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PROPERTIES OF ALTERNATIVE FUELS

October 1994

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U.S. Department
of Transportation
Federal Transit
Administration

PROPERTIES OF ALTERNATIVE FUELS

October 1994

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16. Abstract
This report is intended as a concise reference for transit managers and other fleet managers on the properties of alternative vehicle fuels. The report contains information on a wide variety of fuel properties for a number of alternative fuels under consideration for transit bus fleets. Properties of conventional fuels are also included for comparison. The fuels covered include: hydrogen, compressed natural gas, propane gas, methanol, ethanol, biodiesel, gasoline, and diesel. For each of these fuels, key properties are listed under the categories of Physical Properties, Chemical Composition, Combustion Properties, Energy Content, Energy Comparisons, and Health Properties. The report contains references to related literature sources.

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METRIC / ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^{2}) = 6.5 square centimeters (cm^{2})
1 square foot (sq ft, ft^{2}) = 0.09 square meter (m^{2})
1 square yard (sq yd, yd^{2}) = 0.8 square meter (m^{2})
1 square mile (sq mi, mi^{2}) = 2.6 square kilometers (km^{2})
1 acre = 0.4 hectares (he) = 4,000 square meters (m^{2})

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gr)
1 pound (lb) = .45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^{3}) = 0.03 cubic meter (m^{3})
1 cubic yard (cu yd, yd^{3}) = 0.76 cubic meter (m^{3})

TEMPERATURE (EXACT)

[(x - 32) (5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^{2}) = 0.16 square inch (sq in, in^{2})
1 square meter (m^{2}) = 1.2 square yards (sq yd, yd^{2})
1 square kilometer (km^{2}) = 0.4 square mile (sq mi, mi^{2})
1 hectare (he) = 10,000 square meters (m^{2}) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gr) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

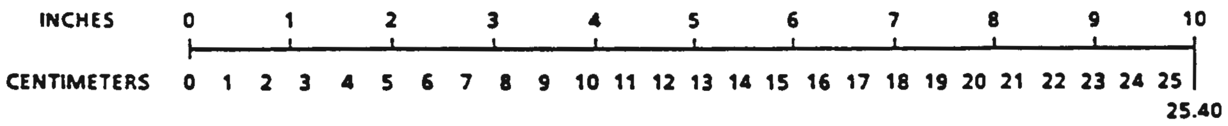
VOLUME (APPROXIMATE)

1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^{3}) = 36 cubic feet (cu ft, ft^{3})
1 cubic meter (m^{3}) = 1.3 cubic yards (cu yd, yd^{3})

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH-CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT-CELCIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and/or other conversion factors, see NBS Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50. SD Catalog No. C13 10 286.

INTRODUCTION

As interest in alternative fuels grows, the need for data on various fuel properties grows also. This report on alternative fuel properties is intended to be provide a convenient reference to a number of alternative fuel properties. In this edition, two additional alternative fuels have been included -- hydrogen and biodiesel.

Hydrogen is of importance not only as a possible internal combustion engine fuel, but also for its role as the primary fuel for fuel cells. The information for hydrogen is given for fuel storage in either gaseous or liquid form. However, we recognize that developments in metal hydride technology to store hydrogen are also proceeding.

Biodiesel fuels are prepared through the reaction of various vegetable oils with methanol in a process called transesterification. Thus, the biodiesel data given are for this product and not for the vegetable oil itself. Because the amount of research data on the use of biodiesel fuels is less than for some other alternative fuels, not all fuel property data were available for inclusion in this report. Additional data will be included in later editions.

Even though some penalty in readability is extracted, an attempt has been made to provide literature references to virtually all the data in the table. Many of these references also contain explanatory material that could not to be included in the tables proper. The reader is urged to consult these references and also the accompanying glossary for additional information on the origin, derivation, and meaning of the data in the tables.

Fuel cost data, formerly contained in this document, are now contained in a separate alternative fuel cost report which can be updated more frequently.

This report was prepared by Michael J. Murphy of Battelle for the Federal Transit Administration, Office of Technical Assistance and Safety. The technical leadership and guidance of Steven Sill and Vincent R. DeMarco is gratefully acknowledged.

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UNIT ABBREVIATIONS

Abbrev.	Unit	Description
C	degrees Celsius	temperature
cP	centipoise	viscosity
gal	gallons	fluid volume
GJ	gigajoules	energy (10^9 joules)
g/m^2-s	grams per square meter per sec.	burning rate: mass per unit area per unit time
kg	kilograms	mass
kg/L	kilograms per liter	density
kJ/kg	kilojoules per kilogram	energy per unit mass
kJ/L	kilojoules per liter	energy per unit volume
kPa	kilopascals	pressure (103 kPa= 1 atm)
mJ	millijoules	energy
MJ	megajoules	energy
MJ/kg	megajoules per kilogram	energy per unit mass
m/s	meters per second	velocity
ppm	parts per million	vapor concentration
uS/m	microsiemens per meter	electrical conductivity

OTHER ABBREVIATIONS

Alg.	Algerian
coeff.	coefficient
cond.	conductivity
CHG	Compressed hydrogen gas
CNG	Compressed natural gas
exp.	expansion
HHV	higher heating value (energy with heat of water vaporization)
ign.	ignition
LHG	Liquefied hydrogen gas
LHV	lower heating value (energy without heat of water vaporization)
LM	Commercial liquid methane
LNG	Liquified natural gas
N.A.	Not applicable
NG	Natural gas
press.	pressure
pt.	point
temp.	temperature
wt.	weight

See Glossary for additional definitions and explanation.

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ALTERNATIVE FUEL DATA SUMMARY: Physical Properties

See accompanying glossary for explanation of terms.

	Hydrogen	Natural Gas	Propane	Methanol	Ethanol	Biodiesel	Gasoline	Diesel Fuel
Appearance	Colorless gas	Colorless gas	Easily liquified gas	Clear liquid	Clear liquid	Amber liquid	Clear-amber liquid	Amber liquid
Boiling pt., C	-253(1)	-162(2)	-38(3)	65(4)	78.5(5)	approx. 280(6)	33-213(7)	188-340(8)
Fuel density, kg/L	CHG: 0.0175(9) LHG: 0.071(10)	CNG: 0.19(11) Algerian LNG: 0.453(12) LM: 0.424(13)	0.51(14)	0.791(15)	0.789(16)	0.889(17)	0.77(18)	0.81-0.88, Avg:0.85(19)
Relative vapor density, air = 1.00	0.07(20)	0.60(21)	1.5(22)	1.11(23)	1.6(24)	10(25)	2-4(26)	4-6(27)
Reid vapor press, kPa	N.A. (gas)	N.A.(gas)	1400(28)	32(29)	15(30)	0.001(31)	50-100(32)	0.1-1.5(33)
Heat of vapor., kJ/kg	58(34)	509(35)	425(36)	1167(37)	920(38)	440(39)	275-365(40)	225-280(41)
Water soluble	no(42)	no(43)	no(44)	yes(45)	yes(46)	no(47)	no(48)	no(49)
Viscosity, cP @ 15 C	H_2: 0.009(50) LHG: 0.013(51)	NG: 0.011(52) CNG: 0.018(53) LNG: 0.202(54)	0.008 (gas)(55) 0.121 (liq)(56)	0.65(57)	1.3(58)	3.6 @ 40 C(59)	0.64(60)	2.6(61)
Cloud pt., C	N.A. (gas)	N.A. (gas)	N.A. (gas)	N.A.(62)	N.A.(63)	0(64)		-20(65)
Pour pt., C	N.A. (gas)	N.A. (gas)	N.A. (gas)	N.A.(66)	N.A.(67)	-4(68)	-60(69)	-29(70)

	Hydrogen	Natural Gas	Propane	Methanol	Ethanol	Biodiesel	Gasoline	Diesel Fuel
Coeff. Cubical Exp.	CHG: N.A.(71)	CNG: N.A.(72)	1.6(73)	1.20(74)	1.12(75)		1.08(76)	0.81(77)
Electrical Cond., uS/m	N.A. (gas)	N.A. (gas)	N.A. (gas)	44(78)	0.14(79)		0.000001(80)	0.0001(81)

(revised 13 October 1994)

ALTERNATIVE FUEL DATA SUMMARY: Chemical Composition

See accompanying glossary for explanation of terms.

