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**Impact of Alternative
Fuels on Engine Test
and Reporting
Procedures**

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IMPACT OF ALTERNATIVE FUELS ON ENGINE TEST AND
 REPORTING PROCEDURES

TABLE OF CONTENTS

<u>SECTION</u>	<u>PAGE NO.</u>
1. INTRODUCTION	2
2. APPLICATION AND OVERVIEW	3
3. COMMON TERMS	3
4. FUEL COMPOSITION and PROPERTIES	7
5. IMPACT OF FUEL ON TEST PROCEDURES AND CALCULATIONS	14
6. PERFORMANCE COMPARISONS	17
APPENDIX I - SAE HANDBOOK DOCUMENTS	19
APPENDIX II - ASTM TEST METHODS	21
APPENDIX III - HEALTH and SAFETY INFORMATION	24
APPENDIX IV - POWER TEST CODES	29
APPENDIX V - EMISSION MEASUREMENT CALCULATIONS	32

TABLES

4-1	11
AIII-1	26
AIII-2	28

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1. INTRODUCTION:

In the past, several major disruptions have occurred in the normal distribution of petroleum derived fuels at the consumer level. With the realization that stable consumer supplies of petroleum fuels might not be assured in the future, efforts were increased to investigate the utilization of non-petroleum derived fuels for automotive engines.

Up until this time, the generally accepted automotive fuels were petroleum derived gasoline for SI (Spark Ignition) engines, and petroleum derived diesel fuel for CI (Compression Ignition) engines. Fuels other than these have generally been considered "alternative fuels." A review of the literature will show that various investigators have considered alcohols, vegetable oils, gaseous fuels, hydrogen, shale oil, and coal products, among others as "alternative fuels" in various engines. As time passes, the label of "alternative" tends to become less meaningful as some fuels drop by the wayside while others move into the realm of practicality. In Brazil, production vehicles are designed to operate on ethanol, and in this case, it could be argued that ethanol is no longer an "alternative fuel." Because of this changing climate, the case could be made that there are no "alternative fuels" -- just "new fuels" or "different fuels." However, because the term "alternative fuels" appears rather entrenched in the technical literature, it can only be suggested that one be aware of the changing climate, and use an expanded definition of fuels when dealing with research in automotive engines.

These different fuels may present a variety of problems concerning testing¹ and evaluating the performance of an engine when compared to the baseline performance with the conventional fuel for that engine. These problems include identifying common terms, determining the fuel properties, determining the health and safety factors associated with use of the fuel, testing the engine, and calculating and reporting the results. Further, if the experimental results are to be compared to the results of others in the field, the variety of techniques that may have been used to obtain and report the data may preclude a legitimate comparison. This variety of reporting techniques may be further confused by different assumptions that may have been made in analyzing the data (not the least of which is -- "What is meant by 'fuel' when determining fuel rates?"). In addition, important non-proprietary information relating to the fuel or energy accounting data may be lacking, leading to difficulties in interpreting the results of others.

The purpose of this information report is to provide guidance for those newly entering the field of alternative fuels as well as those currently involved with testing and reporting engine results with both conventional and alternative fuels. It is hoped that use of this document with its suggested guidelines will allow more convenient and complete comparisons of results between investigations involving different fuels.

¹Health and safety issues when using these alternative fuels in the transportation sector may not be well understood. When using, storing, or transporting such fuels, the investigator should be aware of all potential safety issues. A primary source of safety related information would be the manufacturer of the fuel or fuel additive.

2. APPLICATION AND OVERVIEW:

The guidelines in this document are directed at laboratory engine dynamometer test procedures with alternative fuels, and they are applicable to four-stroke and two-stroke cycle spark ignition (SI) and diesel (CI) engines (naturally aspirated or pressure charged, with or without charge air cooling). A brief overview of investigations with some alternative fuels can be found in SAE J1297. Other SAE documents covering vehicle, engine, or component testing may be affected by use of alternative fuels. Some of the documents that may be affected can be found in Appendix I. Guidelines are provided for the engine power test code (SAE J1349) in Appendix IV. The principles of these guidelines may apply to other procedures and codes, but the effects have not been investigated.

The report is organized into four technical sections, each dealing with an important aspect of testing or reporting of results when using alternative fuels. The first (Section 3, Common Terms) deals with such issues as what is a "fuel" in the context of engine operation. The next (Section 4) is concerned with identifying fuel properties. The third technical section (Section 5) covers the testing considerations and calculations for alternative fuels. The final technical section (Section 6) provides some guidelines for reporting the results so that sufficient information is given in a form that allows convenient comparison of the results from different investigations.

3. COMMON TERMS:

Terms commonly used to report engine performance and test conditions are listed below. Included in this list are a few terms that have been adopted by ASTM through ASTM's broad consensus procedures. These terms are identified as ASTM terms, and are repeated here for two reasons. One is simply for convenience. The other is to highlight the limitations within the ASTM terms, and to counsel against the misuse of ASTM terms.

Most ASTM Test Methods explicitly state the class or range of substances for which the procedures and terms are valid. Departures from these procedures create a risk that both the procedure and the term may be invalidated. For example, ASTM limits the term "Cetane Number" to the performance of diesel fuel during a standardized engine test. To evaluate vegetable oil with this standardized test, and to discuss the performance of the vegetable oil with the term "Cetane Number" would be inappropriate. The preferred use of terminology would be to discuss the performance characteristic (for example, ignition delay) of the vegetable oil when tested by a Modified Cetane Number Test Method.

Once again, these terms are listed only for the expressed purpose of establishing consistency in reporting engine performance or describing testing parameters and conditions relating to that performance. Use of the term descriptions listed here outside of that context is inappropriate.

- 3.1 Alcohol: A class of organic compounds characterized by the presence of a hydroxyl group attached to an alkyl hydrocarbon structure.

- 3.2 Cetane Number: A measure of the ignition performance of a diesel fuel obtained by comparing it to reference fuels in a standardized engine test (1984) (ASTM term, see ASTM D 4175).
- 3.3 Colloidal Suspension (Colloid): A suspension of finely divided particles approximately 5 to 10 000 angstroms (0.5 nm to 1 μm) in size that are dispersed in a continuous medium (for example, a gaseous, liquid, or solid substance), that do not settle or settle very slowly, and are not readily filtered.
- 3.4 Denaturants: Any material authorized under Title 27 of the U.S. Code of Federal Regulations Part 21 for addition to spirits in the production of denatured spirits (from Title 27 U.S. Code of Federal Regulations Part 19, Subpart B). These materials are agents used to make ethanol unfit for human consumption without impairing its usefulness for a specific intended purpose. Denaturants vary depending on the end-use of the alcohol.
- 3.5 Emission Test Fuel: Gasoline or diesel fuels with controlled properties used for engine and emission testing. The specifications for U.S. Emission Test Fuel can be found in Title 40 of the U.S. Code of Federal Regulations Part 86. There are separate requirements for Light-Duty gasoline and diesel vehicles, and for Heavy-Duty gasoline and diesel engines.
- 3.6 Emulsion: A fluid formed by the suspension of a very finely divided immiscible liquid in the continuous phase of another liquid.
- 3.7 Ethanol or Ethyl Alcohol: An alcohol of formula C₂H₅OH.
- 3.8 Equivalence Ratio: A ratio of the actual fuel-air ratio (f/a) divided by the chemically correct (stoichiometric) fuel-air ratio (f/a)_s. This ratio is equivalent to the stoichiometric air-fuel ratio (a/f)_s divided by the actual air-fuel ratio (a/f). The Greek letter "phi" or symbol "φ" is commonly used to designate the equivalence ratio. Equivalence ratio is the preferred method to describe mixture strength.

$$\phi = \text{phi} = \frac{(f/a)}{(f/a)_s} = \frac{(a/f)_s}{(a/f)}$$

- 3.9 Excess Air Ratio: A ratio of the air supplied to the air required for stoichiometric combustion. Referred to by the greek letter "lambda" or symbol "λ", the excess air ratio is equivalent to the inverse of the equivalence ratio. Excess air ratio is not a preferred method to describe mixture strength.

$$= \text{lambda} = \frac{\text{Air (actual)}}{\text{Air (stoich)}} = \frac{1}{\text{phi}}$$

