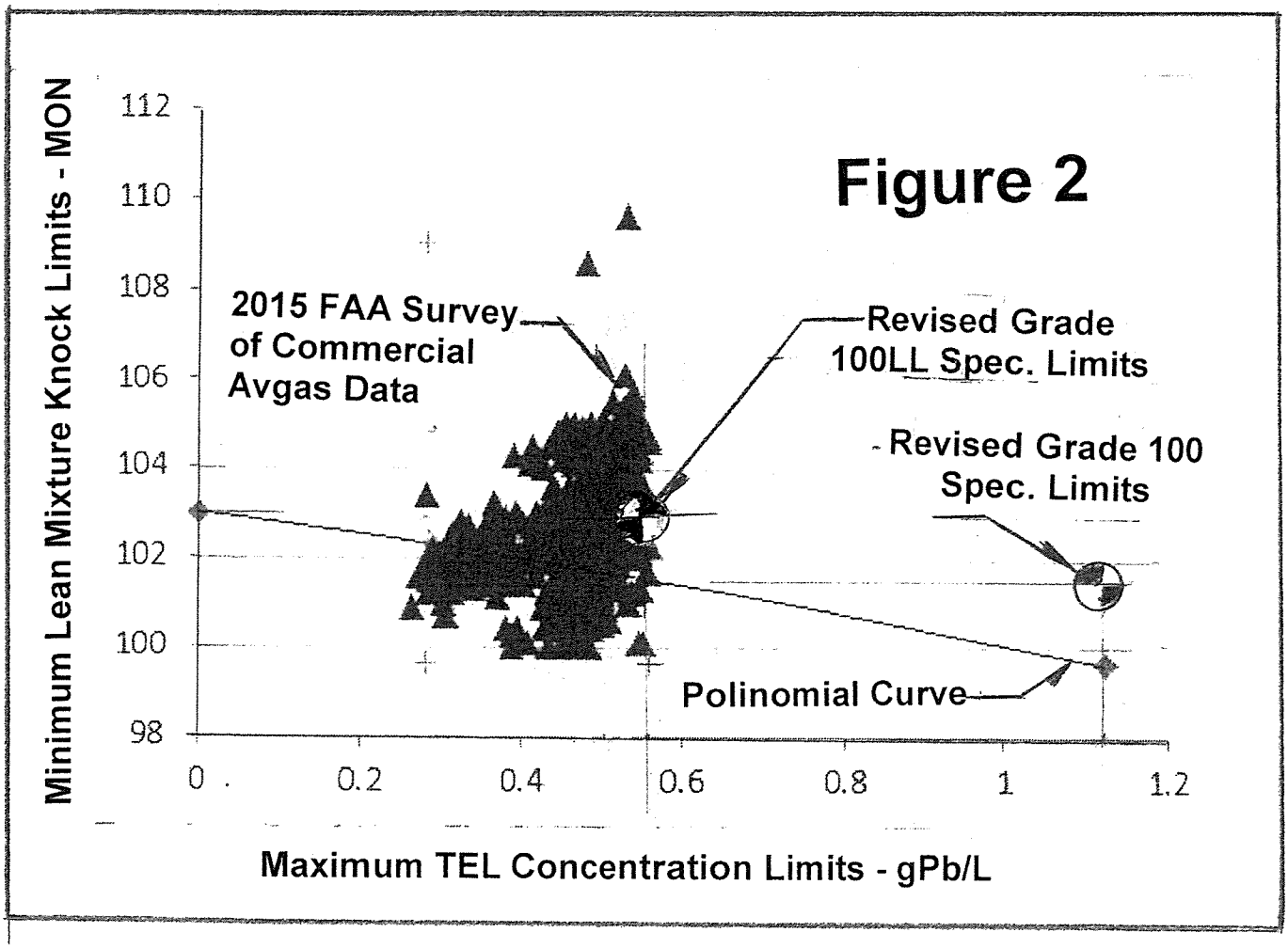
OctaneRatings		Grade 91	Grade 100LL	Grade 100	ASTM Test Method
Lean Mixture Motor Octane	min	90.8	<u>103.0</u>	<u>101.6</u>	D2700
Lean Mixture Aviation Rating	min	91.0	<u>109.1</u>	<u>105.3</u>	D2700
Rich Mixture Octane Number	min	98.0			D909
Rich Mixture Perf. Number	min	—	130	130	D909
Composition					
Sulfur Mass Percent	max	0.05	0.05	0.05	D1266/2622
Tetraethyl Lead					
TEL mL/L(Tetraethyl Lead)	max	0.53	0.53	1.06	D3341 or
Pbg/L	max	0.56	0.56	1.12	D5059