	Hydrogen	Natural Gas	Propane	Methanol	Ethanol	Biodiesel	Gasoline	Diesel Fuel
Chemical Formula	H_2	85-95% CH_4 (82)	Mainly C_3H_8 (83)	CH_3OH (84)	C_2H_5OH (85)	$CH_{1.8}O_{0.1}$ (86)	C_4-C_{12}	C_{14}-C_{19}
Carbon, wt %	0	75.44(87)	81.71(88)	37.49(89)	52.14(90)	78.0(91)	86.74(92)	87.3(93)
Hydrogen, wt %	100.0	24.56(94)	18.28(95)	12.58(96)	13.13(97)	11.7(98)	13.22(99)	12.5(100)
Oxygen, wt %	0	0(101)	0(102)	49.94(103)	34.73(104)	10.3(105)	0(106)	0(107)
Sulfur, ppm by weight	0	11(108)	<123(109)	<100(110)	<100(111)	<50 ppm(112)	339(113)	2000(114) After 1 Oct 93: <500(115)
Nitrogen, ppm by weight	0	0(116)	0(117)	0	0	29(118)	29(119)	

(revised 25 February 1994)

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ALTERNATIVE FUEL DATA SUMMARY: Combustion Properties

See accompanying glossary for explanation of terms.

	Hydrogen	Natural Gas	Propane	Methanol	Ethanol	Biodiesel	Gasoline	Diesel Fuel
Flash point, C	Already a gas	Already a gas	Already a gas	11(120)	13(121)	118(122)	-43(123)	58-116, Avg.73(124)
Autoignition temp., C	400(125)	450(126)	450(127)	385(128)	365(129)	250(130)	300(131)	230(132)
Spark ign. energy, mJ	0.017(133)	0.29(134)	0.25(135)	0.14(136)	0.2(137)		0.24(138)	0.24(139)
Flammability Limits, %	4.0-75(140)	5-15(141)	2.1-9.5(142)	6.7-13(143)	3.3-5.4(144)		1.4-7.6(145)	0.6-5.5
Stoichiometric Air/Fuel Ratio	34.5(146)	17.2(147)	15.7(148)	6.45(149)	9.0(150)	12.6(151)	14.7(152)	15.0(153)
Octane number	Poor(154)	117(155)	106(156)	99(157)	98(158)	73(159)	87(160)	30(161)
Cetane number		-10(162)	-5 to 0(163)	0-4(164)	5-15(165)	47(166)-52(167)	8-14(168)	40-47, Avg. 45(169)
Flame visibility, relative		0.6(170)	0.6(171)	0.0003(172)	0.03(173)		1.0(174)	1.0(175)
Pool burn rate, g/m^2-s	CHG: N.A. (gas) LHG: 16(176)	CNG: N.A. (gas) LNG: 78(177)	99(178)	17(179)	15(180)		55(181)	35-39(182)

	Hydrogen	Natural Gas	Propane	Methanol	Ethanol	Biodiesel	Gasoline	Diesel Fuel
Flame spread rate, m/s	N.A. (gas)	N.A. (gas)	N.A. (gas)	2-4(183)	unk.	unk.	4-6(184)	0.02-0.08
Flame temp., C	2115(185)	1884(186)	1990(187)	1886(188)	1930(189)	2003(190)	1977(191)	2054(192)

(revised 9 March 1994)

ALTERNATIVE FUEL DATA SUMMARY: Energy Content

See accompanying glossary for explanation of terms.

	Hydrogen	Natural Gas	Propane	Methanol	Ethanol	Biodiesel	Gasoline	Diesel Fuel
Fuel energy value , LHV, MJ/kg	120.0(193)	Avg. NG: 47.0(194) Alg. LNG: 48.8(195) LM: 49.7(196)	46.3(197)	20.1(198)	27.0(199)	37.3(200)	42.6(201)	42.8(202)
Fuel energy value, LHV, MJ/L	CHG: 2.1(203) LHG: 8.5(204)	CNG: 8.9(205) Alg. LNG: 22.1(206) LM: 21.1(207)	23.6(208) In tank: 18.9(209)	15.9(210)	21.3(211)	33.2(212)	32.9(213)	36.4(214)
Fuel energy value, HHV, MJ/kg	141.8(215)	Avg. NG: 52.2(216) Alg. LNG: 54.1(217) LM: 55.2(218)	50.3(219)	22.7(220)	29.7(221)	39.7(222)	45.4(223)	45.6(224)
Fuel energy value, HHV, MJ/L	CHG: 2.5(225) LHG: 10.0(226)	CNG: 9.8(227) Alg. LNG: 22.5(228) LM: 23.4(229)	25.7(230) In tank: 20.5(231)	18.0(232)	23.4(233)	35.3(234)	34.0(235)	38.8(236)

(revised 30 August 1994)

ALTERNATIVE FUEL DATA SUMMARY: Energy Comparisons

See accompanying glossary for explanation of terms.

	Hydrogen	Natural Gas	Propane	Methanol	Ethanol	Biodiesel	Gasoline	Diesel Fuel
Mass fuel with same energy (LHV) as one mass of diesel:	0.36(237)	0.91(238)	0.92(239)	2.13(240)	1.59(241)	1.15(242)	1.00(243)	1(244)
Mass fuel with same energy (LHV) as one mass of gasoline:	0.36(245)	0.91(246)	0.92(247)	2.12(248)	1.58(249)	1.14(250)	1(251)	1.00(252)
Volume fuel with same energy (LHV) as one volume of diesel:	CHG: 17.3(253) LHG: 4.3(254)	CNG: 4.09(255) LNG: 1.65(256)	1.54(257) In tank: 1.93(258)	2.29(259)	1.71(260)	1.10(261)	1.11(262)	1(263)
Volume fuel with same energy (LHV) as one volume of gasoline:	CHG: 15.7(264) LHG: 3.9(265)	CNG: 3.70(266) LNG: 1.49(267)	1.37(268)	2.04(269)	1.54(270)	0.99(271)	1(272)	0.89(273)

(revised 30 August 1994)

ALTERNATIVE FUEL DATA SUMMARY: Health Properties

See accompanying glossary for explanation of terms.

	Hydrogen	Natural Gas	Propane	Methanol	Ethanol	Biodiesel	Gasoline	Diesel Fuel
Odor threshold, ppm	Odorless	10,000(with odorant)(274)	4200 (with odorant)(275)	2000 (100-5900)(276)	10(277)	See value for diesel fuel(278)	0.2(279)	0.08(280)
TLV-TWA, ppm	none est.(281)	10,500(282)	1000(283)	200(284)	1000(285)	See value for diesel fuel(286)	300(287)	14(288)
TLV-STEL, ppm	none est.(289)	none est.(290)	none est.(291)	250(292)	none est.(293)	none est.(294)	500(295)	none est.(296)
Vapor Hazard Ratio	N.A. (gas)	N.A. (gas)	N.A. (gas)	820(297)	76(298)	See value for diesel fuel(299)	approx. 1000	approx. 1

(revised 1 March 1994)

GLOSSARY

Appearance The way the fuel appears to the eye.

Autoignition Temperature The temperature at which a substance will ignite in the absence of an external ignition source. In other words, ignition from heat alone and not from a spark or flame.

Biodiesel Biodiesel fuel is a fuel made by reacting vegetable oils, such as soybean or canola oil with methanol to make a product that is less viscous and more suitable as a diesel engine fuel. The term *biodiesel* is sometimes used to refer to a mixtures of this vegetable oil product with diesel fuel. Biodiesel made from soybean oil is sometimes called methyl soyate because chemically this fuel is in a class of chemical compounds called esters which are usually named with an -ate ending.

Boiling Point The temperature at which the liquid boils at a given pressure, usually atmospheric. Methanol and ethanol are pure substances and have definite boiling points, while natural gas, commercial propane, gasoline and diesel fuel, being mixtures, boil over a range of temperatures.

Carbon, Hydrogen, Oxygen Weight Percent The percent by weight of each element in the fuel. The weight percents can be used to calculate an apparent chemical formula for the fuel, which may then be used in combustion calculations.

Cetane Number A measure of the tendency of a fuel to cause engine knock in a diesel engine. The scale is based on a comparison of the knock tendency of the fuel in question to that of two reference fuels, cetane and alpha-methylnaphthalene. Cetane, which has good compression ignition properties is assigned a value of 100. Alpha-methylnaphthalene, which has very poor compression ignition qualities is assigned a value of zero. Fuels with high cetane numbers tend to have low octane numbers and vice versa.

Chemical Formula The chemical composition. Methanol and ethanol are pure substances with a definite formula. Natural gas, commercial propane, gasoline, and diesel fuel have variable compositions.

Cloud Point The temperature at which a liquid fuel just shows a cloud or haze of wax crystals when cooled under standard test conditions as defined in ASTM test D-2500.

Coeff. Cubical Expansion The coefficient of cubical expansion is the increase in volume experienced by the liquid fuel as the temperature increases. The coefficients cited in this table are 1000 times the change in fuel density per degree C at 20 C.

Diesel Fuel Diesel fuel the most common fuel for heavy duty engines and therefore a standard of comparison for other, alternative fuels.

Electrical Conductivity The degree to which a fluid will conduct electricity. A typical conductivity for water in a city supply (Chicago) is 26,000 uS/m.