- 3.10 Flammability Limits: The limits of volume percentage composition of mixtures of fuel and air, within which flame propagation takes place when the mixture is ignited. The lower limit of flammability corresponds to the minimum amount of combustible fuel and the upper limit to the maximum amount of combustible fuel capable of conferring flammability on the mixture. Flammability limits are dependent on pressure, temperature, ignition energy, and combustor design, and are usually given at standard atmospheric conditions.
- 3.11 Flash Point: The lowest temperature at which vapors arising from a combustible substance will ignite momentarily (that is, flash) on application of an ignition source under specified conditions. ASTM has several Test Methods for determining the flash point of various substances. The conditions and statement of the term "Flash Point" vary slightly between Test Methods.
- 3.12 Fuel: Any solid, liquid, or gaseous substance which contains chemical energy that is released during the combustion process in an engine for the purpose of producing mechanical work is defined as fuel. Any other substance, combustible or non-combustible (for example, water), which is mixed with or added to the base combustible substance to modify the combustion process or to control emissions, or is inherently present in the base substance should be included as fuel in the calculation of fuel and energy consumption. For the energy consumption calculations prescribed in this document, fuel scavengers, corrosion inhibitors, lubricating oil, etc., which when combined, change the heating value by less than 0.25%, need not be considered as fuel. Recirculated exhaust products are not considered fuel.
- 3.13 Heating Value: The energy liberated when a unit mass of fuel is completely oxidized and the temperature of the reactants is equal to the products. For the lower (or net) heating value, the water produced is assumed to be in a gaseous phase; while for the higher (or gross) heating value, the water is assumed to be in the liquid phase. For a more detailed discussion of heating value, refer to paragraph 4.2.2.
- 3.14 Kerogen: The substantially organic material in oil shale, consisting primarily of carbon and hydrogen with quantities of sulfur, nitrogen, and oxygen, which upon pyrolysis will yield gas and raw shale oil.
- 3.15 Manufacturer's Designated Fuel (MDF): The fuel or fuels specified by the engine manufacturer for ordinary engine operation. All other fuels are considered alternative fuels unless redesignated by the engine manufacturer for a particular engine or class of engines.
- 3.16 Material Safety Data Sheet (MSDS): Written or printed material concerning a hazardous chemical which is prepared in accordance with paragraph (g) of Title 29 of the U.S. Code of Federal Regulations, Part 1910.1200.
- 3.17 Methanol or Methyl Alcohol: An alcohol of formula CH_3OH .

- 3.18 Octane Number: (for spark ignition engine fuels). Any one of several numerical indicators of resistance to knock obtained by comparison with reference fuels in standardized engine or vehicle tests (1986) (ASTM Term, see ASTM D 4175).
- 3.19 Oil Shale: A sedimentary rock containing a relatively high (5 - 30%) content of kerogen from which shale oil can be produced by heating.
- 3.20 Oxygenate: An oxygen-containing organic compound, which may be used as a fuel or fuel supplement; for example, various alcohols and ethers (1984) (ASTM Term, see ASTM D 4175).
- 3.21 Oxygenated Fuel: A class of fuels with chemically bound oxygen (for example, oxygenates) such as alcohols, vegetable oils, esters, or ethers.
- 3.22 Phase: A portion of a physical system (solid, liquid, or gas) that is homogeneous throughout, has definable boundaries, and can be separated physically from the other phases. The act of separating different phases is commonly termed "phase separation."
- 3.23 Proof: The ethyl alcohol content of a liquid at 60°F (15.56°C), stated as twice the percent of ethyl alcohol by volume (from Title 27 U.S. Code of Federal Regulations Part 19, Subpart B).
- 3.24 Slurry: A mixture of a pulverized solid and a liquid carrier that behaves as a liquid.
- 3.25 Specific Energy Consumption (SEC): The ratio of the rate of fuel energy supplied divided by the rate of work done by the engine, (kJ/s)/kW, which is also the inverse of thermal efficiency. The values to be used for fuel energy units are lower or net heating values. SEC can be reported as either Brake or Indicated consumption.
- 3.26 Stoichiometric Fuel-Air Ratio: The ratio of the mass of fuel to the mass of air of a stoichiometric mixture of fuel and air. The inverse is the stoichiometric air-fuel ratio.
- 3.27 Stoichiometric Mixture: The chemically correct mixture of fuel (fuel as defined in this report) and air or oxidizer that will enable complete oxidation of the combustible components of the fuel with no excess oxygen.
- 3.28 Surfactant: A surface active agent which can enhance emulsification, dispersion, or demulsification by modifying the liquid surface tension.
- 3.29 Thermal Efficiency: The ratio of the rate of work done by an engine divided by the rate of fuel energy supplied, kW/(kJ/s). The inverse of thermal efficiency is Specific Energy Consumption. The values to be used for fuel energy units are lower or net heating values. Thermal efficiency can be reported as either Brake Thermal Efficiency (BTE or η_b) or Indicated Thermal Efficiency (ITE or η_i).

- 3.30 Vapor Pressure: The pressure exerted when a solid or liquid substance is in equilibrium with its own vapor. The vapor pressure is a function of the substance and of the temperature. ASTM has several Test Methods that determine the vapor pressure under specified conditions for a number of substances (see paragraph 4.2.3).
- 3.31 Vegetable Oil: Any oil from plant origin as distinguished from animal (origin) oil, including the fixed oils of plants (for instance, glyceryl esters of various fatty acids) which are also known as glycerides, specifically triacylglycerols.
- 3.32 Volatility: The tendency of a substance to evaporate readily at ordinary temperatures and pressures. An indirect quantification of this quality can usually be determined through various ASTM Test Methods which measure the distillation curve, the flammability or flash point, the vapor/liquid ratio, and the vapor pressure of the substance (see paragraph 4.2.3).

4. FUEL COMPOSITION AND PROPERTIES:

- 4.1 Background: Because limits for the composition and physical properties have generally been established for commercial automotive fuels, they have not been of great concern during engine testing, unless specific tests were directed toward particular fuel properties. With the increased interest in and use of alternative fuels, more concern must now be directed towards a broader scope of fuel properties.

Therefore, before proceeding to test an engine, one should first investigate the chemical composition and physical properties of the fuel to be used. This step is necessary for physical compatibility with the facility and the engine. The elemental composition is also needed to determine the stoichiometric fuel-air ratio of the fuel for proper engine adjustments, as well as for performance comparisons and reporting of results. In addition to the fuel composition, other properties of the fuel such as heating value, volatility, viscosity, and density (among others) are necessary to properly compare and report engine performance.

4.2 Determining Fuel Properties:

- 4.2.1 Elemental and Chemical Composition: It is necessary to know the composition of any fuel in terms of mass percent C, H, O, N, S, and any other elements which could react during combustion if the stoichiometric fuel-air ratio and equivalence ratio are to be calculated. The exact values of the elemental mass percentages should be determined and reported for the particular fuel used. Note also that the contributions to the elemental mass percentage from fuel additives should be included if they affect the energy content by more than 0.25%. In addition, a determination of the quantity of additives and trace compounds or elements in the fuel (such as corrosion inhibitors, chloride levels, iodine number, peroxide number, etc.) may be necessary in order to select corrosion resistant components for the fuel system.

4.2.1 Elemental and Chemical Composition: (Continued)

Carbon, hydrogen, and oxygen content can be determined analytically by a variety of micro-combustion techniques. In addition, Appendix II lists a number of ASTM Test Methods for analysis of non-hydrocarbon constituents. There are also a number of non-standardized micro-analytical techniques for nitrogen and sulfur. Researchers are advised to consult their laboratory for the details of precision errors and bias errors when applied to the particular fuel used. Researchers should also note that many times, ASTM Test Methods are valid only for a specific class or range of substances (for example, petroleum products). Use of such procedures for other substances (for example, non-petroleum products) requires a careful examination of the procedure by the researcher, and an analysis of the errors that could occur by such a modified procedure. The method of modification (if any) and error analysis used should be reported.

4.2.2 Heating Values of Fuels: The heating value or heat of combustion is a measure of the energy available from the complete oxidation of a fuel. Because the fraction of the heat of combustion that is converted to useful work is a measure of the thermal efficiency of an engine, a knowledge of the heat of combustion of any fuel used is essential when quantifying the performance of an automotive engine.

4.2.2.1 The measurement, calculation, reporting, and use of heating values of fuels is covered in detail in the SAE Handbook under SAE J1498. For the purpose of performing engine tests using alternative fuels, the following interpretations and concepts from SAE J1498 are emphasized here:

4.2.2.1.1 Only the lower or net heating value should be used for all energy input calculations.

4.2.2.1.2 Since heats of combustion are not always additive when compounds are mixed, calorimetric measurements are recommended when dealing with alternative fuels or mixtures of alternatives with traditional petroleum fuels.

