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PROPERTIES OF
ALTERNATIVE FUELS

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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.

**Key Words**
- Transit bus
- Bus fuels
- Alternative fuels
- Energy content
- Hydrogen
- Natural gas
- Propane
- Liquefied natural gas
- Methanol
- Ethanol
- Biodiesel
- Diesel
- Gasoline

**Distribution Statement**
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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, in²) = 6.5 square centimeters (cm²)
- 1 square foot (sq ft, ft²) = 0.09 square meter (m²)
- 1 square yard (sq yd, yd²) = 0.8 square meter (m²)
- 1 acre = 0.4 hectares (he) = 4,000 square meters (m²)

**MASS - WEIGHT (APPROXIMATE)**
- 1 ounce (oz) = 28 grams (gr)
- 1 pound (lb) = 0.45 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, ft³) = 0.03 cubic meter (m³)
- 1 cubic yard (cu yd, yd³) = 0.76 cubic meter (m³)

**TEMPERATURE (EXACT)**

\[(\frac{9}{5}y + 32) \text{ °F} = y \text{ °C} \]

#### 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 (cm²) = 0.16 square inch (sq in, in²)
- 1 square meter (m²) = 1.2 square yards (sq yd, yd²)
- 1 square kilometer (km²) = 0.4 square mile (sq mi, mi²)
- 1 hectare (he) = 10,000 square meters (m²) = 2.5 acres

**MASS - WEIGHT (APPROXIMATE)**
- 1 gram (gr) = 0.036 ounce (oz)
- 1 kilogram (kg) = 2.2 pounds (lb)
- 1 short ton = 2,000 pounds (lb) = 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 (m³) = 36 cubic feet (cu ft, ft³)
- 1 cubic meter (m³) = 1.3 cubic yards (cu yd, yd³)

**TEMPERATURE (EXACT)**

\[\left(\frac{9}{5}y + 32\right) \text{ °C} = y \text{ °F} \]

### QUICK INCH-CENTIMETER LENGTH CONVERSION

<table>
<thead>
<tr>
<th>INCHES</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>CENTIMETERS</td>
<td>0</td>
<td>2.5</td>
<td>5</td>
<td>7.5</td>
<td>10</td>
<td>12.5</td>
<td>15</td>
<td>17.5</td>
<td>20</td>
<td>22.5</td>
<td>25</td>
</tr>
</tbody>
</table>

### QUICK FAHRENHEIT-CELSIUS TEMPERATURE CONVERSION

<table>
<thead>
<tr>
<th>°F</th>
<th>-40°</th>
<th>-22°</th>
<th>-4°</th>
<th>14°</th>
<th>32°</th>
<th>50°</th>
<th>68°</th>
<th>86°</th>
<th>104°</th>
<th>122°</th>
<th>140°</th>
<th>158°</th>
<th>176°</th>
<th>194°</th>
<th>212°</th>
</tr>
</thead>
<tbody>
<tr>
<td>°C</td>
<td>-40°</td>
<td>-30°</td>
<td>-20°</td>
<td>-10°</td>
<td>0°</td>
<td>10°</td>
<td>20°</td>
<td>30°</td>
<td>40°</td>
<td>50°</td>
<td>60°</td>
<td>70°</td>
<td>80°</td>
<td>90°</td>
<td>100°</td>
</tr>
</tbody>
</table>

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 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.
### UNIT ABBREVIATIONS

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

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

See Glossary for additional definitions and explanation.
This page intentionally blank.
# Alternative Fuel Data Summary: Physical Properties

See accompanying glossary for explanation of terms.