Ethanol Ethanol is an alternative fuel that belongs (along with methanol, isopropanol, etc) to the general class of alcohols. Ethanol fuel is usually used in some type of fuel blend. Because of its tax-free status, fuel ethanol must be "denatured" to prevent diversion to a taxable use for beverages. This means some other chemical is mixed with the ethanol such that the resulting mixture cannot be consumed. There are many different approved denaturants. These denaturants are chosen to be compatible with the intended use of the ethanol while also being difficult to remove.

Flammability Limits The range of volume percents of fuel vapors in air over which burning can occur. Below the lower flammability limit there is not enough fuel to burn. Above the higher flammability limit there is not enough air to support combustion.

Gasoline In this report gasoline refers to 87 octane unleaded gasoline.

Flash Point The temperature below which the liquid does not produce sufficient vapors for immediate ignition by an external ignition source. If a flammable substance is not above its flash point, it must be heated to the flash point before ignition can occur.

Heat of Vaporization The amount of heat energy necessary to vaporize one kilogram of liquid fuel. For comparison, the latent heat of vaporization of water is 2550 kJ/kg.

Flame Spread Rate The speed with which a flame will spread across the surface of a liquid pool of fuel.

Flame Temperature The temperature of a flame burning a stoichiometric mixture (neither fuel nor air is in excess) of fuel and air.

Flame Visibility The amount of visible light produced by a flame of burning fuel relative to the flame from burning unleaded gasoline.

Fuel Density The mass of the fuel per volume. Water has a density of 1 kg/L.

Fuel Energy Value The amount of energy contained in the fuel. Fuel heating values are listed as higher heating values, HHV, or lower heating values, LHV, depending on whether the latent heat of vaporization of the water formed from combustion of the fuel is considered to be available. If it is, then the higher or gross heating value is used. If the water formed from combustion is not condensed and therefore not considered to be available, then the lower, or net, heating value is used. In USA practice, gross fuel heating values are generally used for all types of energy analysis, except in the transportation industry. In Europe lower or net heating values are more common. In this table fuel values are also given on both a mass and a volume basis, e.g. MJ/kg and MJ/L.

Hydrogen An alternative fuel consisting of hydrogen gas. Hydrogen gas has the formula H_2.

Methanol Methanol is an alternative fuel that belongs (along with ethanol, isopropanol, etc) to the general class of alcohols. Fuel methanol is usually at least 98 percent pure methanol.

Natural Gas An alternative fuel, natural gas is the same natural gas burned for heating and cooking. Natural gas varies in composition with location. Natural gas is usually more than 90 percent methane with smaller amounts of other hydrocarbons.

Nitrogen, ppm by Weight The amount of nitrogen that is chemically combined with the fuel. This nitrogen content does not include nitrogen gas from the atmosphere.

Octane Number A measure of the tendency of a fuel to cause engine knock in a spark-ignited engine. The scale is based on a comparison of the knock tendency of the fuel in question to that of two reference fuels, isooctane and n-heptane. Isooctane, which has good knock resistance is assigned a value of 100. N-heptane, which has very poor knock resistance is assigned a value of zero. Fuels with high octane numbers tend to have low cetane numbers and vice versa.

Odor Threshold The lowest concentration at which the human nose can detect that an odor is present (compared to purified, odor-free air), but not necessarily identify the odor.

Pool Burn Rate The rate at which fuel in a pool of fuel burns. The rate is given as a the mass of fuel burned per unit of time per unit area. The burn rate is a measure of the intensity of the fire which may result from a given size fuel spill.

Pour Point The lowest temperature at which a fuel will just flow when tested under standard conditions as defined in ASTM test D-97.

Propane Commercial propane usually contains 90 percent or more of the hydrocarbon propane along with smaller amounts of other hydrocarbons. Liquefied petroleum gas (LPG) is a broader term which includes commercial propane as well as other fuel gas mixtures (such as butane-propane mixtures) which can be liquified under moderate pressure.

Reid Vapor Pressure The pressure exerted by the vapor over the liquid in a closed container of a specified type at 38 C. Reid vapor pressure is a measure of the fuel volatility.

Relative Fuel Vapor Density The density of the fuel vapor compared to air. Thus, on this scale, air equals 1.00.

Viscosity The resistance to flow of a fluid. The viscosity of water at room temperature is approximately 1.0 cP.

Spark Ignition Energy The minimum spark size required to ignite the most flammable mixture of the vapor and air under the most favorable conditions. The details of the test apparatus used can easily account for a factor of two variation in the experimental results. Note also that a typical two-cell flashlight produces about 2000 mJ of energy per second, so the ignition energies listed represent very small amounts of energy.

STEL Short-term exposure limit type of threshold limit value. The maximum concentration to which workers can be exposed for a period of up to 15 minutes without suffering from irritation, tissue change, or narcosis.

Stoichiometric Air/Fuel Ratio The mass of air that is just enough to burn a unit mass of fuel. A stoichiometric ratio of 6.45 implies that one kg of fuel requires 6.45 kg of air for combustion if neither fuel nor air is to be in excess.

Sulfur, ppm by Weight The amount of sulfur in the fuel.

TLV Threshold limit value. The airborne concentration of a substance to which it is believed that nearly all workers may be exposed day after day without adverse effects.

TWA Time-weighted average type of threshold limit value. The time-weighted average for an 8-hour workday or a 40-hour week to which all workers can be repeatedly exposed without ill effects.

Volume Fuel with Same Energy This is the ratio of the volumetric energy content of the fuel to that of gasoline or diesel fuel. Numerically, this is the ratio of the lower heating value(LHV) in MJ/L for the fuel to the lower heating value of gasoline or diesel fuel in MJ/L.

Vapor Hazard Ratio Ratio (ppm/ppm) of equilibrium vapor pressure at 25 C to the threshold limit value. The vapor hazard ratio is a measure of the tendency of a substance to form hazardous vapors.

Water Solubility The degree to which the fuel will dissolve in water. Methanol and ethanol will mix with water in any proportion, and are said to be totally miscible with water.

REFERENCES

1. Handbook of Chemistry and Physics, 72nd Edition. David R. Lide, Editor, 1991. p. 5-62.

2. Kirk-Othmer Encyclopedia of Chemical Technology. 3rd Edition, p. 11-645.

3. Kirk-Othmer Encyclopedia of Chemical Technology. 3rd Edition, p. 14-392. This is the temperature at which 95 percent of the LPG has evaporated.

4. Handbook of Chemistry and Physics.

5. Handbook of Chemistry and Physics.

6. Estimate of boiling point of methyl linoleate at 1 atmosphere pressure using Clausius-Clapeyron equation and reduced pressure data from Merck Index, 11th Edition, p. 958.

7. Initial and final boiling points for industry average gasoline. "Fuel Blending and Analysis for the Auto/Oil Air Quality Improvement Research Program," R.H. Pahl and M.J. McNally, SAE Paper 902098 (1990).

8. Boiling point range for national average diesel number 2 as reported in "Diesel Fuel Oils, 1986," C.L. Dickson and P.W. Woodward, National Institute for Petroleum and Energy Research, Bartlesville, OK. p. 9.

9. Based on a tank pressure of 24 MPa and an interpolation of compressibility factors calculated from specific volume data for hydrogen as listed in Perry's Chemical Engineers Handbook, Sixth Edition. p. 3-197.

10. Handbook of Chemistry and Physics, 72nd Edition, David R. Lide, Editor, 1991. p. 4.14.

11. Density of compressed methane gas. The density of a gas varies with pressure. A pressure of 24 MPa was chosen here for the density calculation.

12. At -162 C. Based on composition of Algerian LNG reported in "Fuel Issues for Liquefied Natural Gas Vehicles," William E. Liss, Shiro Okazaki, George H. Acker, Jr., and David S. Moulton, SAE paper 922360, 1992 and the LNG fuel density calculation in "How to Calculate Density of NG at Cryogenic Temperatures," G.J. Boyle and D. Reece, Oil and Gas Journal, 18 Jan 1971, p. 56. The Algerian LNG was 91.5 percent methane, 5.6 percent ethane, 1.5 percent propane, 0.5 percent butanes, and 0.9 percent nitrogen.

13. At -162 C. Based on LNG of composition 99.6 mole percent methane and 0.4 mole percent nitrogen and the LNG fuel density calculation in "How to Calculate Density of NG at Cryogenic Temperatures," G.J. Boyle and D. Reece, Oil and Gas Journal, 18 Jan 1971, p. 56.

14. Kirk-Othmer Encyclopedia of Chemical Technology 3rd Edition, p. 14-392. This is the density of propane.

15. Handbook of Chemistry and Physics.

16. Handbook of Chemistry and Physics.

17. "Combustion of Soybean Oil Methyl Ester in a Direct Injection Diesel Engine," Kyle W. Scholl and Spencer C. Sorenson, SAE paper 930934. Table 3.

18. Density of industry average gasoline. "Fuel Blending and Analysis for the Auto/Oil Air Quality Improvement Research Program," R.H. Pahl and M.J. McNally, SAE Paper 902098 (1990).