4.2.2.1.3 Empirical methods for estimating heats of combustion are based on observed correlations, accurately measured properties, and the heats of combustion of a particular class of fuels. Because such estimates may be in error by large amounts even within the same class of fuels, they are not substitutes for precisely measured heats of combustion, particularly for alternative fuels. For comparing engine results, empirical estimates should be avoided.

4.2.2.2 The need to accurately characterize the heating value of the baseline fuel should not be overlooked when performance comparisons are being made between two fuels. Typically, but not always, automotive gasoline or diesel fuel would be the baseline fuel. The precepts in SAE J1498 along with SAE J312 and SAE J313 should be used in determining the heating value of the baseline fuel.

- 4.2.3 Physical Properties: ASTM has many Test Methods for determining the physical properties of substances. However, most ASTM Test Methods explicitly state the class or range of substances for which the procedures are valid. Departures from these substances, or modifications to these procedures, run the risk of erroneous results. Since some alternative fuels are not covered by ASTM Test Methods, use of such procedures for substances other than those specified by ASTM requires a careful examination of the procedure, and an analysis of the errors that could occur by such a modified procedure. The modifications (procedure or substance) should be clearly reported.
- 4.2.3.1 Density: Density measurements should be performed in a manner that will allow calculation of the mass per unit volume of the fuel, in the form that the fuel is introduced to the engine. For pure liquid or pure gaseous fuels, density measurements should not create any unique problems with the caveat that ASTM Test Methods may not address the particular substance under consideration. For example, the scope of the glass hydrometer method (ASTM D 1298) includes liquid petroleum products, and liquid mixtures of petroleum products and non-petroleum products, but does not include pure non-petroleum products. However, ASTM D 3505 may apply to these substances. ASTM D 1480 apparently can be used for any material that is fluid between 20 and 100°C. Determining the density of powdered solid fuels may be more difficult, particularly since the density may vary with handling techniques. ASTM D 4292 provides one method of sample preparation, but the scope of this method only includes calcined petroleum coke. Determining the density of fuels consisting of any combination of gaseous, liquid, or solid substances could pose significant conceptual and physical measurement problems.
- 4.2.3.2 Flash Point: ASTM has established several Test Methods for determining the flash point of substances. One difference between these Test Methods includes the physical characteristics of the substance. For example, ASTM D 56 can be used for liquids that have viscosities below certain values at specific temperatures and flash below 93°C, and do not contain suspended solids or form a surface film. Higher viscosity liquids and those containing suspended solids generally fit the criteria for ASTM D 93. Care should be taken to insure that the proper procedure is used for the substance to be tested in the engine.
- 4.2.3.3 Vapor Pressure: Vapor pressure of many pure organic or inorganic compounds can be found in reference books such as The Handbook of Chemistry and Physics (a CRC publication). The limitation on this data is that it applies only to pure compounds. For substances where the exact composition is not known, ASTM has developed several Test Methods. These Test Methods have limitations on their applicability as well. For example, the scope of ASTM D 2551 only includes air-containing, volatile, nonviscous petroleum products at pre-selected vapor-to-liquid ratios and temperatures. The scope is further limited to substances that have a vapor pressure between 0.5 and 17 lbf/in² (3.4 to 117.2 kPa). Vapor Pressure of Petroleum Products by the Reid Method (ASTM D 323) or Reid Vapor Pressure (RVP) is another common procedure. The scope of this Test Method is limited to gasoline, volatile crude oil, and other volatile petroleum products. Specifically

4.2.3.3 Vapor Pressure: (Continued)

excluded from ASTM D 323 are liquified petroleum gases and oxygenated fuels. For fuels containing alcohols, a dry method and an automatic method described in ASTM D-2 P-176 has been proposed as a future ASTM Test Method. Because of the various limitations on methods to determine vapor pressure, identifying an accepted standard procedure for fuel consisting of certain combinations of gaseous, liquid, or solid substances may be difficult.

4.2.3.4 Volatility: The volatility characteristics of a substance can be determined by a number of different measures. For this reason, the method used to measure volatility generally depends on the specific concern of interest. For instance, the flash point would be a volatility concern in safety issues. The vapor pressure of the substance at different temperatures might also be a safety concern if the possibility exists of forming a combustible mixture within the test cell (or other confined space) due to spills or leaks. Within the engine and fuel delivery system, the volatility of the substance can affect the fuel distribution in some induction systems, the degree of wall wetting, cold starting capabilities, and vapor lock to name just a few of the possible effects. ASTM has various Test Methods to measure different volatility characteristics of certain substances. Included are Test Methods to measure distillation curves, flash points, vapor/liquid ratios, and vapor pressures. SAE J312 and ASTM D 439 provide some insight on the significance of these different volatility characteristics relative to automotive gasoline. Flash point and vapor pressure are also briefly discussed in this section of this document. It is important to select the appropriate volatility measure for the concern at hand.

4.2.3.5 Viscosity: Viscosity measurements for pure liquid fuels should not create any unique conceptual measurement problems. ASTM D 445 describes one method for measuring kinematic viscosity, but the scope of the Test Method only includes transparent and opaque petroleum products. Measuring viscosity of fuels consisting of gas and a liquid, a liquid and solid, or some other combination could pose significant measurement problems.

4.3 Determining Stoichiometric Fuel-Air Ratio: The stoichiometric fuel-air ratio is needed to calculate the operating equivalence ratio so that engine performance can be compared at the same equivalence ratio. Changes in stoichiometric fuel-air ratio must also be known in advance of engine experiments when sizing or making adjustments to fuel injection or carburetion systems.

The stoichiometric fuel-air ratio can be calculated from knowledge of the fuel composition with the assumption that combustion occurs with dry air of the composition found in Table 4-1. It is further assumed that the fuel can be represented by the formula in Equation 4-1.



4.3 Determining Stoichiometric Fuel-Air Ratio: (Continued)

where:

x = the atoms of carbon per mole of fuel

y = the atoms of hydrogen per mole of fuel

z = the atoms of oxygen per mole of fuel

v = the atoms of nitrogen per mole of fuel

w = the atoms of sulfur per mole of fuel

Ash is not included in the fuel, since it is not common practice to give molar analysis of ash contained in fuels.

Table 4-1

MOLECULAR WEIGHTS AND ASSUMED FRACTIONAL VOLUME

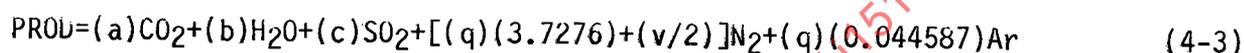
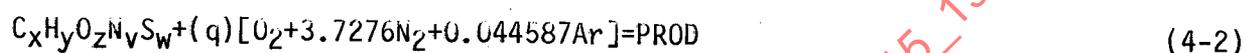
Composition of Sea Level Dry Air

Gas Species	Fractional Volume ¹	Molecular Weight kg/kmole ²	Relative Mass ³	Oxygen Normalized Volume Ratio ⁴
N ₂	0.78084	28.0134	21.873983	3.7276 E+00
O ₂	0.209476	31.9988	6.702981	1.0000 E+00
Ar	0.00934	39.948	0.373114	4.4587 E-02
CO ₂	0.000314	44.0098	0.013819	1.4990 E-03
Ne	0.00001818	20.179	0.000365	8.6788 E-05
He	0.00000524	4.002602	0.000021	2.5015 E-05
Kr	0.00000114	83.80	0.000092	5.4422 E-06
Xe	0.00000087	131.29	0.000011	4.1532 E-07
CH ₄	0.000002	16.04276	0.000032	9.5476 E-06
H ₂	0.0000005	2.01588	<u>0.000001</u>	<u>2.3869 E-06</u>
			28.964419	4.7738

1. Data from Table 3 of "U.S. Standard Atmosphere, 1976," National Oceanic and Atmospheric Administration; National Aeronautics and Space Administration; United States Air Force, Washington, DC, October 1976.
2. Calculated from 1983 IUPAC Atomic Weights, N. E. Holden and R. L. Martin, Pure and Applied Chemistry, 56,663 (1983).
3. Relative mass = fractional volume X molecular weight.
4. The ratio of the fractional volume of each gas species relative to oxygen.