THE FOLLOWING TABLE 1 OF ADJUSTED MOTOR OCTANE NUMBERS VERSUS TEL (TETRAETHYL LEAD) CONCENTRATIONS, SHOULD BE CONSIDERED FOR INCORPORATION IN THE ASTM D910 SPECIFICATION.

TEL gPb/L	MON, ON	TEL gPb/L	MON, ON
0.02	102.96	0.58	101.46
0.04	102.92	0.60	101.39
0.06	102.87	0.62	101.33
0.08	102.82	0.64	101.27
0.1	102.77	0.66	101.20
0.12	102.73	0.68	101.14
0.14	102.68	0.70	101.08
0.16	102.63	0.72	101.01
0.18	102.58	0.74	100.95
0.2	102.53	0.76	100.88
0.22	102.47	0.78	100.81
0.24	102.42	0.80	100.75
0.26	102.37	0.82	100.68
0.28	102.32	0.84	100.61
0.3	102.26	0.86	100.54
0.32	102.21	0.88	100.47
0.34	102.15	0.90	100.40
0.36	102.10	0.92	100.33
0.38	102.04	0.94	100.26
0.4	101.99	0.96	100.19
0.42	101.93	0.98	100.12
0.44	101.87	1.00	100.04
0.46	101.81	1.02	99.97
0.48	101.76	1.04	99.90
0.5	101.70	1.06	99.82
0.52	101.64	1.08	99.75
0.54	101.58	1.10	99.67
0.56	101.52	1.12	99.60

IMPACT OF ADJUSTED MOTOR OCTANE LIMITS ON THE SUPPLY OF COMMERCIAL US AVIATION GASOLINES.

FIGURE 2 SHOWS THAT OVER 20% OF COMMERCIAL US AVIATION GASOLINES FALL BELOW THE POLINOMIAL CURVE.



SURVEY FUEL SAMPLES THAT MEET AND EXCEED RATINGS OF 103 MON, FALL ABOVE THE POLINOMIAL CURVE, AND CLEARLY REVEAL THE IMPACT OF "*Producer's Octane Bonus*", ONLY ATTAINABLE WITH THE USE OF TEL ADDITIVE.

THE SUCCESFUL USE OF COMMERCIAL 100LL AVGAS IS ATTRIBUTED TO THIS *"Producer's Octane Bonus"*, AND NOT TO ANY PARTICULAR SPECIFICATION REQUIREMENT.