<table>
<thead>
<tr>
<th></th>
<th>Hydrogen</th>
<th>Natural Gas</th>
<th>Propane</th>
<th>Methanol</th>
<th>Ethanol</th>
<th>Biodiesel</th>
<th>Gasoline</th>
<th>Diesel Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appearance</td>
<td>Colorless gas</td>
<td>Colorless gas</td>
<td>Easily liquified gas</td>
<td>Clear liquid</td>
<td>Clear liquid</td>
<td>Amber liquid</td>
<td>Clear-amber liquid</td>
<td>Amber liquid</td>
</tr>
<tr>
<td>Boiling pt., C</td>
<td>-253(17)</td>
<td>-162(22)</td>
<td>-38(3)</td>
<td>65(4)</td>
<td>78.5(5)</td>
<td>approx. 280(6)</td>
<td>33-213(7)</td>
<td>188-340(8)</td>
</tr>
<tr>
<td>Fuel density, kg/L</td>
<td>CHG: 0.0175(9)</td>
<td>CNG: 0.19(11)</td>
<td>0.51(14)</td>
<td>0.791(15)</td>
<td>0.789(16)</td>
<td>0.889(17)</td>
<td>0.77(18)</td>
<td>0.81-0.88, Avg: 0.85(19)</td>
</tr>
<tr>
<td>Relative vapor density, air = 1.00</td>
<td>0.07(20)</td>
<td>0.60(21)</td>
<td>1.5(22)</td>
<td>1.11(23)</td>
<td>1.6(24)</td>
<td>10(25)</td>
<td>2-4(26)</td>
<td>4-6(27)</td>
</tr>
<tr>
<td>Reid vapor press, kPa</td>
<td>N.A. (gas)</td>
<td>N.A.(gas)</td>
<td>1400(28)</td>
<td>32(29)</td>
<td>15(30)</td>
<td>0.001(31)</td>
<td>50-100(32)</td>
<td>0.1-1.5(33)</td>
</tr>
<tr>
<td>Heat of vapor, kJ/kg</td>
<td>58(34)</td>
<td>509(35)</td>
<td>425(36)</td>
<td>1167(37)</td>
<td>920(38)</td>
<td>440(39)</td>
<td>275-365(40)</td>
<td>225-280(41)</td>
</tr>
<tr>
<td>Water soluble</td>
<td>no(42)</td>
<td>no(42)</td>
<td>no(44)</td>
<td>yes(45)</td>
<td>yes(46)</td>
<td>no(47)</td>
<td>no(48)</td>
<td>no(49)</td>
</tr>
<tr>
<td>Viscosity, cP @ 15 C</td>
<td>H2: 0.009(50)</td>
<td>NG: 0.011(52)</td>
<td>0.008 (gas)(55)</td>
<td>0.65(57)</td>
<td>1.3(58)</td>
<td>3.6 @ 40 C(59)</td>
<td>0.64(60)</td>
<td>2.6(61)</td>
</tr>
<tr>
<td></td>
<td>LHG: 0.013(51)</td>
<td>CNG: 0.018(53)</td>
<td>0.121 (liq)(56)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cloud pt., C</td>
<td>N.A. (gas)</td>
<td>N.A. (gas)</td>
<td>N.A. (gas)</td>
<td>N.A.(62)</td>
<td>N.A.(63)</td>
<td>0(64)</td>
<td>-20(65)</td>
<td></td>
</tr>
<tr>
<td>Pour pt., C</td>
<td>N.A. (gas)</td>
<td>N.A. (gas)</td>
<td>N.A. (gas)</td>
<td>N.A.(66)</td>
<td>N.A.(67)</td>
<td>-4(68)</td>
<td>-60(69)</td>
<td>-29(70)</td>
</tr>
<tr>
<td>Coeff.</td>
<td>Cubical Exp.</td>
<td>Hydrogen</td>
<td>Natural Gas</td>
<td>Propane</td>
<td>Methanol</td>
<td>Ethanol</td>
<td>Biodiesel</td>
<td>Gasoline</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td>----------</td>
<td>-------------</td>
<td>---------</td>
<td>----------</td>
<td>---------</td>
<td>-----------</td>
<td>----------</td>
</tr>
<tr>
<td>CHG: N.A.</td>
<td>CNG: N.A.</td>
<td>1.6&lt;sup&gt;(73)&lt;/sup&gt;</td>
<td>1.20&lt;sup&gt;(74)&lt;/sup&gt;</td>
<td>1.12&lt;sup&gt;(75)&lt;/sup&gt;</td>
<td>1.08&lt;sup&gt;(76)&lt;/sup&gt;</td>
<td>0.81&lt;sup&gt;(77)&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N.A. (gas)</td>
<td>N.A. (gas)</td>
<td>N.A. (gas)</td>
<td>44&lt;sup&gt;(78)&lt;/sup&gt;</td>
<td>0.14&lt;sup&gt;(79)&lt;/sup&gt;</td>
<td>0.000001&lt;sup&gt;(80)&lt;/sup&gt;</td>
<td>0.0001&lt;sup&gt;(81)&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(revised 13 October 1994)
## ALTERNATIVE FUEL DATA SUMMARY: Chemical Composition

See accompanying glossary for explanation of terms.