4.3 Determining Stoichiometric Fuel-Air Ratio: (Continued)

The basic chemical equation for combustion of the fuel identified in Equation 4-1 is provided in Equations 4-2 and 4-3. Note that species other than those in Equation 4-1 are assumed to be non-reactive with the oxygen or the nitrogen in the air. As indicated in Equation 4-3, the products of stoichiometric fuel combustion are assumed to be CO₂, H₂O, N₂, and SO₂. (Note, also that these products may be subject to interpretation if exhaust gas analysis is used to compute the operating equivalence ratio because of assumptions about the final form of the nitrogen and sulfur compounds.) Should an unusual fuel be encountered that is not consistent with these assumptions, the following equations should not be used, and the basic chemical balance (4-1, 4-2, and 4-3) should be re-formulated for the fuel under test. Such reformulations should be reported.



where:

$$q = [x + (0.25)y + w - (0.5)z] = \text{the moles of oxygen necessary for stoichiometric combustion}$$

The fundamental form of the stoichiometric fuel-air ratio is given by Equation 4-4.

$$(f/a)_s = MW_f / (q)(MW_a) \quad (4-4)$$

where:

MW_f = Molecular weight of the fuel in the reactants of (4-2)

$MW_a = 138.2703 = (28.964419)\#(4.7738)\#$
 = The mass of air containing one molecular weight of oxygen.

From Table 4-1.

If the number of atoms for each element in the fuel is easily obtainable, which might be the case for some pure component fuels, determining the stoichiometric fuel-air ratio by Equation 4-4 can be rather straightforward. However, many fuels are not pure compounds, and a precise number of atoms for each element may be difficult or impractical to determine; for example, where a blend of hydrocarbons is used or where hydrocarbons are blended with alcohols. Further, for these non-pure compound fuels, the fuel analysis typically available is one which determines the mass fractions of the elements - not the number of atoms. Therefore, in these more common situations, Equation 4-5 is preferred for calculation of the stoichiometric fuel-air ratio.

$$(f/a)_s = (0.7232) / [(\%C/12.011) + 0.25(\%H/1.00794) + (\%S/32.066) - 0.5(\%O/15.9994)] \quad (4-5)$$

4.3 Determining Stoichiometric Fuel-Air Ratio: (Continued)

Where:

$\%C = (FC)(100)$ = the mass percentage of carbon in the fuel
 $\%H = (FH)(100)$ = the mass percentage of hydrogen in the fuel
 $\%S = (FS)(100)$ = the mass percentage of sulfur in the fuel
 $\%O = (FO)(100)$ = the mass percentage of oxygen in the fuel
 $0.7232 = (1/138.2703)(100)$

and where:

FC = the mass fraction of carbon in the fuel
FH = the mass fraction of hydrogen in the fuel
FS = the mass fraction of sulfur in the fuel
FO = the mass fraction of oxygen in the fuel

Although the amounts of any non-reactive species that may be contained in the fuel (for example, water) do not appear explicitly in Equation 4-5, their effects are included accurately, provided that the percentages appearing in Equation 4-5 are determined on the total fuel sample which includes the non-reactive species. In other words, the sum of the percentages in Equation 4-5 does not necessarily have to equal 100.

If the fuel being used contains a significant amount of ash, the researcher should consider the possibility that some forms or a certain portion of the ash is reactive. If any of the ash is reactive, then equation (4-5) would not be applicable.

An alternative calculation for the stoichiometric fuel-air ratio can be found in SAE J1829. The procedure in SAE J1829 which uses a ratio technique (hydrocarbon/carbon, oxygen/carbon, etc.) allows some flexibility in the selection of the combustion products of fuel nitrogen and fuel sulfur. For example one equilibrium product allowed in SAE J1829 from the combustion of fuel nitrogen is NO. In an engine, the amount of NO produced is affected by many variables such as compression ratio, combustion chamber shape, and ignition timing. Because it would be difficult to separate any NO produced by fuel nitrogen from that produced by high temperature air reactions, and to preclude the possibility of the stoichiometric fuel-air ratio changing with engine design or operating conditions, the convention of fuel nitrogen going to N₂ and fuel sulfur going to SO₂ should ALWAYS be used when reporting engine performance on different fuels. If these assumptions are used in the equations found in SAE J1829 (fuel nitrogen to N₂ and fuel sulfur to SO₂), there is essentially no difference in the results between SAE J1829 and Equation 4-5.

5. IMPACT OF FUEL ON TEST PROCEDURES AND CALCULATIONS:

- 5.1 Background: SAE has developed several specific test codes that deal with reciprocating engine test procedures and performance calculations (SAE J607, J1312, J1349)², emissions measurement (SAE J177, J215, J254, J1003, J1088, J1094, J1130, J1243)², and vehicle fuel economy (SAE J1082, J1256, J1376)². These codes and procedures have historically focused on tests with conventional distillate fuels. When using alternative fuels, a broader range of physical and chemical fuel properties must be addressed as outlined in Section 4. For safety considerations and to give better assurance of a proper comparison of the engine performance with alternative fuels, engine personnel need to become better acquainted with the technical details of the fuel chemistry and combustion reactions than has been the case for engine tests with conventional distillate fuels.
- 5.2 Test Procedure for Alternative Fuel Utilization: If an engine has been designed to operate on a specific alternative fuel, then many technical concerns with the test facility and the fuel supply may have been addressed and the focus can immediately be on the performance, emissions, and calculated results. However, many alternative fuel investigations occur with existing engine designs. In these situations, facility and fuel supply questions must be addressed before testing.
- 5.2.1 Health and Safety: An initial fuel property assessment should focus on health and safety. These aspects are foremost considerations for personnel handling the fuel or conducting the test, the end consumer or vehicle operator, and others in contact with the environment around the operating engine. The possible toxicity of the fuel vapors to the respiratory system, liquids to the skin, or combustion products to either must be investigated. Combustion of even trace elements or compounds could cause harmful exhaust. Explosion hazards can occur from volatile fuels with low ignition temperatures, combinations of fuels causing combustible vapors where individually there is no concern, or unstable mixtures self-igniting. In addition, health hazards for combinations of fuels can in some cases be greater than those exhibited by the individual fuels or components. If the health and safety related fuel properties are not known or incomplete, they should be determined before testing. Since many alternative fuels are by-products from the production of other chemicals, details of chemical composition of the fuels may not be readily available. A source of safety information should be the facility Safety Officer (who should be consulted); fuel composition and other related safety information should be available from the fuel manufacturer by means of a Material Safety Data Sheet (MSDS)³. Other sources of health and safety information are described in Appendix III.

²See Appendix I for complete SAE titles. Note also that SAE continually updates the documents listed in the SAE Handbook, therefore, the latest version should be consulted.

³Material Safety Data Sheets are required to be available by U.S. Federal Regulation (29 CFR 1910.1200). See Appendix III for additional information.

5.2.2 Facility Considerations: Safety considerations above may establish special facility or handling requirements such as automatic fire protection systems, special test area ventilation or personal protective clothing, etc. One of the first engine test facility considerations is to determine the amount of fuel required, that is, the size of the cell fuel tank, the bulk tank, special transportation requirements, etc. This can be determined by the test duration, heating values of the alternative fuel(s), projected combustion efficiency, and the average energy consumption rate of the conventional fuel. For test consistency, the total quantity of fuel required may need to be prepared or stored as a single batch with limits dictated by the weathering performance of the fuel (for example, loss of volatile components, oxidation stability, etc.).

Containment of the fuel is an important aspect, since incompatibilities between the fuel and equipment may cause changes in fuel uniformity or composition that could result in poor test consistency. Assessment of fuel compatibility with tank, lines, valves, seals, pumps, coolers, etc., should include a detailed review of every component of the supply system from the delivery container to the combustion chamber.

Fuel viscosity, stoichiometry, and melting points will determine whether supply lines or pumps need to be sized differently or special temperature controls added. Care should be taken when heating fuels to reduce viscosity such that an unsafe fuel condition is not created, or that degradation of the fuel does not occur. Extra energy added to the engine fuel handling system to overcome adverse fuel properties should be taken into consideration in calculations of performance comparisons (see Section 6).

5.2.3 Engine Fuel System(s) Considerations: The objectives of the particular alternative fuel test will determine if fuel system modifications are needed. The simplest approach is to utilize the conventional fuel system if compatible, and to document the change in power or performance that occurs with the alternative fuel. Possible overloading of the engine or drive train, or shortage of power for the application should then be addressed.

If the test is to demonstrate equivalent engine or application performance with the alternative fuels, then the fuel system setting, fuel metering, metering control, or even the entire system may need to be changed for equal energy input rate. In this case, the flexibility to operate on conventional fuels when they are available may not be able to be retained unless an independent secondary system is added for the alternative fuel. However, it should be noted that if a dual fuel or pilot fuel system is used, care should be taken to avoid overloading or overfueling the engine.

