

(R) Diesel Fuels

- 1. Scope**—Automotive and railroad diesel fuels, in general, are derived from petroleum refinery products which are commonly referred to as middle distillates. Middle distillates represent products which have a higher boiling range than gasoline and are obtained from fractional distillation of the crude oil or from streams from other refining processes. Finished diesel fuels represent blends of middle distillates.

The properties of commercial distillate diesel fuels depend on the refinery practices employed and the nature of the crude oils from which they are derived. Thus, they may differ both with and within the region in which they are manufactured. Such fuels generally boil over a range between 163 and 371 °C (325 to 700 °F). Their makeup can represent various combinations of volatility, ignition quality, viscosity, sulfur level, gravity, and other characteristics. Additives may be used to impart special properties to the finished diesel fuel.

2. References

- 2.1 Applicable Publications**—The following publications form a part of this specification to the extent specified herein. Unless otherwise specified, the latest issue of SAE publications shall apply.

- 2.1.1 SAE PUBLICATIONS**—Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

SAE J183—Engine Oil Performance and Engine Service Classification (Other Than "Energy-Conserving")
SAE J304—Engine Oil Tests
SAE J1498—Marine Circuit Breakers
SAE Paper 830594—1981 CRC Diesel Fuel Low-Temperature Operability Field Test, Coordinating Research Council Report 528 (September 1983), Summarized by M. L. McMillan and E. G. Barry, "Fuel and Vehicle Effects on Low-Temperature Operation of Diesel Vehicles—The 1981 CRC Field Test"

- 2.1.2 ASTM PUBLICATIONS**—Available from ASTM, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959.

ASTM D 86—Method for Distillation of Petroleum Products
ASTM D 93—Test Method for Flash Point by the Pensky-Martens Closed Tester
ASTM D 97—Test Method for Pour Point of Petroleum Oils
ASTM D 129—Test Method for Sulfur in Petroleum Products by the Bomb Method
ASTM D 130—Method for Detection of Copper Corrosion from Petroleum Products by the Copper Strip Tarnish Test
ASTM D 240—Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter

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- ASTM D 287—Test Method for API Gravity of Crude Petroleum and Petroleum Products (Hydrometer Method)
- ASTM D 445—Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (and the Calculation of Dynamic Viscosity)
- ASTM D 482—Test Method for Ash from Petroleum Products
- ASTM D 524—Test Method for Ramsbottom Carbon Residue of Petroleum Products
- ASTM D 611—Test Method for Aniline Point and Mixed Aniline Point of Petroleum Products and Hydrocarbon Solvents
- ASTM D 613—Test Method for Ignition Quality of Diesel Fuels by the Cetane Method
- ASTM D 665—Test Method for Rust-Preventing Characteristics of Inhibited Mineral Oil in the Presence of Water
- ASTM D 975—Specification for Diesel Fuel Oils
- ASTM D 976—Method for Calculated Cetane Index of Distillate Fuels
- ASTM D 1266—Test Method for Sulfur in Petroleum Products and Liquefied Petroleum (LP) Gases (Lamp Method)
- ASTM D 1298—Test Method for Relative Density (Specific Gravity)
- ASTM D 1405—Method for Estimation of Net Heat of Combustion of Aviation Fuels
- ASTM D 1552—Test Method for Sulfur in Petroleum Products (High Temperature Method)
- ASTM D 1796—Test Method for Water and Sediment in Fuel Oils by Centrifuge Method (Laboratory Procedure)
- ASTM D 2274—Test Method for Oxidation Stability of Distillate Fuel Oil (Accelerated Method)
- ASTM D 2500—Test Method for Cloud Point of Petroleum Oils
- ASTM D 2622—Test Method for Sulfur in Petroleum Products (X-Ray Spectrographic Method)
- ASTM D 3117—Test Method for Wax Appearance Point of Distillate Fuels
- ASTM D 3338—Method for Estimation of Heat of Combustion of Aviation Fuels
- ASTM D 4539—Filterability of Diesel Fuels by Low Temperature Flow Test (LTFT)
- ASTM D 4737—Method for Calculated Cetane Index by Four Variable Equation
- ASTM D 5001—Test Method for Measurement of Lubricity of Aviation Turbine Fuels by the Ball-on-Cylinder Lubricity Evaluator (BOCLE)
- ASTM D 5452—Test Method for Particulate Contamination of Aviation Fuels by Laboratory Filtration