OTHER ASTM D910 SPECIFICATION REVISIONS

Aromatics Content

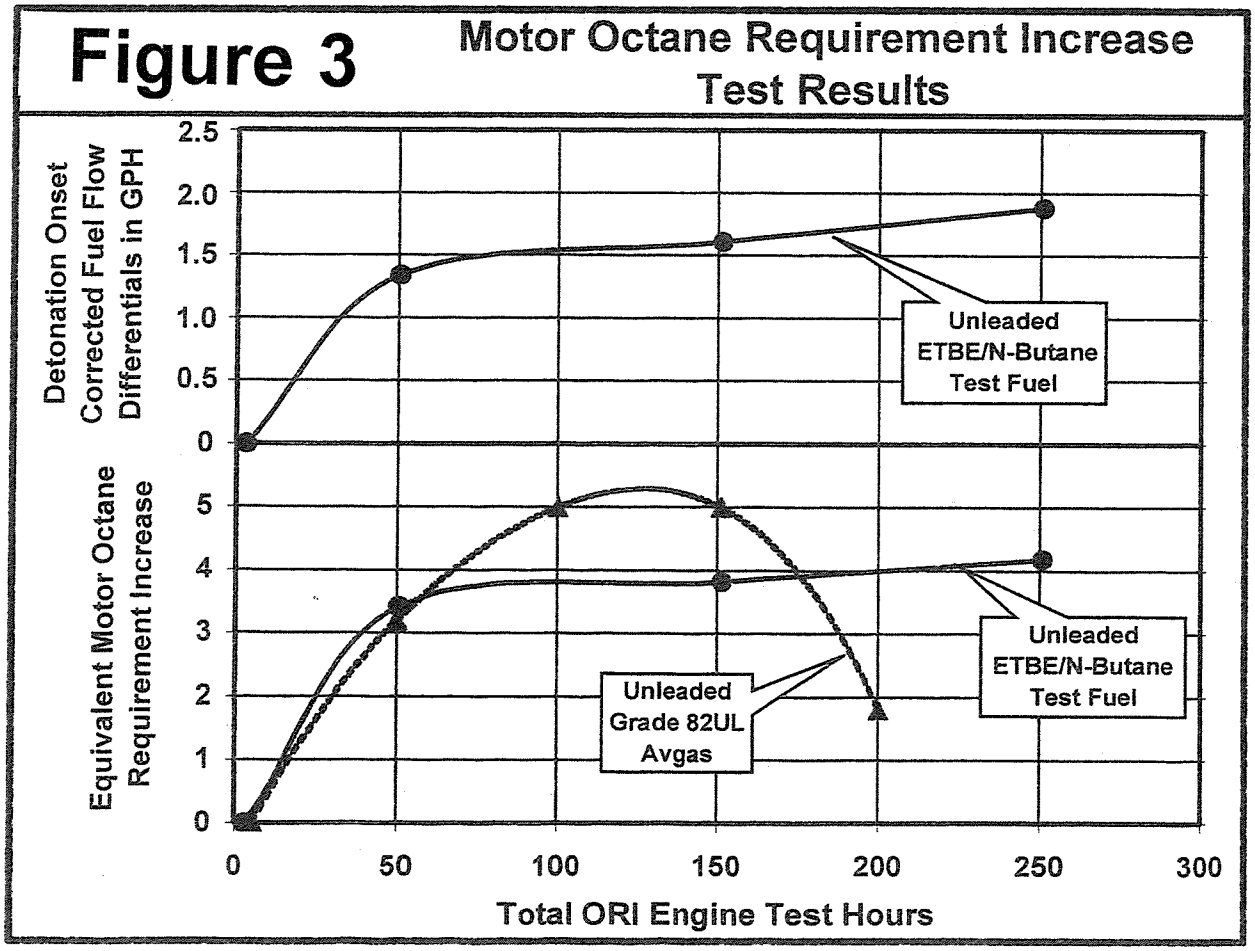
ENGINE OVERHEATING AND DETONATION EVENTS EXPERIENCED IN SERVICE, HAVE SHOWN A CONSISTENT CORRELATION WITH THE CONCENTRATION OF AROMATICS IN THE FUEL [REF 2].

AN AROMATICS MAXIMUM LIMIT OF 12%SHOULD BE CONSIDERED FOR INCORPORATION IN TABLE 1 OF REQUIREMENTS AND IN THE APPENDIX.

Octane Requirement Increase (ORI).
FIGURE 3 SHOWS A TYPICAL GENERAL AVIATION ENGINE OCTANE INCREASE OF 4 TO 6 MON, THAT SHOULD BE ACCOUNTED DURING THE RATING OF ENGINE INSTALLATIONS [REF 1].

BASED ON CESSNA TEST RESULTS, THE SPECIFICATION SHOULD BE AMMENDED TO INCLUDE AN ENGINE OPERATION CAUTION PERIOD OF 80 TO180 HOURS, FOR NEW OR REMANUFACTURED ENGINES.

Figure 3 Motor Octane Requirement Increase Test Results



Heat of Combustion.
THE D910 SPECIFICATION PARAGRAPH SHOULD BE AMMENDED, TO STATE THAT THE SPECIFIED HEAT OF COMBUSTION APPLIES ONLY TO HYDROCARBON BASED AVGAS.

IN SOME INSTANCES, OTHER FUELS WITH LOWER SPECIFIED LEVELS OF ENERGY, YIELD HIGHER POWER OUTPUTS AND LOWER FUEL CONSUMPTIONS THAN CURRENT AVGAS.

THIS IS INTENDED TO AVOID THE PREMATURE DISMISSAL OF NEW CANDIDATE FUELS ON THE BASIS OF A LOWER MINIMUM HEAT OF COMBUSTION.