5.2.4 Performance and Emissions Test: Instrumentation and procedures described in SAE codes and listed in paragraph 5.1 should be consulted when performing engine tests. Additional guidance can be found in Appendices I through V of this document. Deviations from these procedures for specific test goals should be outlined clearly in the report on the test results. Additional instrumentation may be required to accurately determine total energy input (that is, voltage and current of auxiliary pumps or heaters necessary for proper use of a specific alternative fuel, unique density,

5.2.4 Performance and Emissions Test: (Continued)

volume, or mass fuel rate measuring requirements, etc.). Since combustion characteristics can be drastically influenced by an alternative fuel, in-cylinder dynamic combustion pressure measurements (when available) are most valuable in determining the direction for preliminary engine adjustment or modification. Simultaneous exhaust gas emission measurements further enhance this understanding when these measurements are correlated to inlet fuel rates and fuel chemistry.

Emissions (both regulated and unregulated) also are ultimately necessary to determine environmental impact of a final configuration. The possibility of unexpected problems that could alter the emission results should be a major concern when testing with alternative fuels. Some of these concerns are discussed in Appendix V.

5.2.5 Calculation of Results: Calculation procedures to determine the results obtained from testing with alternative fuels generally require only the inclusion of additional terms or changes to constants in the standard equations found in SAE codes listed in paragraph 5.1. However, some required changes are more broad based, such as determining the energy accounting system with which to report the results. Formal test reports should document or reference changes made to standard calculations, and methods used for energy input accounting, including the boundaries or limits of the accounting technique.

Specific guidance on calculation changes for engine dynamometer performance testing is given in Appendix IV. Similar guidance on emission measurements is given in Appendix V.

5.2.6 Other Considerations: Alternative fuel engine tests can contribute to technical information and understanding in many different areas. Areas that are sometimes investigated are (1) whether combustion can occur, if so (2) the quality of combustion, (3) emissions from the fuel or combustion, (4) health and safety, immediate or long term, (5) materials compatibility with engine components or lubricants, (6) specific or overall operating performance, (7) appropriate lubricant properties and their possible effect on engine performance, (8) steady-state dynamometer performance or transient operation, (9) cold starting, local ambient or expected extremes, (10) structural impact, (11) short term wear or extended life, (12) specific application performance or all applications, etc. These areas as well as many others have generally been defined or investigated for conventional fuels. Testing an alternative fuel in one or several of these areas may not imply acceptable results in other areas. The overall assessment of an alternative fuel may require a more comprehensive understanding and testing program than a normal development program with conventional fuels.

6. PERFORMANCE COMPARISONS:

Due to the different properties of alternative fuels, special care must be exercised when comparing the performance of engine and vehicular systems operated on non-petroleum fuels. It is useful in this regard to specify recommended parameters for reporting operating conditions, engine performance, and emissions results.

- 6.1 Engine Performance Parameters: Engine performance tests should be conducted as closely as possible in accordance with recommended procedures to be found in the SAE Handbook for the size and type of engines at hand. Necessary changes should be documented where specific SAE codes and procedures do not address specific test goals. It is recommended that speed be reported in revolutions per minute (rpm) and that load be reported as mean effective pressure in units of kPa. Maximum values of speed and loads should also be given. Other engine parameters, such as displacement and number of cylinders, should be reported so that parameters given above can be converted into power and torque.

Acceptable practice for multicylinder engines is to report performance parameters on a brake basis, that is, brake power, brake mean effective pressure, etc. In the case of the development of new engine systems for the combustion of alternative fuels, initial work is often performed on single-cylinder engines. In this case, engine friction data are usually available either from motoring tests or as determined from brake power and measured pressure-volume diagrams. Since single-cylinder engines typically have lower mechanical efficiencies than multicylinder engines, the use of both indicated and brake mean effective pressure and associated parameters is recommended for single-cylinder tests.

- 6.2 Efficiency: For engines operating on alternative fuels, it is recommended that comparisons be made on the basis of thermal efficiency on a brake or indicated basis, in agreement with the guidelines from the previous paragraph. In reporting the thermal efficiency, it should be clearly stated which heating value of the fuel is used, and the physical state of the fuel in the heating value tests. Specific energy consumption, as described in Section 3, is also an acceptable measure of efficiency. Again, the heating value used should be clearly stated.

In the calculation of engine efficiency, care must be taken to include all of the input energy to the engine. For example, if engine-mounted systems are used which change the chemical structure of the fuel and the systems require external energy sources for start-up or continuous operation and if the energy supplied to operate the systems is not supplied by the fuel input to the engine, this additional energy must be added to the fuel energy supplied when determining the thermal efficiency of the engine. Also, any energy supplied to the engine or associated fuel processing system which is stored before a test and then depleted during a test, such as a battery which is charged before a test and then discharged during a test, must also be included in the energy supply to the engine. In other words, if a system is essential for the operation of the engine, or is an "on-board" fuel processing system, or is used to supplement the power output of the engine, the energy consumed should be included in the calculation of thermal efficiency.

- 6.3 Exhaust Emissions: Exhaust emissions should be reported on a basis which gives a true comparison of the effects of the fuel used. For engine tests, it is recommended that emissions be reported on a brake or indicated specific basis in terms of grams emitted per hour per unit of power (g/kW-hr)⁴. The emission index, typically grams of emitted substance per kilogram (kg) of fuel consumed, is also a satisfactory parameter for reporting emission results. If the emissions are a weighted average, the test cycle and weighting procedures should be described.
- 6.4 Fuel Composition: Fuel composition should be reported on a basis that allows a true comparison of and evaluation of the fuel used. It is preferred that blend fractions of common fuels as well as elemental fractions be reported on a mass basis. If reported on a different basis (for example, volume or energy split), sufficient information should be included that will allow a determination of the mass fractions (where possible ASTM D 2421 should be used). In addition to the basic composition information, the phase of the fuel (liquid, gas, or solid) as used by the engine should be clearly evident in the report of the results.
- 6.5 Mixture Strength: Since many alternative fuels have stoichiometric fuel-air ratios which are significantly different from the typical values for pure hydrocarbon fuels, special care should be exercised when reporting mixture strength. The recommended parameter is the fuel-air equivalence ratio as defined in Section 3 and paragraph 4.3. In reporting the properties of the fuel, the stoichiometric fuel-air ratio of the fuel tested should be given, but the equivalence ratio should be the only parameter used for the actual comparison of mixture strength.

⁴The U.S. Federal and State of California Emission Regulations for Heavy-Duty Vehicles require emissions to be reported in the non-SI unit of g/BHP-h.

Appendix I

SAE Handbook Documents That
May Be Affected by Use of Alternative Fuels¹

<u>SAE Number</u>	<u>Title</u>
<u>I.1 Power Test Codes²:</u>	
J607	Small Spark Ignition Engine Test Code
J1228	Marine Engine Rating Code
J1312	Procedure for Mapping Engine Performance - Diesel and Spark Ignition Engines
J1349	Engine Power Test Code - Spark Ignition and Diesel
<u>I.2 Emissions:</u>	
J35	Diesel Smoke Measurement Procedure
J177	Measurement of Carbon Dioxide, Carbon Monoxide, and Oxides of Nitrogen in Diesel Exhaust
J215	Continuous Hydrocarbon Analysis of Diesel Emissions
J254	Instrumentation and Techniques for Exhaust Gas Emissions Measurement
J255	Diesel Engine Smoke Measurement
J1003	Diesel Engine Emission Measurement Procedure
J1088	Test Procedure for the Measurement of Exhaust Emissions from Small Utility Engines
J1094	Constant Volume Sampler System for Exhaust Emissions Measurement
J1130	Determination of Emissions from Gas Turbine Powered Light Duty Surface Vehicles
J1243	Diesel Emission Production Audit Test Procedure
<u>I.3 Fuels:</u>	
J312	Automotive Gasolines
J313	Diesel Fuels
J1297	Alternative Automotive Fuels
J1498	Heating Values of Fuels
J1829	Stoichiometric Air/Fuel Ratios of Automotive Fuels

¹This list may not cover all of the SAE Handbook documents that could be affected by use of Alternative Fuels. The more obvious documents are listed here. Note also that SAE continually updates the documents listed in the SAE Handbook and the latest version should be consulted.

²Note SAE J245 and J816 have been superseded by SAE J1349.