19. National average and range for diesel number 2 fuels as reported in "Diesel Fuel Oils, 1986," C.L. Dickson and P.W. Woodward, National Institute for Petroleum and Energy Research, p. 9.

20. Vapor density is calculated from the ratio of the molecular weight of hydrogen, 2, to the molecular weight of air, 29.

21. Vapor density is calculated for natural gas with the U.S. average heating value as compared to air.

22. Vapor density is calculated from the ratio of the molecular weight of propane, 44.1, to the molecular weight of air, 29.

23. Vapor density is calculated from the ratio of the molecular weight of methanol vapor, 32, to the molecular weight of air, 29.

24. Vapor density is calculated from the ratio of the molecular weight of the vapor to the molecular weight of air, 29.

25. Based on molecular weight of methyl linoleate, 294. Methyl linoleate is the principal constituent of methyl soyate accounting for 50-60 percent of the methyl soyate mixture.

26. Vapor density is calculated from the ratio of the molecular weight of the vapor to the molecular weight of air, 29.

27. Vapor density is calculated from the ratio of the molecular weight of the vapor to the molecular weight of air, 29.

28. Kirk-Othmer Encyclopedia of Chemical Technology, 3rd Edition, Vol. 17, p. 269.

29. Calculated vapor pressure at 37.8 C.

30. Calculated vapor pressure at 37.8 C.

31. Estimate of vapor pressure of methyl linoleate at 38 C using Clausius-Clapeyron equation and reduced pressure boiling point data from Merck Index, 11th Edition, p. 958.

32. Range for average winter and summer unleaded gasolines as reported in "Motor Gasolines," DOE publications DOE/BETC/PPS-83/1 and DOE/BETC/PPS-83/3.

33. Material Safety Data Sheet for No. 2 fuel oil prepared by Marathon Oil Company.

34. Matheson Gas Data Book, Sixth Edition, Matheson Corporation, 1980. p. 365.

35. Internal Combustion Engines and Air Pollution, E.F. Obert, p. 235. Value listed is for methane.

36. Internal Combustion Engines and Air Pollution, E.F. Obert, p. 235. Value listed is for propane.

37. Internal Combustion Engines and Air Pollution, E.F. Obert, p. 241.

38. Internal Combustion Engines and Air Pollution, E.F. Obert, p. 241.

39. Estimated for methyl linoleate from vapor pressure data and Clasius-Clapeyron equation. Vapor pressure data from Merch Index, 11th Edition. p. 958.

40. Internal Combustion Engines and Air Pollution, E.F. Obert, p. 235-241. Value listed is range for typical gasoline components.

41. Internal Combustion Engines and Air Pollution, E.F. Obert, p. 235-241. Value listed is for typical diesel fuel components.

42. One liter of water will dissolve 18 mL of hydrogen. Compare 48 mL per liter of water for oxygen and 14 mL per liter of water for nitrogen. Gas solubility data from Matheson Gas Data Book, 6th Edition, pp. 365, 562,and 522.

43. One liter of water will dissolve 33 mL of methane, the principal constituent of natural gas. Compare 48 mL per liter of water for oxygen and 14 mL per liter of water for nitrogen. Gas solubility data from Matheson Gas Data Book, 6th Edition, pp. 441, 562,and 522.

44. One liter of water will dissolve 65 mL of propane, the principal constituent commercial propane. Compare 48 mL per liter of water for oxygen and 14 mL per liter of water for nitrogen. Gas solubility data from Matheson Gas Data Book, 6th Edition, pp. 615, 562,and 522.

45. "Alcohols as Motor Fuel," J.L. Keller, Hydrocarbon Processing, May 1979. p. 132.

46. "Alcohols as Motor Fuel," J.L. Keller, Hydrocarbon Processing, May 1979. p. 132.

47. Handbook of Chemistry and Physics, 73rd Edition, David R. Lide Editor. p. 3-308. Data for methyl linoleate, a typical component of biodiesel fuel.

48. "Alcohols as Motor Fuel," J.L. Keller, Hydrocarbon Processing, May 1979. p. 132.

49. "Alcohols as Motor Fuel," J.L. Keller, Hydrocarbon Processing, May 1979. p. 132.

50. Matheson Gas Data Book, 6th Edition, page 365.

51. Matheson Gas Data Book, 6th Edition, page 365.

52. Matheson Gas Data Book, 6th Edition, page 441. Value given is for methane at a temperature of 20 C and a pressure of 1 atm.

53. Viscosity for methane at 20 C, 1 atm corrected to 20 C, 200 atm using the reduced pressure method described in, Transport Phenomena, R.B. Bird, W.E. Steward, and E.N. Lightfoot, p. 17.

54. Viscosity of liquid methane at -180 C. Matheson Gas Data Book, 6th Ed. p. 441.

55) Matheson Gas Data Book, 6th Edition, page 615. Value given is for propane.

56) ASHRAE Handbook of Fundamentals, 1985 ed. p. 17.41.

57. "A Neat Methanol Direct Injection Combustion System for Heavy-Duty Applications," C.A. Kroeger, SAE Paper 861169.

58. "A Neat Methanol Direct Injection Combustion System for Heavy-Duty Applications," C.A. Kroeger, SAE Paper 861169.

59. Calculated from the kinematic viscosity and density given in "Combustion of Soybean Oil Methyl Ester in a Direct Injection Diesel Engine," Kyle W. Scholl and Spencer C. Sorenson, SAE paper 930934. Table 3.

60. "A Neat Methanol Direct Injection Combustion System for Heavy-Duty Applications," C.A. Kroeger, SAE Paper 861169.

61. "A Neat Methanol Direct Injection Combustion System for Heavy-Duty Applications," C.A. Kroeger, SAE Paper 861169.

62. Methanol is a pure substance and does not show a cloud point aside from the freezing point.

63. Ethanol is a pure substance and does not show a cloud point aside from the freezing point.

64. Value given is for sunflower oil-based biodiesel fuel. The cetane number of soybean oil-based biodiesel fuel is expected to be similar. Sunflower oil value from: "Sunflower Methyl Esters for Direct Injected Diesel Engines" K.R. Kaufman and M. Ziejewski, Transactions of the American Society of Agricultural Engineers, 1626 (1964).

65. Value given is for Phillips 2-D reference fuel. "Sunflower Methyl Esters for Direct Injected Diesel Engines" K.R. Kaufman and M. Ziejewski, Transactions of the American Society of Agricultural Engineers, 1626 (1964).

66. Methanol is a pure substance and does not show a pour point aside from the freezing point.

67. Ethanol is a pure substance and does not show a pour point aside from the freezing point.

68. Value given is for sunflower oil-based biodiesel fuel. The cetane number of soybean oil-based biodiesel fuel is expected to be similar. Sunflower oil value from: "Sunflower Methyl Esters for Direct Injected Diesel Engines" K.R. Kaufman and M. Ziejewski, Transactions of the American Society of Agricultural Engineers, 1626 (1964).

69. Value is for 87 octane aviation gasoline. "Handbook of Aviation Fuel Properties," Coordinating Research Council, 1983. p. 4.

70. Value given is for Phillips 2-D reference fuel. "Sunflower Methyl Esters for Direct Injected Diesel Engines" K.R. Kaufman and M. Ziejewski, Transactions of the American Society of Agricultural Engineers, 1626 (1964).

71. Since the compressed gas is contained, an increase in temperature causes an increase in pressure, but no change in volume.

72. Since the compressed gas is contained, an increase in temperature causes an increase in pressure, but no change in volume.

73. Value given is for pentane. Values for actual LPG constituents are not expected to differ greatly.

74. Perry's Chemical Engineers' Handbook, 6th Edition, R.H. Perry and D. Green. p. 3-106.

75. Perry's Chemical Engineers' Handbook, 6th Edition, R.H. Perry and D. Green. p. 3-106.

76. Perry's Chemical Engineers' Handbook, 6th Edition, R.H. Perry and D. Green. p. 9-10.

77. Perry's Chemical Engineers' Handbook, 6th Edition, R.H. Perry and D. Green. p. 9-10. Interpolated value for diesel fuel of density 0.850 kg/L.

78. Alcohols and Ethers, API Publication 4261, July 1988. p. 80.

79. Alcohols and Ethers, API Publication 4261, July 1988. p. 80.

80. Alcohols and Ethers, API Publication 4261, July 1988. p. 80.

81. Alcohols and Ethers, API Publication 4261, July 1988. p. 80.

82. In this report the natural gas composition used is that for Atlanta natural gas as listed in Gas Engineers Handbook, Industrial Press 1974, Table 2-9, p. 2/10. A gas with this composition has a heating value equal to the national average as given in the U.S. Energy Information Administration Monthly Energy Review, April 1990, p. 123.