2.1.3 U.S. BUREAU OF STANDARDS

Miscellaneous Publication No. 97, 1929, Thermal Properties of Petroleum Products

2.1.4 OTHER PUBLICATIONS

1. U.S. Clean Air Act (1970)
2. Federal Register, March 5, 1980
3. Federal Register, March 15, 1985
4. U.S. Clean Air Act Amendments 1990
5. Govt. of Canada Gazette
6. Stockholm Club Emissions—Impact on European Truck Engines. H. D. Freeman—Ricardo Consulting Engineers Autotech 89
7. Worldwide Developments in Motor Vehicle Diesel Particulate Control. Michael P. Walsh, SAE 890168
8. Fuel Effects and Heavy Duty Diesel Particulate Control. J. C. Wall & S. K. Hoekman, SAE 841364
9. Recommended Federal On Highway Diesel Fuel Specifications to Assist Engine Manufacturers Meet 1991 and 1994 Particulate Standards Joint API/EMA/NPRA/NCFC Report, July 19, 1988
10. Federal Register, August 21, 1990
11. Investigation of the Effects of Fuel Composition and Injection and Combustion System Type on Heavy Duty Diesel Exhaust Emissions. Report from CRC VE-1 Project by Terry Ullman, March 1989
12. Study of Fuel Cetane Number and Aromatic Content Effects on Regulated Emissions from a Heavy Duty Diesel Engine. Report from CRC VE-1 Project by Terry Ullman, Robert Mason and Daniel Montalvo, September 1990

13. Gasoline and Diesel Fuel Qualification—A National Need, K. J. Springer, ASME Paper 90-ICE-19
14. NPRA Diesel Fuel Survey 1988
15. PACE Canadian Diesel Fuel Survey Report 88-3 1988
16. Fuel Lubricity Requirements for Diesel Injection Systems BFLRF Interim Report No. 270 by P. I. Lacey and S. J. Lestz, February 1991
17. Letter from EMA Fuels and Lubricants Committee to SAE Technical Committee 7-Fuels dated February 25, 1991

2.2 Related Publications

2.2.1 GENERAL PROPERTIES

1. Annual Book of ASTM Standards, "Petroleum Products, Lubricants, and Fossil Fuels," Volumes 05.01, 05.02, 05.03, and 05.04.
2. "Significance of Tests for Petroleum Products," ASTM Special Technical Publication Manual One (March 1989).
3. "Manual on Hydrocarbon Analysis," ASTM Special Technical Publication 332-A (1977).
4. H. R. Hultkrans, "Role of Diesel Fuel Properties in Diesel Fleet Economy," SAE Paper 650429.
5. R. Burt and K. A. Troth, "New CFR Cetane Rating Method is More Accurate than ASTM D 613 Method," SAE Paper 680464.
6. R. P. Lindeman, D. K. Lawrence, and T. O. Wagner, "Classification of Fuels that is Compatible with Fuel Availability," SAE Paper 680467.
7. G. K. Brower, "Diesel Fuel Specifications and Their Current Suitability," SAE Paper 700521.
8. "Update Proposed for Diesel Fuel Specs.," Automotive Engineering, Vol. 78, No. 11 (1970), pp. 34-40.
9. T. O. Wagner, "Economics of Manufacturing Automotive Diesel Fuel," SAE Paper 770758.
10. N. A. Henein and N. Y. Elias, "A Modified Cetane Scale for Low Ignition Quality Fuels," SAE Paper 780640.
11. E. G. Barry, F. J. Hills, and L. J. McCabe, "Diesel Fuel—Availability, Trends, and Performance," SAE Paper 790921.
12. D. E. Steere and T. J. Nunn, "Diesel Fuel Quality Trends in Canada," SAE Paper 790922.
13. "Distillate Fuel Stability and Cleanliness," ASTM Special Technical Publication 751 (1981).
14. D. K. Lawrence, D. A. Plautz, B. D. Keller, and T. O. Wagner, "Automotive Fuels—Refining Energy and Economics," SAE Paper 800225.
15. T. Currie and R. B. Whyte, "Broad Cut Fuels for Automotive Diesels," SAE Paper 811182.
16. C. L. Wong and D. E. Steere, "The Effects of Diesel Fuel Properties and Engine Operating Conditions on Ignition Delay," SAE Paper 821231.
17. J. W. Taracha and J. O. Cliffe, "The Effect of Cetane Quality on the Performance of Diesel Engines," SAE Paper 821232.
18. D. E. Steere, "Development of the Canadian Cetane Index," SAE Paper 841344.
19. M. C. Ingham, J. A. Bert, and L. J. Painter, "Improved Predictive Equations for Cetane Number," SAE Paper 860250.