Appendix I (Continued)

SAE NumberTitleI.4 Vehicle Fuel Economy:

J1082	Fuel Economy Measurement - Road Test Procedure
J1256	Fuel Economy Measurement - Road Test Procedure - Cold Start and Warm-Up Fuel Economy
J1376	Fuel Economy Measurement Test (Engineering Type) for Trucks and Buses

I.5 Other:

J30	Fuel and Oil Hoses
J905	Fuel Filter Test Methods
J1350	Selection and Application Guidelines for Diesel, Gasoline, and Propane Fired Liquid Cooled Engine Pre-Heaters

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Appendix II

ASTM Test Methods That May Be Useful for Characterizing
Fuel Properties¹

<u>ASTM Number</u>	<u>ASTM Title</u>
D 4175	Standard Terminology Relating to Petroleum, Petroleum Products, and Lubricants
<u>Fuel Properties</u>	
D 56	Test Method for Flash Point by Tag Closed Tester
D 93	Test Method for Flash Point by Pensky-Martens Closed Tester
D 323	Test Method for Vapor Pressure of Petroleum Products (Reid Method)
D 613	Test Method for Ignition Quality of Diesel Fuels by the Cetane Method
D 909	Test Method for Knock Characteristics of Aviation Gasolines by the Supercharge Method
D 976	Methods for Calculated Cetane Index of Distillate Fuels
D 1298	Test Method for Relative Density (Specific Gravity) or API Gravity of Crude Petroleum and Liquids Petroleum Products by Hydrometer Method
D 2623	Test Method for Knock Characteristics of Liquefied Petroleum (LP) Gas by the Motor (LP) Method
D 2699	Test Method for Knock Characteristics of Motor Fuels by the Research Method
D 2700	Test Method for Knock Characteristics of Motor and Aviation Fuels by the Motor Method
D 2885	Test Method for Research and Motor Method Octane Ratings Using On-Line Analyzers
D 2886	Test Method for Knock Characteristics of Motor Fuels by the Distribution Octane Number (DON) Method
D 4052	Test Method for Density and Relative Density of Liquids by Digital Density Meter
<u>Heating Value</u>	
D 240	Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter
D 1405	Method for Estimation of Net Heat of Combustion of Aviation Fuels
D 1826	Test Method for Calorific Value of Gases in Natural Gas Range by Continuous Recording Calorimeter

¹This list may not cover all of the ASTM Test Methods or procedures that may be of use in characterizing fuel properties. For further information, consult the most current "Annual Book of ASTM Standards." Additionally, most ASTM Test Methods explicitly state the class or range of substances for which the procedures are valid. Departures from these substances or modifications to the procedures run the risk of erroneous results. However, if departures or modifications are made, they should be well documented, and the documentation should include an estimation of potential errors in the results.

Appendix II (Continued)

ASTM NumberASTM TitleHeating Value (cont'd)

D 2015	Test Method for Gross Calorific Value of Solid Fuel by the Adiabatic Bomb Calorimeter
D 2382	Test Method for Heat of Combustion of Hydrocarbon Fuels by Bomb Calorimeter (High Precision Method)
D 3286	Test Method for Gross Calorific Value of Coal and Coke by the Isothermal-Jacket Bomb Calorimeter
D 3588	Method for Calculating Calorific Value and Specific Gravity (Relative Density) of Gaseous Fuels
D 4529	Test Method for Estimation of Net Heat of Combustion of Aviation Fuels
E 711	Test Method for Gross Calorific Value of Refuse Derived Fuel (RDF-3) by the Bomb Calorimeter

Fuel Composition

D 129/ IP 61	Test Method for Sulfur in Petroleum Products (General Bomb Method)
D 1018	Test Method for Hydrogen in Petroleum Fractions
D 1072	Test Method for Total Sulfur in Fuel Gases
D 1266/ IP 107	Test Method for Sulfur in Petroleum Products (Lamp Method)
D 1552	Test Method for Sulfur in Petroleum Products (High-Temperature Method)
D 1685	Test Method for Traces of Thiophene in Benzene by Spectrophotometry
D 2385	Test Method for Hydrogen Sulfide and Mercaptan Sulfur in Natural Gas (Cadmium Sulfate Iodometric Titration Method)
D 2420	Test Method for Hydrogen Sulfide in Liquefied Petroleum (LP) Gases (Lead Acetate Method)
D 2421	Standard Method for Interconversion of Analysis of C ₅ and Lighter Hydrocarbons to Gas-Volume, Liquid-Volume, or Weight Basis
D 2504	Test Method for Noncondensable Gases in C ₃ and Lighter Hydrocarbon Products by Gas Chromatography
D 2622	Test Method for Sulfur in Petroleum Products (X-Ray Spectrographic Method)
D 2725	Test Method for Hydrogen Sulfide in Natural Gas (Methylene Blue Method)
D 2747	Test Method for Trace Quantities of Total Sulfur in Volatile Organic Liquids (Oxy-Hydrogen Combustion Method)
D 2784	Test Method for Sulfur in Liquefied Petroleum Gases (Oxy-Hydrogen Burner or Lamp)
D 2785	Test Method for Trace Quantities of Total Sulfur (Wickbold and Beckman Combustion Apparatus)
D 3031	Test Method for Total Sulfur in Natural Gas by Hydrogenation
D 3120	Test Method for Trace Quantities of Sulfur in Light Liquid Petroleum Hydrocarbons by Oxidative Microcoulometry
D 3227/ IP 342	Test Method for Mercaptan Sulfur in Gasoline, Kerosene, Aviation Turbine and Distillate Fuels (Potentiometric Method)

Appendix II (Continued)

ASTM NumberASTM TitleFuel Composition (cont'd)

D 3228	Test Method for Total Nitrogen In Lubricating Oils by Modified Kjeldahl Method
D 3230	Test Method for Salts in Crude Oil (Electrometric Method)
D 3235	Test Method for Solvent Extractables in Petroleum Wax
D 3246	Test Method for Sulfur in Petroleum Gas by Oxidative Microcoulometry
D 3343	Method for Estimation of Hydrogen Content of Aviation Fuels
D 3431	Test Method for Trace Nitrogen in Liquid Petroleum Hydrocarbons (Microcoulometric Method)
D 3701/ IP 338	Test Method for Hydrogen Content of Aviation Turbine Fuels by Low Resolution Nuclear Magnetic Resonance Spectrometry
D 3703	Test Method for Peroxide Number of Aviation Turbine Fuels
D 4045	Test Method for Sulfur in Petroleum Products by Hydrogenolysis and Rateometric Colorimetry
D 4046	Test Method for Alkyl Nitrate in Diesel Fuels by Spectrophotometry
D 4084	Method for Analysis of Hydrogen Sulfide in Gaseous Fuels (Lead Acetate Reaction Rate Method)
D 4294	Test Method for Sulfur in Petroleum Products by Non-Dispersive X-Ray Fluorescence Spectrometry
E 147	Specification for Apparatus for Microdetermination of Nitrogen by Kjeldahl Method
E 148	Specification for Apparatus for Microdetermination of Nitrogen by Dumas Method
E 191	Specification for Apparatus for Microdetermination of Carbon and Hydrogen in Organic and Organo-Metallic Compounds
E 258	Test Method for Total Nitrogen in Organic Materials by Modified Kjeldahl Method
E 379	Specification for Apparatus for Direct Microdetermination of Oxygen in Organic Compounds

Appendix III

Potential Sources of
Health and Safety Information¹

III.1 One source of health and safety related information is standard reference books (three are listed in the bibliography - there may be others). In addition, many countries may have government agencies which have promulgated standards, regulations, or which have related information for exposure, handling, storage, transport, or disposal of particular fuels or fuel components. The primary agencies in the U.S.A. are OSHA - Occupational Safety and Health Administration, Dept. of Labor; NIOSH - National Institute for Occupational Safety and Health, Dept. of Health and Human Services; DOT - Department of Transportation; and EPA - Environmental Protection Agency. Another source of information are the codes of Fire Protection Associations such as the National Fire Protection Association in the U.S.A.

III.2 To distinguish between the various U.S. Federal Agencies in general terms, OSHA can be described as a regulatory Administration primarily concerned with setting exposure limits for various substances in the work place. NIOSH primarily makes available research data on toxicology and exposure levels to OSHA for OSHA's regulation process. DOT (in this context) deals mainly with the interstate transportaton of various substances. The EPA is concerned with emission hazards from the transportation, storage, and use of the fuel or fuel components, as well as the hazards that may occur from disposal (water supplies, land fill, etc.).

OSHA Standards can be found in a set of books called the Code of Federal Regulations (CFR) which are published and updated each year by the U.S. Federal Government. These books are labeled by "Title" numbers, and are available in most major university libraries. OSHA information is in Title 29. The most relevant portions of Title 29 are in Part 1910, (Subpart Z-Toxic and Hazardous Substances) Section 1000 (Air Contaminants) and Section 1200 (Hazard Communication). The correct references would be 29CFR1910.1000 and 29CFR1910.1200.