83. LPG includes "any material having a vapor pressure not exceeding that allowed for commercial propane composed predominantly of the following hydrocarbons either by themselves or in mixtures: propane, propylene, butane, and butylenes." (Liquified Petroleum Gases Handbook 2nd Ed., T.C. Lemoff, editor, p. 5.) Thus, the composition of LPG can be highly variable. Special-Duty Propane (HD-5) is usually specified for use in internal combustion engines. Special-duty propane consists of propane with no more than 5 percent propylene and no more than 2.5 percent butane and heavier. Properties of special duty propane of composition 95 percent propane, 2.5 percent butane and 2.5 percent propylene are given here.

84. Note that methanol fuel is a pure substance with a definite chemical formula and composition.

85. Note that ethanol fuel is a pure substance with a definite chemical formula and composition.

86. Apparent empirical formula based on carbon, hydrogen, oxygen analysis given below.

87. Based on composition of Atlanta natural gas as listed in Gas Engineers Handbook, Industrial Press 1974, Table 2-9, p. 2/10. A gas with this composition has a heating value equal to the national average as given in the U.S. Energy Information Administration Monthly Energy Review, April 1990, p. 123.

88. Calculated from molecular formula of propane.

89. Calculated from molecular formula.

90. Calculated from molecular formula.

91. "Combustion of Soybean Oil Methyl Ester in a Direct Injection Diesel Engine," Kyle W. Scholl and Spencer C. Sorenson, SAE paper 930934. Table 3.

92. Industry average gasoline as defined in "Fuel Blending and Analysis for the Auto/Oil Air Quality Improvement Research Program", R.H. Pahl and M.J. McNally, SAE paper 902098 (1990). Table 10.

93. Value is for #2 Fuel Oil as reported in North American Combustion Handbook, Second Edition, Richard J. Reed, (1978). p. 16.

94. Based on composition of Atlanta natural gas as listed in Gas Engineers Handbook, Industrial Press 1974, Table 2-9, p. 2/10. A gas with this composition has a heating value equal to the national average as given in the U.S. Energy Information Administration Monthly Energy Review, April 1990, p. 123.

95. Calculated from molecular formula of propane.

96. Calculated from molecular formula.

97. Calculated from molecular formula.

98. "Combustion of Soybean Oil Methyl Ester in a Direct Injection Diesel Engine," Kyle W. Scholl and Spencer C. Sorenson, SAE paper 930934. Table 3.

99. Industry average gasoline as defined in "Fuel Blending and Analysis for the Auto/Oil Air Quality Improvement Research Program", R.H. Pahl and M.J. McNally, SAE paper 902098 (1990). Table 10.

100. Value is for #2 Fuel Oil as reported in North American Combustion Handbook, Second Edition, Richard J. Reed, (1978). p. 16.

101. Natural gas does not generally contain a significant amount of oxygen.

102. Propane does not generally contain a significant amount of oxygen.

103. Calculated from molecular formula.

104. Calculated from molecular formula.

105. "Combustion of Soybean Oil Methyl Ester in a Direct Injection Diesel Engine," Kyle W. Scholl and Spencer C. Sorenson, SAE paper 930934. Table 3.

106. Industry average gasoline as defined in "Fuel Blending and Analysis for the Auto/Oil Air Quality Improvement Research Program", R.H. Pahl and M.J. McNally, SAE paper 902098 (1990). Table 10.

107. Diesel fuel contains a negligible amount of oxygen.

108. "Variability of Natural Gas Composition in Select Major Metropolitan Areas of the United States," W.E. Liss, W.H. Thrasher, G.F. Steinmetz, P. Chowdiah, and A. Attari, Gas Research Institute report GRI-92/0123. p. 15. The sulfur contribution from the natural gas odorant is typically about 8 ppm: "Odorization Manual", American Gas Association, (1983).

109. Based on maximum sulfur content allowed by ASTM specification for HD-5 grade propane. ASTM D-1835.

110. Maximum. Based on CARB draft specifications for alternative fuels.

111. Maximum. Based on CARB draft specifications for alternative fuels.

112. "Combustion of Soybean Oil Methyl Ester in a Direct Injection Diesel Engine," Kyle W. Scholl and Spencer C. Sorenson, SAE paper 930934. Table 3.

113. Industry average gasoline as defined in "Fuel Blending and Analysis for the Auto/Oil Air Quality Improvement Research Program", R.H. Pahl and M.J. McNally, SAE paper 902098 (1990). Table 10.

114. Value is for #2 Fuel Oil as reported in North American Combustion Handbook, Second Edition, Richard J. Reed, (1978). p. 16.

115. The Clean Air Act Amendments of 1990 require that effective 1 October 1993, the sulfur content of diesel fuel is limited to 0.05 weight percent.

116. Although natural gas may contain small percentages of molecular nitrogen, this molecular nitrogen is relatively inert compare to the nitrogen in nitrogen-containing organic compounds.

117. Although commercial propane may contain small percentages of molecular nitrogen, this molecular nitrogen is relatively inert compare to the nitrogen in nitrogen-containing organic compounds.

118. "Combustion of Soybean Oil Methyl Ester in a Direct Injection Diesel Engine," Kyle W. Scholl and Spencer C. Sorenson, SAE paper 930934. Table 3.

119. Industry average gasoline as defined in "Fuel Blending and Analysis for the Auto/Oil Air Quality Improvement Research Program", R.H. Pahl and M.J. McNally, SAE paper 902098 (1990). Table 10.

120. Fire Protection Guide on Hazardous Materials, Seventh Ed., National Fire Protection Association, 1978. p.325M-132.

121. Fire Protection Guide on Hazardous Materials, Seventh Ed., National Fire Protection Association, 1978. p.325M-95.

122. Value given is for Diesel-Bi as listed in "Diesel-Bi" Novamount publication, November 1991. p. 11.

123. Fire Protection Guide on Hazardous Materials, Seventh Ed., National Fire Protection Association, 1978. p.325M-111.

124. National average and range for diesel number 2 fuels as reported in "Diesel Fuel Oils, 1986," C.L. Dickson and P.W. Woodward, National Institute for Petroleum and Energy Research, p. 9.

Fire Protection Guide on Hazardous Materials, Seventh Ed., National Fire Protection Association, 1978. p.325M-109. lists flash point for as 52 C min.

125. Flammability Characteristics of Combustible Gases and Vapors, Michael G. Zabetakis, Bulletin 627, U.S. Bureau of Mines, 1965. p. 115.

126. The value for pure methane is 540 C. The value used here is for propane since "... it is the usual practice to assume that the auto-ignition temperature of a mixture of fuels corresponds to the component with the lowest ignition temperature." "Combustion Fundamentals Relevant to the Burning of Natural Gas," P.F. Jessen and A. Melvin, Progress in Energy and Combustion Science, 2, 239 (1977). Quote and data are from p. 251.

127. Gas Explosions in Buildings and Heating Plant, R.J. Harris, 1983. p. 7. Based on value for propane.

128. Flammability Characteristics of Combustible Gases and Vapors, Michael G. Zabetakis, Bulletin 627, U.S. Bureau of Mines, 1965. p. 115.

129. Flammability Characteristics of Combustible Gases and Vapors, Michael G. Zabetakis, Bulletin 627, U.S. Bureau of Mines, 1965. p. 115.

130. This is a rough estimate based on the autoignition temperature of diesel fuel and the fact that fuels with similar cetane numbers tend to have similar autoignition temperatures.

131. Automotive Handbook, Bosch. 1986. p. 216. For regular gasoline; same ref. lists an autoignition temperature for premium gasoline as 400 C. NFPA 325M lists a value of 456 C for 100 octane aviation gasoline.

132. Flammability Characteristics of Combustible Gases and Vapors, Michael G. Zabetakis, Bulletin 627, U.S. Bureau of Mines, 1965. p. 88. Note: for 55 cetane diesel fuel.

133. Fire Protection Handbook, Sixteenth Edition, National Fire Protection Association. p. 12-72.

134. Gas Explosions in Buildings and Heating Plant, R.J. Harris, 1983. p. 6.

135. Gas Explosions in Buildings and Heating Plant, R.J. Harris, 1983. p. 6.

136. An Introduction to Fire Dynamics, D. Drysdale, 1985. p. 80.

137. Experimental ignition energy data for ethanol has not been found. This value is an estimate based on the observation that "most fuels have a least minimum ignition energy in the region of 0.2 mJ," Combustion, 2nd Edition, I. Glassman, 1987. p. 486.

138. Combustion, Flames and Explosions of Gases, B. Lewis and G. von Elbe, pp. 330ff. Estimated for typical hydrocarbon components. The minimum ignition energies of nearly all hydrocarbons vary over the narrow range of 0.18-0.29 mJ.

139. Combustion, Flames and Explosions of Gases, B. Lewis and G. von Elbe, pp. 330ff. Estimated for typical hydrocarbon components. The minimum ignition energies of nearly all hydrocarbons vary over the narrow range of 0.18-0.29 mJ.