<table>
<thead>
<tr>
<th></th>
<th>Hydrogen</th>
<th>Natural Gas</th>
<th>Propane</th>
<th>Methanol</th>
<th>Ethanol</th>
<th>Biodiesel</th>
<th>Gasoline</th>
<th>Diesel Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chemical Formula</strong></td>
<td>$H_2$</td>
<td>85-95% CH$_4$ ($^{(82)}$)</td>
<td>Mainly C$_3$H$_8$ ($^{(83)}$)</td>
<td>CH$_3$OH ($^{(84)}$)</td>
<td>C$_2$H$_5$OH ($^{(85)}$)</td>
<td>CH$<em>{1.4}$O$</em>{0.1}$ ($^{(86)}$)</td>
<td>C$<em>4$-C$</em>{12}$</td>
<td>$C_{14}-C_{16}$</td>
</tr>
<tr>
<td><strong>Carbon, wt %</strong></td>
<td>0</td>
<td>75.44 ($^{(87)}$)</td>
<td>81.71 ($^{(88)}$)</td>
<td>37.49 ($^{(89)}$)</td>
<td>52.14 ($^{(90)}$)</td>
<td>78.0 ($^{(91)}$)</td>
<td>86.74 ($^{(92)}$)</td>
<td>87.3 ($^{(93)}$)</td>
</tr>
<tr>
<td><strong>Hydrogen, wt %</strong></td>
<td>100.0</td>
<td>24.56 ($^{(84)}$)</td>
<td>18.28 ($^{(85)}$)</td>
<td>12.58 ($^{(86)}$)</td>
<td>13.13 ($^{(87)}$)</td>
<td>11.7 ($^{(88)}$)</td>
<td>13.22 ($^{(89)}$)</td>
<td>12.5 ($^{100}$)</td>
</tr>
<tr>
<td><strong>Oxygen, wt %</strong></td>
<td>0</td>
<td>11 ($^{(100)}$)</td>
<td>&lt;123 ($^{(106)}$)</td>
<td>&lt;100 ($^{(110)}$)</td>
<td>&lt;100 ($^{(111)}$)</td>
<td>&lt;50 ppm ($^{112}$)</td>
<td>339 ($^{113}$)</td>
<td>2000 ($^{114}$)</td>
</tr>
<tr>
<td><strong>Sulfur, ppm by weight</strong></td>
<td>0</td>
<td>0 ($^{116}$)</td>
<td>0 ($^{117}$)</td>
<td>0</td>
<td>29 ($^{118}$)</td>
<td>29 ($^{119}$)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(revised 25 February 1994)
**ALTERNATIVE FUEL DATA SUMMARY: Combustion Properties**

See accompanying glossary for explanation of terms.