Lead Memory.
THE COMBUSTION CHARACTERISTICS APPENDIX PARAGRAPH SHOULD BE AMMENDED, TO ADVISE THE READER THAT MEMORY CONDITIONS EXPERIENCED DURING THE TRANSITION FROM A LEADED FUEL TO AN UNLEADED ONE ARE TRANSITORY.

THESE CONTAMINATION CONDITIONS MAY BE CLEARED WITH AN ENGINE RUN OF 30 MINUTES, USING LEAD- FREE FUELS ON A TYPICAL AIRCRAFT INSTALLATION.

TEST PROCEDURES AND EQUIPMENT FOR SCREENING AND EVALUATION OF NEW FUELS

PROCEDURES AND EQUIPMENT ADOPTED BY CESSNA AIRCRAFT DURING THE 1990's UNTIL DECEMBER 2002, REPLACED EARLIER ENGINE LABORATORY PRACTICES [REF 3].

ENGINE LABORATORY TEST SETTINGS FEATURE POWER ABSORPTION DYNAMOMETERS (NO PROPELLERS), INDEPENDENT ENGINE AIR COOLING, AND TEST MANAGEMENT PRACTICES, NOT REPRESENTATIVE OF ACTUAL IN-SERVICE INSTALLED ENGINE CONDITIONS.

OVER THE YEARS, RESULTS OF TESTS PERFORMED UNDER THESE ENGINE LABORATORY CONDITIONS, EXHIBITED SIGNIFICANT DEVIATIONS FROM THOSE PERFORMED WITH ACTUAL AIRCRAFT INSTALLED ENGINES.

CESSNA TEST PRACTICES INCLUDE INSTALLATION FACTORS THAT TAKE INTO ACCOUNT THE IMPACT OF VIBRATING PROPELLERS, THAT PROVIDE SLIP-STREAM AIR COOLING THUS REPLACING THE INDEPENDENT ENGINE COOLING AIR FANS.

WITH THE ONLY EXCEPTION OF INLET AIR TEMPERATURES, THE TEST OPERATORS ARE LIMITED TO THOSE CONTROL MANAGEMENT FUNCTIONS AVAILABLE TO A PILOT.

BACK TO BACK TEST SEQUENCES COMPARE THE PERFORMANCE AND CHARACTERISTICS OF TEST FUELS AGAINST THOSE OF A STANDARD 100LL BASELINE, OR REFERENCE AVGAS.

CYLINDER HEADS AND OIL TEMPERATURES, AND IN SOME INSTANCES ENGINE RPM's,ARE ALLOWED TO FLOAT TO AVOID BIASING OF RESULTS.

FUEL SCREENING AND EVALUATION TESTS MAY BE CARRIED OUT ON A STATIC PROPELLER GROUND TEST STAND, FEATURING A COMPLETE AIRCRAFT ENGINE INSTALLATION.

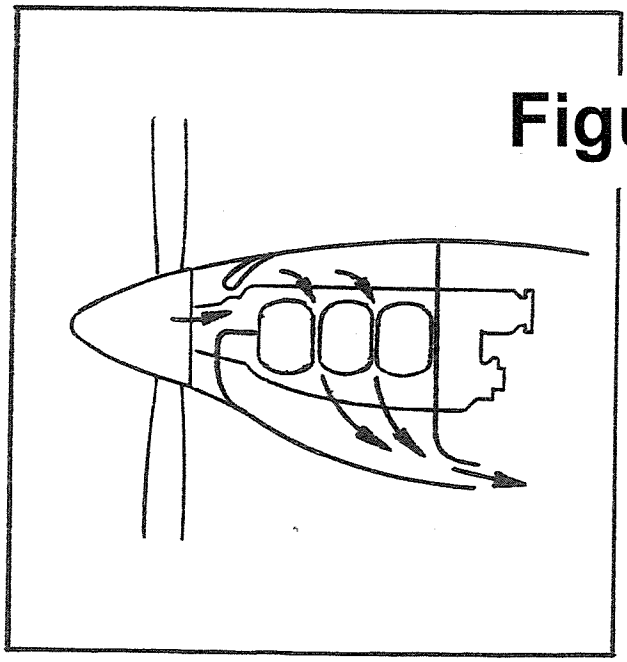
HOWEVER, EXPERIENCE HAS SHOWN THAT OPERATION OF AN ACTUAL AIRCRAFT IN A STATIC GROUND SETTING, HAS PROVEN TO BE MORE PRACTICAL AND ECONOMICAL.