140. Flammability Characteristics of Combustible Gases and Vapors, Michael G. Zabetakis, Bulletin 627, U.S. Bureau of Mines, 1965. p. 115.

141. Flammability Characteristics of Combustible Gases and Vapors, Michael G. Zabetakis, Bulletin 627, U.S. Bureau of Mines, 1965. p. 115. Value given is for methane.

142. Flammability Characteristics of Combustible Gases and Vapors, Michael G. Zabetakis, Bulletin 627, U.S. Bureau of Mines, 1965. p. 115.

143. The vapor pressure of methanol is such that 13 percent by volume is maximum saturated concentration. At 60 C a higher flammability limit of 36 percent is observed. Flammability Characteristics of Combustible Gases and Vapors, Michael G. Zabetakis, Bulletin 627, U.S. Bureau of Mines, 1965. p. 115.

144. The vapor pressure of ethanol is such that 5.4 percent by volume is maximum saturated concentration. At 60 C a higher flammability limit of 19 percent is observed. Flammability Characteristics of Combustible Gases and Vapors, Michael G. Zabetakis, Bulletin 627, U.S. Bureau of Mines, 1965. p. 115.

145. Flammability Characteristics of Combustible Gases and Vapors, Michael G. Zabetakis, Bulletin 627, U.S. Bureau of Mines, 1965. p. 115.

146. Calculated from fuel composition and stoichiometry of combustion reaction.

147. Calculated from fuel composition and stoichiometry of combustion reaction.

148. ASHRAE Handbook 1985 Fundamentals, p. 15.2. Value given fuel composition 95 percent propane, 2.5 percent propene, and 2.5 percent butane.

149. Calculated from fuel composition and stoichiometry of combustion reaction.

150. Calculated from fuel composition and stoichiometry of combustion reaction.

151. "Combustion of Soybean Oil Methyl Ester in a Direct Injection Diesel Engine," Kyle W. Scholl and Spencer C. Sorenson, SAE paper 930934. Table 3.

152. Calculated from fuel composition and stoichiometry of combustion reaction.

153. Calculated from fuel composition and stoichiometry of combustion reaction.

154. Hydrogen's susceptibility to pre-ignition and detonation precludes measurement of the octane number according to the standard procedure. "The Hydrogen Engine: Combustion Knock and the Related Flame Velocity," Transactions of the Engineering Institute of Canada, **2**, 143 (1958).

155. R+M/2. Based on data for pure methane in SAE paper 901499, Table 1. Actual octane rating of natural gas is lower due to presence of other hydrocarbons, such as ethane, which have lower octane numbers.

156. Kirk-Othmer Encyclopedia of Chemical Technology Vol. 11, p. 691. LPG is generally 90-95 percent propane. The presence of a small amount of propene is reported to change the octane number only slightly as compared with pure propane.

157. R+M/2, based on research and motor octane ratings reported in Internal Combustion Engines and Air Pollution, E.F. Obert, p. 241.

158. R+M/2, based on research and motor octane ratings reported in Internal Combustion Engines and Air Pollution, E.F. Obert, p. 241.

159. Estimated, based on a cetane number below and a correlation between octane number and cetane number reported in The Internal Combustion Engine in Theory and Practice, Volume 2, Revised Edition, Charles Fayette Taylor, 1985. p. 147.

160. R+M/2. Based on standard specification for unleaded gasoline.

161. Estimated, based on a cetane number of 45 for diesel fuel and a correlation between octane number and cetane number reported in The Internal Combustion Engine, by F.A.F. Schmidt, p. 140.

162. Estimated, based on an octane number of 120 for methane reported in Internal Combustion Engines by E.F. Obert, p. 234-5, and a correlation between octane number and cetane number reported in The Internal Combustion Engine, by F.A.F. Schmidt, p. 140. Natural gas is generally 80-95 percent methane. The other hydrocarbons present tend to lower the octane number and raise the cetane number of natural gas as compared with pure methane.

163. Estimated, based on an octane number of 106 for propane reported in Kirk-Othmer Encyclopedia of Chemical Technology Vol. 11, p. 691, and a correlation between octane number and cetane number reported in The Internal Combustion Engine, by F.A.F. Schmidt, p. 140. LPG is generally 90-95 percent propane. The presence of propene is reported to change the octane number only slightly as compared

with pure propane.

164. Cetane number values are reported in several reports:

> "Alternative Fuels in Diesel Engines--A Review," C.D. Wood, SAE Paper 810248 (1981).
>
> "Use of Alcohol-in-Diesel-Fuel Emulsions and Solutions in a Medium Speed Diesel Engine," Q.A. Baker, SAE Paper 810254 (1981).
>
> "The Utilization of Alternative Fuels in a Diesel Engine Using Different Methods," E. Holmer, P.S. Berg, B-I Bertilisson, SAE Paper 800544 (1980).
>
> "An Evaluation of Methanol, Ethanol, the Propanols, and the Butanols as Ship Propulsion Fuels," D.O. Newton, David Taylor Navel Ship Research and Development Center Report MAT-75-20 (1976).

165. Cetane number values are reported in several reports:

> "Alternative Fuels in Diesel Engines--A Review," C.D. Wood, SAE Paper 810248 (1981).
>
> "Use of Alcohol-in-Diesel-Fuel Emulsions and Solutions in a Medium Speed Diesel Engine," Q.A. Baker, SAE Paper 810254 (1981).
>
> "The Utilization of Alternative Fuels in a Diesel Engine Using Different Methods," E. Holmer, P.S. Berg, B-I Bertilisson, SAE Paper 800544 (1980).
>
> "An Evaluation of Methanol, Ethanol, the Propanols, and the Butanols as Ship Propulsion Fuels," D.O. Newton, David Taylor Navel Ship Research and Development Center Report MAT-75-20 (1976).

166. Value given is for sunflower oil-based biodiesel fuel. The cetane number of soybean oil-based biodiesel fuel is expected to be similar. Sunflower oil value from: "Diesel Engine Combustion of Sunflower Oil Fuels," J. Zubik, S.C. Sorenson, and C.E. Goering, Transactions of the American Society of Agricultural Engineers, **27**, 1252 (1984).

167. Based on value for Diesel-Bi listed in "Diesel-Bi", Novamont publication, November 1991. p.11. Value is stated to be based on ASTM methods.

168. "A Neat Methanol Direct Injection Combustion System for Heavy-Duty Applications," C.A. Kroeger, SAE Paper 861169.

169. National average and range for diesel number 2 fuels as reported in "Diesel Fuel Oils, 1986," C.L. Dickson and P.W. Woodward, National Institute for Petroleum and Energy Research, p. 9. Marathon Oil Company Specification for #2 Diesel is minimum of 40, and for their #1 Diesel, a minimum of 43. Recent diesel #2 purchases for transit properties are likely to be in the 41-43 range.

170. Estimated to be 0.6 because radiant intensity has been shown to decrease as the hydrogen content of the fuel increases. See Gas Turbine Combustion, A.H. Lefebvre, 1983. p. 272.

171. Estimated to be 0.6 because radiant intensity has been shown to decrease as the hydrogen content of the fuel increases. See Gas Turbine Combustion, A.H. Lefebvre, 1983. p. 272.

172. "Fuel Methanol Additives: Issues and Concerns," J.E. Anderson and R.J. Nichols, 10th Energy Technology Conference and Exposition.

173. "Fuel Methanol Additives: Issues and Concerns," J.E. Anderson and R.J. Nichols, 10th Energy Technology Conference and Exposition.

174. "Fuel Methanol Additives: Issues and Concerns," J.E. Anderson and R.J. Nichols, 10th Energy Technology Conference and Exposition.

175. "Fuel Methanol Additives: Issues and Concerns," J.E. Anderson and R.J. Nichols, 10th Energy Technology Conference and Exposition.

176. "Investigation of Fire and Explosion Accidents in the Chemical, Mining, and Fuel-Related Industries," Joseph M. Kuchta, U.S. Bureau of Mines Bulletin 680. p. 41.

177. Fire Protection Handbook, 16th Edition, Arthur E. Cote and Jim L. Linville, editors, National Fire Protection Association, 1986. p. 21-37

178. Fire Protection Handbook, 16th Edition, Arthur E. Cote and Jim L. Linville, editors, National Fire Protection Association, 1986. p. 21-37

179. Fire Protection Handbook, 16th Edition, Arthur E. Cote and Jim L. Linville, editors, National Fire Protection Association, 1986. p. 21-37

180. Fire Protection Handbook, 16th Edition, Arthur E. Cote and Jim L. Linville, editors, National Fire Protection Association, 1986. p. 21-37

181. Fire Protection Handbook, 16th Edition, Arthur E. Cote and Jim L. Linville, editors, National Fire Protection Association, 1986. p. 21-37

182. Fire Protection Handbook, 16th Edition, Arthur E. Cote and Jim L. Linville, editors, National Fire Protection Association, 1986. p. 21-37 Values given are for heavy fuel oil and kerosene, respectively. The value for diesel fuel is expected to be in between.