<table>
<thead>
<tr>
<th></th>
<th>Hydrogen</th>
<th>Natural Gas</th>
<th>Propane</th>
<th>Methanol</th>
<th>Ethanol</th>
<th>Biodiesel</th>
<th>Gasoline</th>
<th>Diesel Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flash point, C</td>
<td>Already a gas</td>
<td>Already a gas</td>
<td>14(120)</td>
<td>13(121)</td>
<td>118(122)</td>
<td>-43(123)</td>
<td>58-116, Avg. 73(124)</td>
<td></td>
</tr>
<tr>
<td>Autoignition temp., C</td>
<td>400(125)</td>
<td>450(126)</td>
<td>450(127)</td>
<td>385(128)</td>
<td>365(129)</td>
<td>250(130)</td>
<td>300(131)</td>
<td>230(132)</td>
</tr>
<tr>
<td>Spark ign. energy, mJ</td>
<td>0.017(133)</td>
<td>0.29(134)</td>
<td>0.25(135)</td>
<td>0.14(136)</td>
<td>0.2(137)</td>
<td>0.24(138)</td>
<td>0.24(139)</td>
<td></td>
</tr>
<tr>
<td>Flammability Limits, %</td>
<td>4.0-75(140)</td>
<td>5-15(141)</td>
<td>2.1-9.5(142)</td>
<td>6.7-13(143)</td>
<td>3.3-5.4(144)</td>
<td>1.4-7.5(145)</td>
<td>0.6-5.5</td>
<td></td>
</tr>
<tr>
<td>Stoichiometric Air/Fuel Ratio</td>
<td>34.5(148)</td>
<td>17.2(147)</td>
<td>15.7(148)</td>
<td>6.45(149)</td>
<td>9.0(150)</td>
<td>12.6(151)</td>
<td>14.7(152)</td>
<td>15.0(153)</td>
</tr>
<tr>
<td>Octane number</td>
<td>Poor(154)</td>
<td>117(155)</td>
<td>106(156)</td>
<td>99(157)</td>
<td>98(158)</td>
<td>73(159)</td>
<td>87(160)</td>
<td>30(161)</td>
</tr>
<tr>
<td>Cetane number</td>
<td>-10(162)</td>
<td>-5 to 0(163)</td>
<td>0.4(164)</td>
<td>5.15(166)</td>
<td>47(168)-52(87)</td>
<td>8-14(168)</td>
<td>40-47, Avg. 45(169)</td>
<td></td>
</tr>
<tr>
<td>Flame visibility, relative</td>
<td>0.6(170)</td>
<td>0.6(171)</td>
<td>0.0003(172)</td>
<td>0.03(173)</td>
<td>1.0(174)</td>
<td>1.0(175)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pool burn rate, g/m²-s</td>
<td>CHG: N.A. (gas)</td>
<td>CNG: N.A. (gas)</td>
<td>LNG: 16(176)</td>
<td>99(178)</td>
<td>17(179)</td>
<td>15(180)</td>
<td>55(181)</td>
<td>35-39(182)</td>
</tr>
<tr>
<td></td>
<td>Hydrogen</td>
<td>Natural Gas</td>
<td>Propane</td>
<td>Methanol</td>
<td>Ethanol</td>
<td>Biodiesel</td>
<td>Gasoline</td>
<td>Diesel Fuel</td>
</tr>
<tr>
<td>------------------</td>
<td>----------</td>
<td>-------------</td>
<td>---------</td>
<td>----------</td>
<td>---------</td>
<td>-----------</td>
<td>----------</td>
<td>-------------</td>
</tr>
<tr>
<td>Flame spread rate, m/s</td>
<td>N.A. (gas)</td>
<td>N.A. (gas)</td>
<td>N.A. (gas)</td>
<td>2-4[^163]</td>
<td>unk.</td>
<td>unk.</td>
<td>4-6[^164]</td>
<td>0.02-0.08</td>
</tr>
</tbody>
</table>

(revised 9 March 1994)
## ALTERNATIVE FUEL DATA SUMMARY: Energy Content
See accompanying glossary for explanation of terms.

<table>
<thead>
<tr>
<th></th>
<th>Hydrogen</th>
<th>Natural Gas</th>
<th>Propane</th>
<th>Methanol</th>
<th>Ethanol</th>
<th>Biodiesel</th>
<th>Gasoline</th>
<th>Diesel Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuel energy value, LHV, MJ/kg</strong></td>
<td></td>
<td>Avg. NG: 47.0</td>
<td>46.3</td>
<td>20.1</td>
<td>27.0</td>
<td>37.3</td>
<td>42.6</td>
<td>42.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Alg. LNG: 48.8</td>
<td>199</td>
<td>199</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>LM: 49.7</td>
<td>198</td>
<td>197</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Fuel energy value, LHV, LHG, MJ/L</strong></td>
<td></td>
<td>Avg. LNG: 22.1</td>
<td>208</td>
<td>15.9</td>
<td>21.3</td>
<td>33.2</td>
<td>32.9</td>
<td>36.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Avg. LNG: 22.1</td>
<td>209</td>
<td>18.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Avg. LNG: 22.1</td>
<td>209</td>
<td>18.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Fuel energy value, HHV, MJ/kg</strong></td>
<td></td>
<td>Avg. NG: 52.2</td>
<td>218</td>
<td>22.7</td>
<td>29.7</td>
<td>39.7</td>
<td>45.4</td>
<td>45.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Avg. LNG: 54.1</td>
<td>217</td>
<td>217</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>LM: 55.2</td>
<td>218</td>
<td>218</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Fuel energy value, HHV, LHG, MJ/L</strong></td>
<td></td>
<td>Avg. LNG: 22.5</td>
<td>230</td>
<td>25.7</td>
<td>18.0</td>
<td>35.3</td>
<td>34.0</td>
<td>38.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Avg. LNG: 22.5</td>
<td>231</td>
<td>20.5</td>
<td>18.0</td>
<td>35.3</td>
<td>34.0</td>
<td>38.8</td>
</tr>
</tbody>
</table>

(revised 30 August 1994)
**ALTERNATIVE FUEL DATA SUMMARY: Energy Comparisons**

See accompanying glossary for explanation of terms.