Section 1200 includes the Federal requirements for Material Safety Data Sheets (MSDS). The sheets are required by regulation to be provided to "manufacturing purchasers" by "chemical manufacturers" or "importers" (as defined in Section 1200) for each hazardous chemical (also defined in Section 1200). The sheets include labeling information, physical and chemical characteristics, physical hazards, health hazards, primary route of entry, permissible exposure limits, whether it is listed as a carcinogen, general precautions, control measures, emergency procedures, and a phone number for additional information.

¹The information provided in this Appendix is not to be taken as endorsement of any particular reference nor is it to be implied that with a review of these references the obligation to investigate health and safety related issues is necessarily complete. The information listed is only intended as a guideline with which to start the investigation.

Appendix III (Continued)

EPA standards and regulations are contained in Title 40 of the Code of Federal Regulations.

III.3 Reference Books:

- III.3.1 Condensed Chemical Dictionary, G. G. Hawley, Van Nostrand Reinhold - (use latest edition).
- III.3.2 Dangerous Properties of Industrial Materials, N. I. Sax, Van Nostrand Reinhold - (use latest edition).
- III.3.3 Handbook of Toxic and Hazardous Chemicals, M. Sittig, Noyes Publications - (use latest edition).
- III.3.4 Safe Handling and Testing of Alternative Fuels, U.S. Department of Energy, Number DOE/CS/-56051-6 UC-96, January of 1982.
- III.3.5 Additional sources (that is, reference books and data bases) can be found in Appendix C to 29 CFR 1910.1200.

III.4 Data Bases:

The data bases referenced are primarily computer records of chemicals and their physical, environmental, and toxicological properties. Both public and commercial data bases are available. Most require a fee for use in addition to a computer terminal and trained personnel.

There are also many commercial literature search companies that for a fee will access or provide access to private as well as public data bases. As would be expected, the information available from the different sources may overlap. To aid in identifying such sources, those that are currently available to Environmental Protection Agency personnel through the EPA library system are listed in Table AIII-1 and -2. There may be other sources that may be more convenient, useful, relevant, etc. Information on locating additional sources should be available through the local public or university library.

III.5 National Fire Protection Agency (NFPA) Codes:
(Battery March Park, Quincy, MA 00269)

National Fire Protection codes are mainly concerned with combustion of flammable substances at atmospheric pressure. Codes that may be relevant are listed below.

- III.5.1 Hazardous Chemical Data, No. 49.
- III.5.2 Combustion Engines and Gas Turbines, No. 37.
- III.5.3 Flammable and Combustible Liquids Classification, No. 321.
- III.5.4 Flammable and Combustible Liquids Code, No. 30.
- III.5.5 Laboratories Using Chemicals, No. 45.
- III.5.6 Flammable Liquids, Gases, and Volatile Solids, No. 325M.
- III.5.7 Manual of Hazardous Chemical Reactions, No. 491M.

Table AIII-1

Chemical Information Data Bases

<u>Data Base</u>	<u>Description</u>	<u>Source Code</u> ¹
CAS On-line	Chemical Abstract Service. Records of chemical abstracts covering journals, books, etc., from all areas of chemistry and chemical engineering worldwide through STN International.	10
CIS	Chemical Information Service. A collection of scientific and regulatory databases pertaining to chemistry.	2, 3
DIALOG	Dialog Information Service, Inc. An umbrella-like collection of many databases; includes hazardous waste information.	4
MSDS	Material Safety Data Sheets on various substances.	7
HAZARDLINE	Regulatory, health and precautionary information on more than 78,000 industrial chemicals. This database is available through a number of sources, including NLM, BRS, and OHS.	1, 6, 7
NLM	National Library of Medicine. Includes a collection of specialized hazardous waste databases. - TOXLINE - Covers pharmacological, biochemical, physiological, environmental, and toxicological effects of drugs and other chemicals. - TOXNET - A new NLM Toxicology Network.	1, 4, 5
OHM/TADS	Oil and Hazardous Materials/Technical Assistance Data System. Overall data fields covering transportation combustibility, toxicity to humans and animals, odor, disposal, and hazards, among other topics.	2
OHS	Occupational Health Services. Contains some 5,000 chemical profiles, including names, CERCLA ² information, disposal information and other materials.	7

¹See Table AIII-2, other sources may be available. Consult your local public or university library.

²Comprehensive Environmental Response Compensation and Liability Act (Superfund).

Table AIII-1 (Continued)

Chemical Information Data Bases

<u>Data Base</u>	<u>Description</u>	<u>Source Code</u> ¹
RTECS	Registry of Toxic Effects of Chemical Substances (RTECS), U.S. Department of Health and Human Services, CDC, NIOSH, Cincinnati, OH 49226.	2, 5, 8
SDS	Systems Development Corp. A collection of databases including those with scientific and technical material.	9

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¹See Table AIII-2, other sources may be available. Consult your local public or university library.

Table AIII-2

Data Base Sources²

<u>Source Code¹</u>	<u>Source</u>
1	BRS Information Technologies, 1200 Rt. 7, Latham, NY 12110; 800/345-4BRS.
2	Chemical Information Systems, a subsidiary of Fein Marquart Assoc., 7215 York Road, Baltimore, MD. 21212; 301/321-8840; 800/247-8737.
3	ICI, Information Consultants, Inc., 1133-15th Street, NW, Suite 300, Washington, DC 20005; 202/822-5200.
4	DIALOG - Information Services, Inc., 3460 Hillview Ave., Palo Alto, CA 94304; 415/858-3785; 800/3DIALOG.
5	Medlars Management Section, National Library of Medicine, 8600 Rockville Pike, Bethesda, MD 20894; 301/496-6193; outside of Maryland 800/638-8480.
6	Mead Data Central, P.O. Box 933, Dayton, OH 45401; 513/865-6800; 800/227-4908.
7	OHS (Occupational Health Services), 400 Plaza Drive, P.O. Box 1505, Secaucus, NJ 07094; 201/865-7500; 800/223-8978.
8	Printed RTECS is generally available through the Superintendent of Documents, U.S. GPO, Washington, DC 20402; 202/783-3238. Yearly microfiche updates are available through the GPO. Computer tapes are available through the National Technical Information Service (NTIS), Port Royal Road, Springfield, VA 22161; 703/487-4650.
9	SDC Information Services, 2525 Colorado Avenue, Santa Monica, CA 90406; 213/453-6194; in California - 800/352-6689; outside of California - 800/421-7229.
10	STN-Columbus, % Chemical Abstracts Service, P.O. Box 02228, Columbus, OH 43202; 614/421-3600; inside Ohio - 800/848-6538; outside Ohio - 800/848-6533.

¹From Table AIII-1.²Other sources may be available; consult your local public or university library.

Appendix IV

Guideline for Adjustments to Power Test
Code Calculations When Using Alternative Fuels

IV.1 Introduction

If published engine test results from various sources are more directly comparable, the selection of the best engine and alternative fuel option to meet the job requirements specified by the manufacturer or the end user can be more efficient. The partial list of affected SAE documents in Appendix I is a focus to help the reader recognize breadth of scope of the requirements. This appendix focuses on both the general and the specific modifications that might be required in the performance calculations for SAE J1349, Engine Power Test Code - Spark Ignition and Diesel. Similar modifications should be considered when using SAE J607, J1228, J1312, or J1376, or when performing unique tests outside of the scope of the various test codes. SAE J916 (SI units of measure) is a further guide for uniformity of results.

IV.2 General Guidance:

IV.2.1 Airflow measurement with alternative fuels should pose no special problems, unless a vapor fuel is aspirated into the air stream before airflow measurement is performed. In this case, caution should be used to obtain the correct airflow measurement, and in subsequent calculations. Volume flow measurements need to be converted to mass flow for fuel-air ratio calculations.

IV.2.2 Barometer corrections for humidity and the humidity calculation shall be in accordance with SAE J177.

IV.2.3 Energy Rate for alternative fuels includes the energy in the actual mass fuel flow plus any auxiliary equipment power not utilized by the engine when running on conventional fuels.

IV.2.3.1 Fuel Energy Rate requires a knowledge of the fuel's lower heating value and the mass rate of fuel flow. The mass rate of fuel flow is preferably determined by a mass/time measurement.