2.2.2 COLD WEATHER OPERATION

20. W. F. Ellison and A. H. Scrimshaw, "Cold Weather Operation of Fuels and Lubricants in Western Canada," SAE Paper 650639.
21. B. L. Mickel and L. D. Fergesen, "Dimensions of Diesel Fuel Performance—Design, Depressants, and Response," SAE Paper 660371.
22. K. A. Beyreis, V. P. Catto, and E. S. Swanson, "Role of Flow Improvers in Solving Autodiesel Winter Fuel Problems," SAE Paper 660372.
23. T. J. Fallon, "Flow Improver Additives are Effective for Winterizing Diesel Fuels," SAE Paper 680537.
24. "Effects of Fuels and Fuel System Designs on Low Temperature Operability of Diesel Vehicles," Coordinating Research Council Report 463 (June 1973).

25. N. Feldman, "Operability of Automotive Diesel Equipment at Temperatures Below Fuel Cloud Point," SAE Paper 730677.
26. J. W. Muzatko, "Reducing Low Temperature Wax Plugging in Fuel Systems of the Diesel Passenger Car," SAE Paper 800222.
27. B. Y. Taniguchi and J. D. Benson, "Cold Weather Fuel Requirements of Oldsmobile Diesels," SAE Paper 800223.
28. J. W. Muzatko, K. A. Frost, and C. C. Bishop, "Winterization of Diesel Fuel Systems in Large Coal Mining Haul Trucks," SAE Paper 800224.
29. J. W. Frankenfield and W. F. Taylor, "Effects of Flow Improver Additives on Distillate Fuels from Oil Shale," SAE Paper 801376.
30. J. P. Marino, R. L. Elliott, M. F. Dooley, and D. H. Rehner, "The Use of Flow Improvers in Extending the Low Temperature Operability of Diesel Fuels," National Petroleum Refiners Association Paper FL-80-81, November 1980.
31. D. E. Steere and J. P. Marino, "Low Temperature Field Performance of Flow Improved Diesel Fuels," SAE Paper 810024.
32. M. L. McMillan and S. R. Reddy, "Fuel and Fuel System Effects on Low Temperature Operation of Diesel Vehicles," SAE Paper 811180.
33. S. R. Reddy and M. L. McMillan, "Understanding the Effectiveness of Diesel Fuel Flow Improvers," SAE Paper 811181.
34. J. D. Rummel, "Development of a New Cold Filterability Test for Automotive Diesel Fuels," SAE Paper 821234.
35. T. R. Coley, "Low Temperature Operability of Diesels," SAE Paper 830596.
36. R. D. Tharby, "Experiences with Diesel Fuel Containing Cold Flow Improver Additives," SAE Paper 831753.
37. R. W. Fenstermaker and R. K. Riley, "Additives for Improving the Low-Temperature Filterability of Diesel Fuel Oils," SAE Paper 841350.
38. S. R. Reddy, "Increasing the Responsiveness of No. 2-D Diesel Fuels to Flow Improvers by Blending with Low-Wax Diluents," SAE Paper 841351.
39. J. Zielinski and F. Rossi, "Wax and Flow in Diesel Fuels," SAE Paper 841352.