IT IS IMPORTANT TO POINT OUT THAT GROUND OPERATIONS, REPRESENT THE MOST SEVERE CONDITIONS OF A NATURAL ASPIRATED ENGINE OPERATING ENVELOPE.

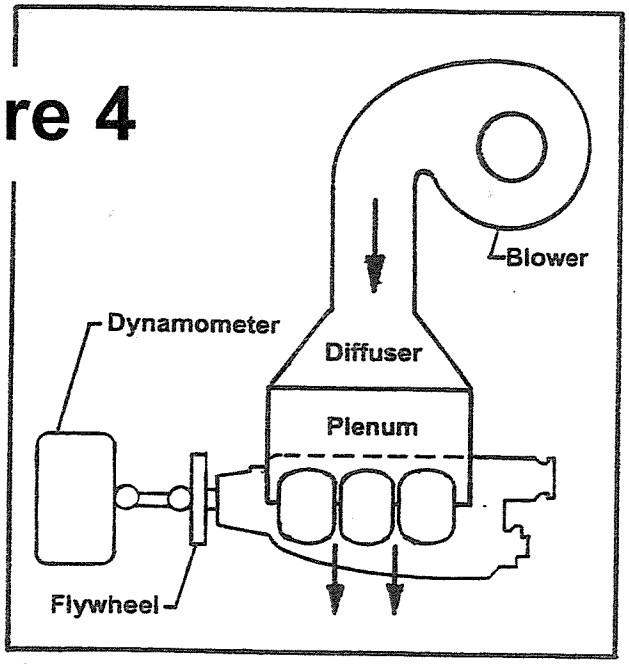
MEANINGFUL FUEL SCREENING AND EVALUATION TESTS WITH TURBOCHARGED ENGINES, CAN ONLY BE PERFORMED ON ACTUAL FLYING AIRCRAFT.

ASTM D6424 AND ASTM D6812 STANDARD PRACTICES FOR OCTANE RATING OF NATURAL ASPIRATED AND TURBOCHARGED ENGINES, SHOULD BE RECLASSIFIED FOR OTHER APPLICATIONS OR DELETED.

Figure 4



Typical Air-Cooled Aircraft Engine Cooling Provisions



Typical Dynamometer Engine Cooling Provisions

CESSNA SAFETY NET FUEL PROGRAM

GIVEN THE UNCERTAIN FUTURE IN THE SUPPLY OF LEADED 100LL AVGAS, AND THE LACK OF A SUITABLE UNLEADED SUBSTITUTE, CESSNA PURSUED THE DEVELOPMENT OF A SAFETY NET FUEL WITH THE COLABORATION OF THE FAA [REF 1].

ETBE EMERGED AS THE MOST PROMISING AVGAS BLEND COMPONENT DURING THE 14 YEARS CESSNA ALTERNATIVE FUEL INVESTGATIONS [REF 1].
IN SPITE OF THE SUCCESFUL COMPLETION OF THE ETBE BASED BLEND PHASE OF THE PROGRAM, LACK OF INDUSTRY INTEREST PROMPTED THE CANCELLATION OF THE PROGRAM IN DECEMBER, 2002.

CESSNA CONCLUDED THAT MEANS TO REDUCE THE OCTANE APPETITE OF THE ENGINES. WAS INDISPENSABLE TO ALLOW THE USE OF THE 95UL UNLEADED ETBE BASED SAFETY NET FUEL, AS WELL AS OTHER UNLEADED CANDIDATE FUELS OF SIMILAR MOTOR OCTANE CARACTERISTICS [REF 4].

EFFORTS TO DEVELOP A SAFE AND AFFORDABLE RETROFIT IGNITION SYSTEM TO

REDUCE THE OCTANE DEMANDS OF THE ENGINES, WERE ABANDONED AS PART OF THE SAFETY NET PROGRAM [REF 4].

FIGURE 5 PROVIDES A WINDOW ON THE SENSITIVITIES OF TEL AND ETBE.