Mass fuel rate (F) is simply

$$F = (m_f) / (\Delta t) \quad \text{[AIV-1]}$$

where: m_f = mass of fuel consumed, g
 Δt = time, s

If a volume/time fuel measurement system is used, the density of the fuel at the measured fuel temperature must be included

$$F = [(1000)(V_f)(d)] / (\Delta t) \quad \text{[AIV-2]}$$

where: V_f = volume of fuel, L or m^3
 d = density of fuel, kg/L or kg/m^3

Appendix IV (Continued)

The fuel energy rate then is:

$$\text{FER} = (F) (\text{LHV}) \quad [\text{AIV-3}]$$

where: FER = fuel energy rate, kJ/s
 F = fuel rate, g/s
 LHV = fuel lower heating value, MJ/kg

IV.2.3.2 Other Energy required to change viscosity, vaporize, pump, inject, maintain solution, assist ignition, etc., if it is not engine driven, must be included in fuel (energy) consumption results for comparison to engines running on other alternative or conventional fuels.

IV.2.4.2 Total Energy Rate

$$\text{TER} = \text{FER} + \text{OE} \quad [\text{IAV-4}]$$

where: TER = total energy rate to the engine, kJ/s--note that one kJ/s equals one kW.
 FER = fuel energy rate, kJ/s
 OE = other energy, kW or kJ/s

IV.2.4 Specific Energy Consumption

$$\text{BSEC} = \text{TER}/\text{bp} \quad [\text{AIV-5}]$$

$$\text{ISEC} = \text{TER}/\text{ip} \quad [\text{AIV-6}]$$

where: bp = brake power, kW
 ip = indicated power, kW
 BSEC = brake specific energy consumption, (kJ/s)/kW
 ISEC = indicated specific energy consumption, (kJ/s)/kW

IV.2.5 Stoichiometric Fuel-Air Ratio is a function of the fuel type, and varies according to the fuel composition. See paragraph 4.3 for stoichiometric determination. Stoichiometric (f/a) ratio calculations in 40 CFR 86.345 (Subpart D), SAE J1088 (paragraph 5.2.2 and Appendices A, B, and C), and J177 (Sections 5 and 6) must be modified to include molecular fuel oxygen, nitrogen, or sulfur when present, and are generally not adequate for alternative fuels (see Appendix V for additional insight).

IV.2.6 Thermal Efficiency

$$\text{BTE} = 100 [\text{bp}/\text{TER}] = 100 [1/\text{BSEC}] \quad [\text{AIV-7}]$$

$$\text{ITE} = 100 [\text{ip}/\text{TER}] = 100 [1/\text{ISEC}] \quad [\text{AIV-8}]$$

where: BTE = brake thermal efficiency (%)
 ITE = indicated thermal efficiency (%)

Note: The fractional thermal efficiency is the inverse of the specific of the specific energy consumption.

Appendix IV (Continued)

IV.3 Specific Guidance for SAE J1349:

IV.3.1 Power Correction factors for non-standard ambient or inlet test conditions shall be determined in accordance with SAE J1349 except for the computation of the mass fuel rate per stroke per unit of engine displacement, or "q" in mg/L-cycle, for diesel engines. The term, which was developed for typical diesel fuels, must be stated on an energy basis because of the varied heating values associated with alternative fuels. (SAE J1498 provides additional information on heating values of fuels.)

$$q = [(120,000 \text{ F}) / (\text{DN})] (\text{LHV}_A / \text{LHV}_B) \text{ mg/L-cycle} \quad [\text{AIV-9}]$$

for a 4-stroke engine (constant 120 000 would be 60 000 for a 2-stroke engine).

where: F = fuel rate, g/s
 D = engine displacement, L
 N = engine speed, r/min
 LHV_A = lower heating value of alternative or off-spec fuel, MJ/kg
 LHV_B = lower heating value of spec diesel fuel, MJ/kg

This corrects the mass flow of the alternative fuel to the mass flow of a typical diesel fuel that would provide the same energy input. Thus modified, "q" can be used in the standard engine factor and in the corrected brake power calculations as specified by SAE J1349.

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Appendix V

Guidelines for Adjustments to Emission
Measurement Calculations When Using Alternative FuelsV.1 Overview:

The U.S. Environmental Protection Agency has published regulations with specified emissions test procedures and equipment performance requirements. These regulations apply to gasoline and diesel powered light duty passenger cars and trucks, and heavy duty gasoline and diesel engines that are being operated on either gasoline or diesel fuels (Title 40, Code of Federal Regulations, Part 86). SAE also has several standard emission measurement procedures (see Appendix I). Regulated emissions from the classes of vehicles and engines described include hydrocarbons (HC)¹, carbon monoxide (CO), oxides of nitrogen (NO_x), and diesel particulate and smoke. All other emissions (for example, PNA, BaP, formaldehyde,² and sulfates) are considered unregulated emissions. The U.S. Clean Air Act and the 1977 Clean Air Act Amendments imply compliance with applicable regulations, but there are no specific procedures for measuring emissions when using alternative fuels².

Because the chemical composition of the alternative fuel used will influence the exhaust emission species, procedures developed for gasoline and diesel fuels may not have adequate safeguards to prevent erroneous or incomplete emission measurements. The possibility of unexpected problems that could alter the emissions results should be a major concern when testing with alternative fuels. The following possible problem areas illustrate some of these concerns:

V.1.1 Emissions Analyzers: The limitations of the emissions analyzers should be identified for the particular alternative fuel under test. For example, current flame ionization detectors (FID's) have a different voltage to concentration response for different classes of organic matter (OM) compounds. When calibrated in accordance with procedures for gasoline and diesel fueled vehicles or engines, these instruments may not be capable of accurately measuring the compound of interest in the exhaust of an engine running on an alternative fuel.

¹Unburned or partially burned fuel emissions have traditionally been labeled hydrocarbon emissions. However, hydrocarbon fuels traditionally have not included oxygen bearing fuels. Southwest Research Institute, under contract to the U.S. EPA, developed the term "Organic Matter" (OM) emissions to encompass all classes of unburned fuel emissions. See the report referenced in Section V.1.4.

²A Notice of Public Rulemaking (NPRM) for emission standards and test procedures for methanol fueled Light Duty Vehicles (LDV) and trucks (LDT) was published by the U.S. EPA on August 29, 1986 in the Federal Register. For methanol, vehicle emission levels of formaldehyde are proposed to be included in the measure of organic matter, and therefore could be considered a regulated emission component.

Appendix V (Continued)

The probable difference in species composition of the engine exhaust may produce a different instrument response. The instrument, therefore, may not produce a reading representative of the actual concentration, resulting in erroneous emission measurements.

Other analyzers for either regulated or unregulated emissions may also be affected by the change in species or a change in the ratio of species in the exhaust of an alternative fueled engine when compared to one fueled by either gasoline or diesel fuel.

New species that may be in the exhaust which were not present in the exhaust with typical gasolines and diesel fuels could also interfere with the measurement of the species desired. Changes in concentration of well known interfering species such as water could cause problems. High water concentrations might, under some circumstances, overwhelm water traps in the CO and CO₂ analyzers such that the extra water would be measured as increases in CO and CO₂. In chemiluminescent NO_x analyzers, additional water may increase the amount of quench and reduce the NO_x reading.

In some cases, mathematical corrections can be made after the measurement of data to modify the emissions readings from the instrument to compensate for errors known to result from the use of an alternative fuel. In addition to evaluating the potential impact that the alternative fuel may have on the instruments, and attempting to alleviate these effects, emission data from alternative fueled engines should clearly indicate whether any correction to the data has been made, and the technique used to derive the correction factor.

V.1.2 Sample Handling Systems: A change in concentration or a change in type of exhaust emissions species due to the use of alternative fuels may affect the proper transport of the sample to the emissions analyzer. For example, some alternatively fueled engines may produce significantly more water than current gasoline or diesel fueled engines. This may lead to the need for heated lines, or in the case of CVS testing, higher dilution ratios to prevent water condensation when alternative fuels are used. The use of an alternative fuel may also cause the unburned fuel emissions to change such that increased sample system temperature and reduced transport time are necessary to prevent these new species of unburned fuel emissions from condensing in the sample system. Some alternative fuels may produce compounds that are more corrosive to the sample transport hardware, or react with the other constituents in the exhaust gas. In this case, different system materials may be needed and extremely short transport times may be required to minimize the time available for reactions.

V.1.3 New Emissions: An alternative fuel may create a class of emissions that are not normally associated with the particular type of engine being tested. For example, the use of some forms of alternative fuels in SI engines might possibly create high levels of particulates that are not normally associated with an SI engine.