183. "Flame Spread Rates Over Methanol Fuel Spills," M.J. Murphy, Combustion Science and Technology, **42**, 223 (1984).

184. "Flame Spread Rates Over Methanol Fuel Spills," M.J. Murphy, Combustion Science and Technology, **42**, 223 (1984).

185. Flames, Their Structure Radiation and Temperature, Third Revised Edition, A.G. Gaydon and H.G. Wolfhard, 1970 p. 303.

186. Calculated using Battelle adiabatic flame temperature software and the heating value and carbon-hydrogen ratio of Atlanta natural gas as listed in Gas Engineers Handbook, Industrial Press 1974, Table 2-9, p. 2/10. A gas with this composition has a heating value equal to the national average as given in the U.S. Energy Information Administration Monthly Energy Review, April 1990, p. 123.

187. Calculated for propane and above heat of combustion using Battelle adiabatic flame temperature software.

188. Calculated for above molecular formula and heat of combustion using Battelle adiabatic flame temperature software.

189. Calculated for above molecular formula and heat of combustion using Battelle adiabatic flame temperature software.

190. Calculated for above molecular formula and heat of combustion using Battelle adiabatic flame temperature software.

191. Calculated for above heat of combustion and assuming hydrogen/carbon ratio of 2.0 using Battelle adiabatic flame temperature software.

192. Calculated for above heat of combustion and assuming hydrogen/carbon ratio of 1.8 using Battelle adiabatic flame temperature software.

193. Perry's Chemical Engineers' Handbook, Sixth Edition, Robert H. Perry and Don Green, Editors, 1984. p. 3-155.

194. Lower heating value of Atlanta natural gas as listed in Gas Engineers Handbook, Industrial Press 1974, Table 2-9, p. 2/10. A gas with this composition has a heating value equal to the national average as given in the U.S. Energy Information Administration Monthly Energy Review, April 1990, p. 123.

195. Based on composition of Algerian LNG reported in "Fuel Issues for Liquefied Natural Gas Vehicles," William E. Liss, Shiro Okazaki, George H. Acker, Jr., and David S. Moulton, SAE paper 922360, 1992. The Algerian LNG was 91.5 percent methane, 5.6 percent ethane, 1.5 percent propane, 0.5 percent butanes, and 0.9 percent nitrogen.

196. Based on the calculated heating value of liquid methane of composition 99.6 mole percent methane and 0.4 mole percent nitrogen.

197. Calculated heating value for fuel composition: propane, 95 percent; propylene, 2.5 percent, butane, 2.5 percent.

198. Internal Combustion Engines and Air Pollution, by E.F. Obert, p. 241. Same value is obtained by using JANAF heats of formation and equation for combustion of methanol:
$CH_3OH(l) + 1.5\ O_2 \rightarrow CO_2 + 2\ H_2O(l)$

199. Internal Combustion Engines and Air Pollution, by E.F. Obert, p. 241. Same value is obtained by using JANAF heats of formation and equation for combustion of ethanol:
$C_2H_5OH(l) + 3\ O_2 \rightarrow 2\ CO_2 + 3\ H_2O(l)$

200. "Combustion of Soybean Oil Methyl Ester in a Direct Injection Diesel Engine," Kyle W. Scholl and Spencer C. Sorenson, SAE paper 930934. Table 3.

201. "Fuel Blending and Analysis for the Auto/Oil Air Quality Improvement Research Program", R.H. Pahl and M.J. McNally, SAE paper 902098 (1990). Table 10.

202. Based on higher heating value above, corrected using the expression: $LHV = HHV - 212(\%H)$, found in Hydrocarbon Fuels, E.M. Goodger, p. 78. The %H was calculated using the expression: $\%H = 26 - (15)(Density)$ found in ASHRAE Handbook, 1985 Fundamentals, p. 15.5.

203. Calculated using the lower heating value for hydrogen gas given above and the density of compressed hydrogen at 25 MPa.

204. Calculated using the lower heating value for hydrogen gas given above and the density of compressed hydrogen at 25 MPa.

205. Calculated using the lower heating value for natural gas given above and the density of compressed methane gas at 240 atm.

206. Based on composition of Algerian LNG reported in "Fuel Issues for Liquefied Natural Gas Vehicles," William E. Liss, Shiro Okazaki, George H. Acker, Jr., and David S. Moulton, SAE paper 922360, 1992 and the LNG fuel density calculation in "How to Calculate Density of NG at Cryogenic Temperatures," G.J. Boyle and D. Reece, Oil and Gas Journal, 18 Jan 1971, p. 56., and the fuel density reported above. The Algerian LNG was 91.5 percent methane, 5.6 percent ethane, 1.5 percent propane, 0.5 percent butanes, and 0.9 percent nitrogen.

207. Based on the calculated heating value of liquid methane of composition 99.6 mole percent methane and 0.4 mole percent nitrogen and the density as given above.

208. Calculated using the lower heating value above and a density of 0.51 kg/L.

209. Effective energy density only 80 percent of theoretical: Because of the possibility of fuel release upon fuel expansion due to an increase in ambient temperature, vehicle propane tanks are equipped with "stop fill" devices which permit only 80 percent of the tank volume to be filled by propane. "An Assessment of Propane as an Alternative Transportation Fuel in the United States," R.F. Webb Corporation report, June 1989. p. 8-30.

210. Calculated using lower heating value above and density of 0.791 kg/L.

211. Calculated using lower heating value above and density of 0.789 kg/L.

212. Calculated using lower heating value above and density from physical properties table.

213. Calculated using the lower heating value above and a density of 0.749 kg/L.

214. Calculated using the lower heating value given above and a density of 0.85 kg/L.

215. Perry's Chemical Engineers' Handbook, Sixth Edition, Robert H. Perry and Don Green, Editors, 1984. p. 3-155.

216. Based on average higher heating value for non-electric utility users of natural gas as listed in U.S. Energy Information Administration Monthly Energy Review, April 1990. p. 123.

217. Based on composition of Algerian LNG reported in "Fuel Issues for Liquefied Natural Gas Vehicles," William E. Liss, Shiro Okazaki, George H. Acker, Jr., and David S. Moulton, SAE paper 922360, 1992 and the LNG fuel density calculation in "How to Calculate Density of NG at Cryogenic Temperatures," G.J. Boyle and D. Reece, Oil and Gas Journal, 18 Jan 1971, p. 56. The Algerian LNG was 91.5 percent methane, 5.6 percent ethane, 1.5 percent propane, 0.5 percent butanes, and 0.9 percent nitrogen.

218. Based on the calculated heating value of liquid methane of composition 99.6 mole percent methane and 0.4 mole percent nitrogen.

219. Calculated heating value for fuel composition: propane, 95 percent; propylene, 2.5 percent, butane, 2.5 percent.

220. <u>Internal Combustion Engines and Air Pollution</u>, by E.F. Obert, p. 241. Same value is obtained by using JANAF heats of formation and equation for combustion of methanol:
$CH_3OH(l) + 1.5\ O_2 \rightarrow CO_2 + 2\ H_2O(l)$

221. <u>Internal Combustion Engines and Air Pollution</u>, by E.F. Obert, p. 241. Same value is obtained by using JANAF heats of formation and equation for combustion of methanol:
$CH_3OH(l) + 1.5\ O_2 \rightarrow CO_2 + 2\ H_2O(l)$

222. "Combustion of Soybean Oil Methyl Ester in a Direct Injection Diesel Engine," Kyle W. Scholl and Spencer C. Sorenson, SAE paper 930934. Table 3.

223. Based on lower heating value listed above, and the percent hydrogen listed below using the expression: LHV = HHV - 212(%H) , found in Hydrocarbon Fuels, E.M. Goodger, p. 78.

224. Based on an average diesel fuel density of 0.85 and a correlation between density and heating value of:

Higher Heating Value, kJ/kg = 51 916 - [8792 (specific gravity)^2]

Correlation from ASHRAE Handbook, 1985 Fundamentals Volume, p. 15.5.

225. Calculated using the higher heating value for hydrogen gas given above and the density of compressed hydrogen at 25 MPa.

226. Calculated using the higher heating value for hydrogen gas given above and the density of compressed hydrogen at 25 MPa.

227. Calculated using the higher heating value for natural gas given above and the density of compressed methane gas at 240 atm.

228. Based on composition of Algerian LNG reported in "Fuel Issues for Liquefied Natural Gas Vehicles," William E. Liss, Shiro Okazaki, George H. Acker, Jr., and David S. Moulton, SAE paper 922360, 1992 and the LNG fuel density calculation in "How to Calculate Density of NG at Cryogenic Temperatures," G.J. Boyle and D. Reece, Oil and Gas Journal, 18 Jan 1971, p. 56., and the fuel density reported above. The Algerian LNG was 91.5 percent methane, 5.6 percent ethane, 1.5 percent propane, 0.5 percent butanes, and 0.9 percent nitrogen.