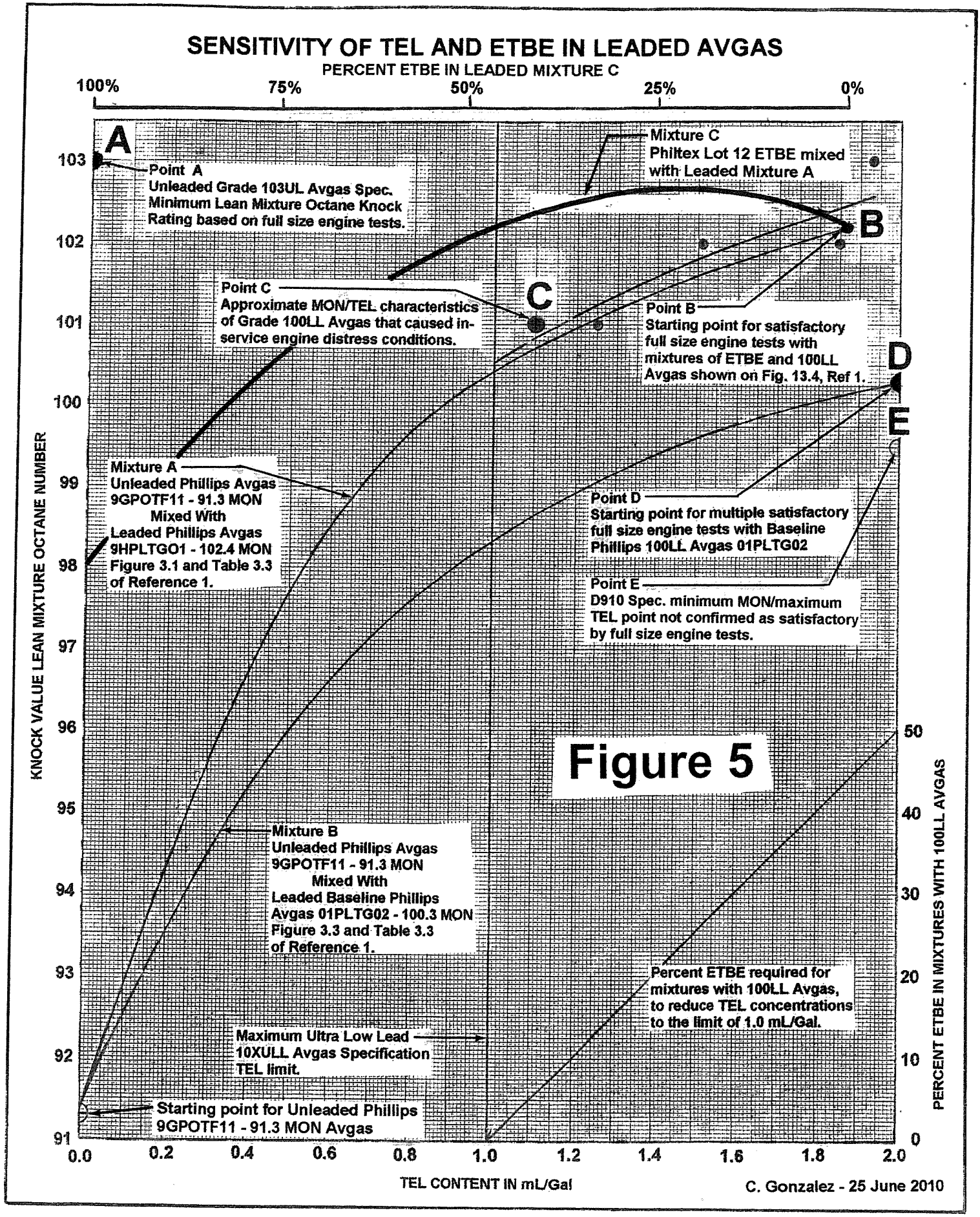
CONCLUSIONS

IN ITS PRESENT FORM, THE ASTM D910 FUEL SPECIFICATION IS NOT CONSIDERED A SUITABLE GUIDE OR ROAD MAP FOR THE DEVELOPMENT OF AN UNLEADED HIGH OCTANE AVGAS.