<table>
<thead>
<tr>
<th></th>
<th>Hydrogen</th>
<th>Natural Gas</th>
<th>Propane</th>
<th>Methanol</th>
<th>Ethanol</th>
<th>Biodiesel</th>
<th>Gasoline</th>
<th>Diesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass fuel with same energy (LHV) as one mass of diesel:</td>
<td>0.36(^{(237)})</td>
<td>0.91(^{(236)})</td>
<td>0.92(^{(238)})</td>
<td>2.13(^{(240)})</td>
<td>1.59(^{(241)})</td>
<td>1.15(^{(242)})</td>
<td>1.00(^{(243)})</td>
<td>1(^{(244)})</td>
</tr>
<tr>
<td>Mass fuel with same energy (LHV) as one mass of gasoline:</td>
<td>0.36(^{(245)})</td>
<td>0.91(^{(246)})</td>
<td>0.92(^{(247)})</td>
<td>2.12(^{(248)})</td>
<td>1.58(^{(249)})</td>
<td>1.14(^{(250)})</td>
<td>1(^{(251)})</td>
<td>1.00(^{(252)})</td>
</tr>
<tr>
<td>Volume fuel with same energy (LHV) as one volume of diesel:</td>
<td>CHG: 17.3(^{(253)}) LHG: 4.3(^{(254)})</td>
<td>CNG: 4.09(^{(255)}) LNG: 1.65(^{(256)})</td>
<td>1.54(^{(257)}) (in tank: 1.93(^{(258)})</td>
<td>2.29(^{(259)})</td>
<td>1.71(^{(260)})</td>
<td>1.10(^{(261)})</td>
<td>1.11(^{(262)})</td>
<td>1(^{(263)})</td>
</tr>
<tr>
<td>Volume fuel with same energy (LHV) as one volume of gasoline:</td>
<td>CHG: 15.7(^{(264)}) LHG: 3.9(^{(265)})</td>
<td>CNG: 3.70(^{(266)}) LNG: 1.49(^{(267)})</td>
<td>1.37(^{(268)})</td>
<td>2.04(^{(269)})</td>
<td>1.54(^{(270)})</td>
<td>0.99(^{(271)})</td>
<td>1(^{(272)})</td>
<td>0.89(^{(273)})</td>
</tr>
</tbody>
</table>

(revised 30 August 1994)
## ALTERNATIVE FUEL DATA SUMMARY: Health Properties

See accompanying glossary for explanation of terms.

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

(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 H₂.
**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


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.


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.


15. Handbook of Chemistry and Physics.


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.


29. Calculated vapor pressure at 37.8 C.

30. Calculated vapor pressure at 37.8 C.


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.


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.


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.


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.


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


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.


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).


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).


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.


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


80. 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.


88. Calculated from molecular formula of propane.

89. Calculated from molecular formula.

90. Calculated from molecular formula.


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.


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.


107. Diesel fuel contains a negligible amount of oxygen.


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

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


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 compared 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 compared to the nitrogen in nitrogen-containing organic compounds.


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


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.


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.


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.


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.


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.


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

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


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.


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.
with pure propane.

164. Cetane number values are reported in several reports:


165. Cetane number values are reported in several reports:


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.


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.


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.


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:

\[ \text{CH}_3\text{OH}(l) + 1.5 \text{O}_2 \rightarrow \text{CO}_2 + 2 \text{H}_2\text{O}(l) \]

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:

\[ \text{C}_2\text{H}_5\text{OH}(l) + 3 \text{O}_2 \rightarrow 2 \text{CO}_2 + 3 \text{H}_2\text{O}(l) \]


202. Based on higher heating value above, corrected using the expression: \[ \text{LHV} = \text{HHV} - 212(\%H) \], 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.


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. 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:

\[ \text{CH}_3\text{OH}(l) + 1.5 \text{O}_2 \rightarrow \text{CO}_2 + 2 \text{H}_2\text{O}(l) \]

221. 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:

\[ \text{CH}_3\text{OH}(l) + 1.5 \text{O}_2 \rightarrow \text{CO}_2 + 2 \text{H}_2\text{O}(l) \]

223. Based on lower heating value listed above, and the percent hydrogen listed below using the expression: \[ \text{LHV} = \text{HHV} - 212(\%H) \], 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:

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


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

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.


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."


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.


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.


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.