2.2.3 EXHAUST EMISSIONS

40. H. W. Pearsall, "Measuring the Total Hydrocarbons in Diesel Exhaust," SAE Paper 670089.
41. G. McConnell and H. E. Howells, "Effect of Fuel Properties on Diesel Exhaust Gas Composition," SAE Paper 670091.
42. W. F. Marshall and R. D. Fleming, "Diesel Emissions as Related to Engine Variables and Fuel Characteristics," SAE Paper 710836.
43. E. Shamah and T. O. Wagner, "Fuel Quality or Engine Design: Which Controls Diesel Emissions?" SAE Paper 730168.
44. L. C. Broering and L. W. Holtman, "Effect of Diesel Fuel Properties on Emissions and Performance," SAE Paper 740692.
45. C. T. Hare, K. J. Springer, and R. L. Bradow, "Fuel and Additive Effects on Diesel Particulate-Development and Demonstration of Methodology," SAE Paper 760130.
46. F. J. Hills and C. G. Schleyerbach, "Diesel Fuel Properties and Engine Performance," SAE Paper 770316.
47. G. P. Gross and K. E. Murphy, "The Effects of Diesel Fuel Properties on Performance, Smoke, and Emissions," ASME Paper No. 78-DGP-26, presented at Energy Technology Conference, Houston (Nov. 1978).
48. D. B. Kittelson, D. F. Dolan, R. B. Diver, and E. Aufderheide, "Diesel Exhaust Particle Size Distributions—Fuel and Additive Effects," SAE Paper 780787.
49. L. E. Frisch, J. H. Johnson, and D. G. Leddy, "Effects of Fuels and Dilution Ratio on Diesel Particulate Emissions," SAE Paper 790417.
50. H. A. Burley and T. L. Rosebrock, "Automotive Diesel Engines—Fuel Composition vs. Particulates," SAE Paper 790923.

51. T. W. Ryan, J. O. Storment, B. R. Wright, and R. Waytulonis, "The Effects of Fuel Properties and Composition on Diesel Engine Exhaust Emissions—A Review," SAE Paper 810953.
52. R. A. Bouffard and M. Beltzer, "Light Duty Diesel Particulate Emissions—Fuel and Vehicle Effects," SAE Paper 811191.
53. D. L. Hilden, S. P. Bergin, H. A. Burley, R. D. Tharby, and I. P. Fisher, "The Effect of Hydrotreatment of Diesel Fuel Derived from Canadian Tar Sands on Particulate Exhaust Emissions," SAE Paper 821243.
54. B. B. Bykowski, C. T. Hare, and R. L. Mason, "Comparison of Petroleum and Alternate-Source Diesel Fuel Effects on Light-Duty Diesel Emissions," SAE paper 831712.
55. S. P. Bergin, "The Influence of Fuel Properties and Engine Load Upon the Carbon and Hydrocarbon Fractions of Particulate Emissions from a Light Duty Diesel Engine," SAE Paper 831736.
56. W. R. Wade and C. M. Jones, "Current and Future Light Duty Diesel Engines and Their Fuels," SAE Paper 840105.
57. R. M. Olree and D. L. Lenane, "Diesel Combustion—Cetane Number Effects," SAE Paper 840108.
58. J. C. Wall and S. K. Hoekman, "Fuel Effects on Heavy Duty Diesel Particulate Emissions," SAE Paper 841364.
59. C. T. Hare, "Study of the Effects of Fuel Composition, and Injection and Combustion System Type and Adjustment, on Exhaust Emissions from Light-Duty Diesels," Final Report No. SwRI-6741 on CRC-APRAC Project CAPE-32-80, April 1985.
60. E. G. Barry, L. J. McCabe, D. H. Gerke, and J. M. Perez, "Heavy-Duty Diesel Engine/Fuels Combustion Performance and Emissions—A Cooperative Research Program," SAE Paper 852078.