TO ESTABLISH REPRESENTATIVE ENGINE FUEL MOTOR OCTANE REQUIREMENTS, IT IS NECESSARY TO ADJUST MON RATINGS TO CORRESPONDING MAXIMUM TEL CONCENTRATIONS, IN CONCERT WITH THE TABLE 1 POLINOMIAL CURVE VALUES.

THE CURRENT D910 SPECIFICATION UNIFORM MINIMUM LIMIT OF 99.6 MON MUST BE REPLACED BY ADJUSTED MON VALUES.

IN 1998, CESSNA CONCLUDED THAT MEANS TO REDUCE THE OCTANE APPETITE OF ENGINES WAS INDISPENSABLE, TO ALLOW THE USE OF


SENSITIVITY OF TEL AND ETBE IN LEADED AVGAS
PERCENT ETBE IN LEADED MIXTURE C
100%
75%
50%
25%
0%
A
Point A
Unleaded Grade 103UL Avgas Spec. Minimum Lean Mixture Octane Knock Rating based on full size engine tests.
Mixture C
Philtex Lot 12 ETBE mixed with Leaded Mixture A
B
Point C
Approximate MON/TEL characteristics of Grade 100LL Avgas that caused in-service engine distress conditions.
C
Point B
Starting point for satisfactory full size engine tests with mixtures of ETBE and 100LL Avgas shown on Fig. 13.4, Ref 1.
D
E
Mixture A
Unleaded Phillips Avgas 9GPOTF11 - 91.3 MON
Mixed With
Leaded Phillips Avgas 9HPLTGO1 - 102.4 MON
Figure 3.1 and Table 3.3 of Reference 1.
Point D
Starting point for multiple satisfactory full size engine tests with Baseline Phillips 100LL Avgas 01PLTG02
Point E
D910 Spec. minimum MON/maximum TEL point not confirmed as satisfactory by full size engine tests.
Figure 5
Mixture B
Unleaded Phillips Avgas 9GPOTF11 - 91.3 MON
Mixed With
Leaded Baseline Phillips Avgas 01PLTG02 - 100.3 MON
Figure 3.3 and Table 3.3 of Reference 1.
Percent ETBE required for mixtures with 100LL Avgas, to reduce TEL concentrations to the limit of 1.0 mL/Gal.
Maximum Ultra Low Lead 10XULL Avgas Specification TEL limit.
Starting point for Unleaded Phillips 9GPOTF11 - 91.3 MON Avgas
KNOCK VALUE LEAN MIXTURE OCTANE NUMBER
103
102
101
100
99
98
97
96
95
94
93
92
91
PERCENT ETBE IN MIXTURES WITH 100LL AVGAS
50
40
30
20
10
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
TEL CONTENT IN mL/Gal
C. Gonzalez - 25 June 2010

THE 95UL UNLEADED ETBE BASED SAFETY NET FUEL, AS WELL AS OTHER UNLEADED CANDIDATE FUELS OF SIMILAR OCTANE CHARACTERISTICS.

A REVISED ASTM D910 AVGAS SPECIFICATION AND THE ADOPTION OF SUITABLE TEST PRRACTICES AND EQUIPMENT, COULD GESTATE REALISTIC EXPECTATIONS FOR THE DEFINITION OF ACTIVITIES REQUIRED TO REACH THE UNLEADED AVGAS GOALS.

THIS PRESENTATION WAS PREPARED IN RESPONSE TO A REQUEST EXTENDED BY THE WICHITA CHAPTER OF SAE INTERNATIONAL.

OPINIONS AND COMMENTS ARE THOSE OF THE AUTHOR, AND MUST NOT BE ATTRIBUTED TO ANY OTHER INDIVIDUAL(S) OR ORGANIZATION(S).

REFERENCES

1. *"CESSNA/FAA ETBE BASED AVIATION SPARK-IGNITION ENGINE FUEL PROGRAM-REPORT DRAFT"*, DECEMBER 1, 2002, REVISED FEBRUARY 2017.
2. *"THE DAWN OF LOW LEAD AVGAS"*, CESAR GONZALEZ - 15 JANUARY 2014 - REVISED 24 JUNE 2016.
3. *"REVIEW OF ALTERNATIVE SPARK-IGNITION ENGINE FUEL EVALUATION PROCEDURES"*, CESAR GONZALEZ - REVISED AUGUST 2014.
4. *"CAN GENERAL AVIATION SURVIVE WITH A LOWER OCTANE AVGAS?"*, CESAR GONZALEZ - EAA AIRVENTURE, 02 AUGUST 2008.