229. Based on the calculated heating value of liquid methane of composition 99.6 mole percent methane and 0.4 mole percent nitrogen and the density as given above.

230. Calculated using the higher heating value above and a density of 0.51 kg/L.

231. Effective energy density only 80 percent of theoretical: Because of the possibility of fuel release upon fuel expansion due to an increase in ambient temperature, vehicle propane tanks are equipped with "stop fill" devices which permit only 80 percent of the tank volume to be filled by propane. "An Assessment of Propane as an Alternative Transportation Fuel in the United States," R.F. Webb Corporation report, June 1989. p. 8-30.

232. Calculated using higher heating value above and a density of 0.791 kg/L.

233. Calculated using the higher heating value above and a density of 0.789 kg/L.

234. Calculated using higher heating value above and density from physical properties table.

235. Calculated using the higher heating value above and a density of 0.749 kg/L.

236. Calculated using the higher heating value above and a density of 0.85 kg/L.

237. Based on lower heating value of hydrogen in MJ/kg, above, and the lower heating value of diesel fuel in MJ/kg, above.

238. Based on lower heating value of natural gas in MJ/kg, above, and the lower heating value of diesel fuel in MJ/kg, above.

239. Based on lower heating value of propane in MJ/kg, above, and the lower heating value of diesel fuel in MJ/kg, above.

240. Based on lower heating value of methanol in MJ/kg, above, and the lower heating value of diesel fuel in MJ/kg, above.

241. Based on lower heating value of ethanol in MJ/kg, above, and the lower heating value of diesel fuel in MJ/kg, above.

242. Based on lower heating value of biodiesel in MJ/kg, above, and the lower heating value of diesel fuel in MJ/kg, above.

243. Based on lower heating value of gasoline in MJ/kg, above, and the lower heating value of diesel fuel in MJ/kg, above.

244. Base fuel for comparison.

245. Based on lower heating value of hydrogen in MJ/kg, above, and the lower heating value of gasoline in MJ/kg, above.

246. Based on lower heating value of natural gas in MJ/kg, above, and the lower heating value of gasoline in MJ/kg, above.

247. Based on lower heating value of propane in MJ/kg, above, and the lower heating value of gasoline in MJ/kg, above.

248. Based on lower heating value of methanol in MJ/kg, above, and the lower heating value of gasoline in MJ/kg, above.

249. Based on lower heating value of ethanol in MJ/kg, above, and the lower heating value of gasoline in MJ/kg, above.

250. Based on lower heating value of biodiesel in MJ/kg, above, and the lower heating value of gasoline in MJ/kg, above.

251. Base fuel for comparison.

252. Based on lower heating value of diesel fuel in MJ/kg, above, and the lower heating value of gasoline in MJ/kg, above.

253. Obtained by dividing the LHV of diesel fuel in kg/L by the above LHV of hydrogen in kg/L.

254. Obtained by dividing the LHV of diesel fuel in kg/L by the above LHV of hydrogen in kg/L.

255. Obtained by dividing the LHV of diesel fuel in kg/L by the above LHV of CNG.

256. Obtained by dividing the LHV of diesel fuel in kg/L by the above LHV of LNG.

257. Obtained by dividing the LHV of diesel fuel in kg/L by the above LHV of commercial propane.

258. Effective energy density only 80 percent of theoretical: Because of the possibility of fuel release upon fuel expansion due to an increase in ambient temperature, vehicle propane tanks are equipped with "stop fill" devices which permit only 80 percent of the tank volume to be filled by propane. "An Assessment of

Propane as an Alternative Transportation Fuel in the United States," R.F. Webb Corporation report, June 1989. p. 8-30.

259. Obtained by dividing the LHV of diesel fuel in kg/L by the above LHV of methanol.

260. Obtained by dividing the LHV of diesel fuel in kg/L by the above LHV of ethanol.

261. Obtained by dividing the LHV of diesel fuel in kg/L by the above LHV of biodiesel fuel.

262. Obtained by dividing the LHV of diesel fuel in kg/L by the above LHV of unleaded gasoline.

263. The lower heating value of diesel fuel, above, is used as a basis for comparison.

264. Obtained by dividing the LHV of gasoline in kg/L by the above LHV of hydrogen in kg/L.

265. Obtained by dividing the LHV of gasoline in kg/L by the above LHV of hydrogen in kg/L.

266. Obtained by dividing the LHV of gasoline in kg/L by the above LHV of CNG.

267. Obtained by dividing the LHV of gasoline in kg/L by the above LHV of LNG.

268. Obtained by dividing the LHV of gasoline in kg/L by the above LHV of commercial propane.

269. Obtained by dividing the LHV of gasoline in kg/L by the above LHV of methanol.

270. Obtained by dividing the LHV of gasoline in kg/L by the above LHV of ethanol.

271. Obtained by dividing the LHV of gasoline in kg/L by the above LHV of biodiesel fuel.

272. The lower heating value of gasoline, above, is used as a basis for comparison.

273. Obtained by dividing the LHV of gasoline in kg/L by the above LHV of diesel fuel.

274) Natural gas is generally required to be odorized such that a concentration 1/5 of the lower flammable limit is detectable.

275) LPG gas is generally required to be odorized such that a concentration 1/5 of the lower flammable limit is detectable.

276) Typical value 2000 ppm. The range of values reported in the literature is 100-5900 ppm. See background document for critique of reported literature values.

277. "Odor Threshold Determinations of 53 Odorant Chemicals," Journal of the Air Pollution Control Association, **19**, 91 (1969).

278. If vegetable oil methyl esters are mixed with diesel fuel, the diesel fuel will be the more volatile component and the odor threshold is assumed to be determined by the diesel fuel component.

279. Material Safety Data Sheet for gasoline prepared by Occupational Health Services, Inc. 400 Plaza Drive, Secaucus, NJ.

280. Material Safety Data Sheet for diesel fuel prepared by Occupational Health Services, Inc. 400 Plaza Drive, Secaucus, NJ.

281. Listed by ACGIH as a "simple asphyxiant."

282. Based on natural gas composition with 3.9 percent propane, 1.63 percent butane, 0.475 percent pentane, and 0.141 percent hexane. Gas composition is average of first 25 natural gas compositions listed in "Effect of Fuel Gas Composition on Appliance Performance," Gas Research Institute report GRI-82/0037, 1982. TLV is based on OSHA P.E.L. for propane as listed in Fundamentals of Industrial Hygiene. 3rd Ed., B. A. Plog, 1988, p. 829. and TLV's for other hydrocarbons as listed in "Threshold Limit Values and Biological Exposure Indices for 1988-1989," American Conference of Governmental and Industrial Hygienists, 1988.

283. Based on OSHA P.E.L. for propane as listed in Fundamentals of Industrial Hygiene. 3rd Ed., B. A. Plog, 1988. p. 829.

284. Fundamentals of Industrial Hygiene. 2nd Ed., J.B. Olishifski, 1979. p. 1074.

285. Fundamentals of Industrial Hygiene. 2nd Ed., J.B. Olishifski, 1979. p. 1000.

286. If vegetable oil methyl esters are mixed with diesel fuel, the diesel fuel will be the more volatile component. The diesel fuel component is assumed to control the vapor toxicity.

287. Material Safety Data Sheet for gasoline prepared by Marathon Oil Company.

288. Patty's Industrial Hygiene and Toxicology. Third Revised Ed., George D. Clayton and Florence E. Clayton, Editors, (1981). p. 3394. Value listed is NIOSH recommended TWA for kerosene.

289. No STEL established for hydrogen. Fundamentals of Industrial Hygiene. 3rd Ed., B. A. Plog, 1988.

290. No STEL established for any of the major components of natural gas. Fundamentals of Industrial Hygiene. 3rd Ed., B. A. Plog, 1988.

291. Fundamentals of Industrial Hygiene. 3rd Ed., B. A. Plog, 1988. p. 778.

292. Fundamentals of Industrial Hygiene. 2nd Ed., J.B. Olishifski, 1979. p. 1074.

293. Fundamentals of Industrial Hygiene. 2nd Ed., J.B. Olishifski, 1979. p. 1000.

294. Fundamentals of Industrial Hygiene. 2nd Ed., J.B. Olishifski, 1979. p. 1000.

295. Material Safety Data Sheet for gasoline prepared by Marathon Oil Company.

296. Material Safety Data Sheet for No. 2 fuel oil prepared by Marathon Oil Company.

297. Fundamentals of Industrial Hygiene, J.B. Olishifski, 1979. p. 148.

298. Fundamentals of Industrial Hygiene, J.B. Olishifski, 1979. p. 148.

299. If vegetable oil methyl esters are mixed with diesel fuel, the diesel fuel will be the more volatile component. The diesel fuel component is assumed to control the vapor toxicity.