FOR ELECTRONIC (CD) COPIES OF REFERENCES 1 THRU 4 CONTACT:

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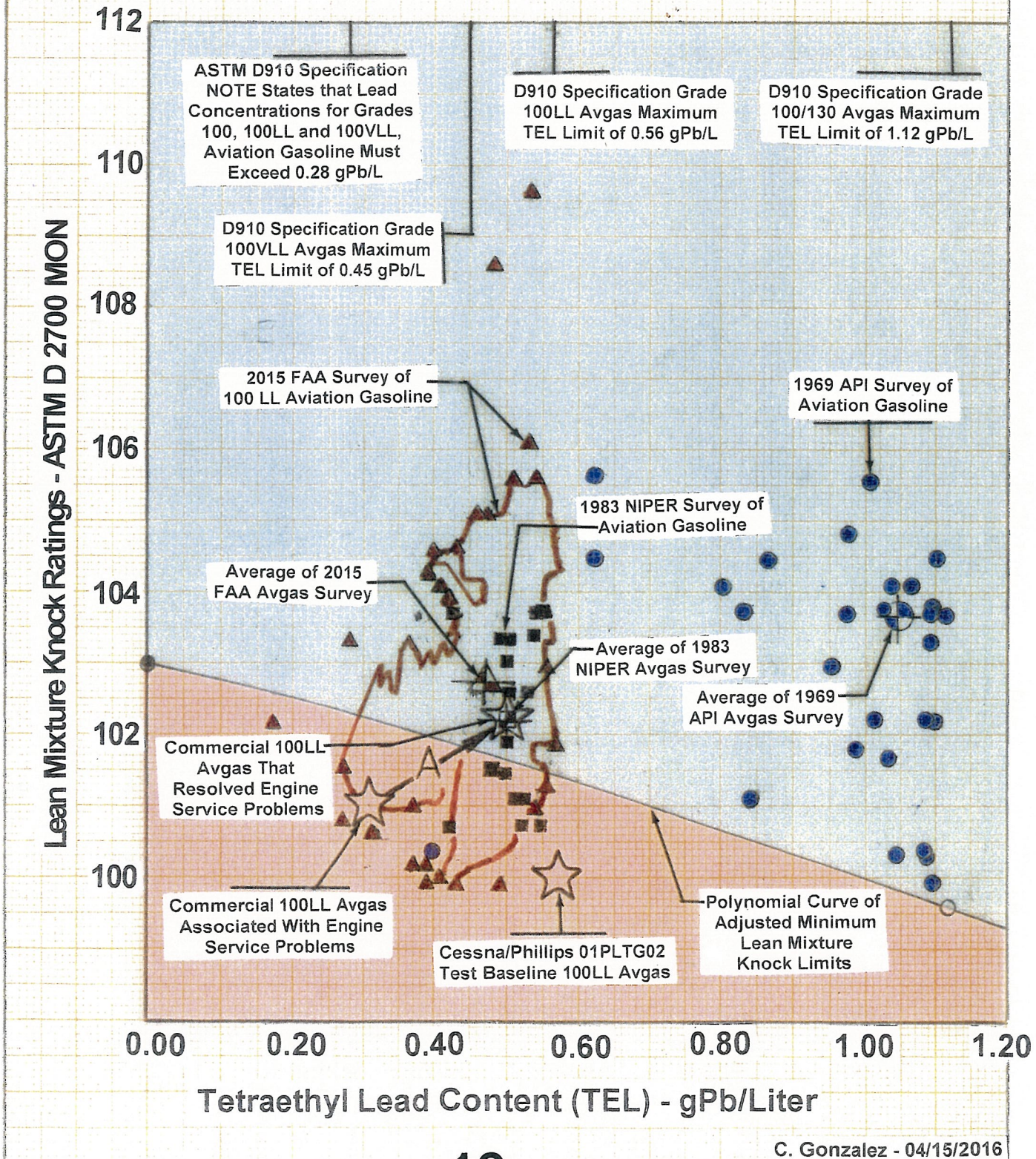
Figure 6 - EVOLUTION OF GRADE 100 AVGAS



C. Gonzalez - 04/15/2016