3. **Classification of Diesel Fuel Oils, ASTM D 975¹**—ASTM D 975, which includes 1-D, 2-D, and 4-D grades of fuel, is intended as a statement of permissible limits of significant fuel properties used for classifying the wide variety of commercially available diesel fuels, in accordance with their service application. The classification chart contained in ASTM D 975 is shown herein as Table 1.

1. References to ASTM Standards in this report are all to be construed as the most recent ASTM publications.

TABLE 1—DETAILED REQUIREMENTS FOR DIESEL FUEL OILS^{(1),(2),(3)}

Grade of Diesel Fuel Oil	Flash Point, °C (°F) Min	Cloud Point, °C (°F) Max	Water and Sediment, Volume % Max	Carbon Residue on, 10 percent Residuuum, % Max	Ash, weight % Max	Distillation Temperatures °C (°F) 90% Point Min	Distillation Temperatures °C (°F) 90% Point Max	Viscosity Kinematic cSt or mm ² /s ⁽⁴⁾ at 40 °C Min	Viscosity Kinematic cSt or mm ² /s ⁽⁴⁾ at 40 °C Max	Viscosity Saybolt, SUS at 100 °F Min	Viscosity Saybolt, SUS at 100 °F Max	Sulfur ⁽⁵⁾ , weight % Max	Copper Strip Corrosion Max	Cetane Number ⁽⁶⁾ Min
No. 1-D A volatile distillate fuel oil for engines in service requiring frequent speed and load changes.	38 (100)	(7)	0.05	0.15	0.01	—	288 (550)	1.3	2.4	—	34.4	0.50	No. 3	40 ⁽⁸⁾
No. 1-DLS A volatile fuel oil required for on-highway operations in engines requiring frequent speed and load changes in the 49 State area of the USA (except Alaska).	38	(7)	0.05	0.15	0.01	—	288	1.3	2.4	—	34.4	0.050	No. 3	40 ⁽⁹⁾
No. 2-D A distillate fuel oil of lower volatility for engines in industrial and heavy mobile service.	52 (125)	(7)	0.05	0.35	0.01	282 ⁽¹⁰⁾ (540)	338 (640)	1.9	4.1	32.6	40.1	0.50	No. 3	40 ⁽⁸⁾
No. 2-DLS A distillate fuel oil required for on-highway operations in engines in industrial and heavy mobile service in the 49 State area of the USA (except Alaska).	52	(7)	0.05	0.35	0.01	282 ⁽¹⁰⁾	338	1.9	4.1	32.6	40.1	0.05	No. 3	40 ⁽⁹⁾
No. 4-D A fuel oil for low and medium speed engines.	55 (130)	(7)	0.50	—	0.10	—	—	5.5	24.0	45.0	125.0	2.0	—	30 ⁽⁸⁾

- To meet special operating conditions, modifications of individual limiting requirements may be agreed upon between purchaser, seller, and manufacturer.
- The values in SI units are to be regarded as the standard. The values of U.S. customary units are for information only.
- Nothing in this specification shall preclude observance of federal, state, or local regulations which may be more restrictive.
- Millimeter squared per second (official SI unit) (Note: 1 cSt = 1 mm²/s).
- In countries outside the USA, other sulfur limits may apply.
- Where cetane number by Method D 613 is not available, Method D 976 may be used as an approximation. Where there is disagreement, Method D 613 shall be the referee method.
- It is unrealistic to specify low-temperature properties that will ensure satisfactory operation on a broad basis. The tenth percentile minimum ambient temperatures for the months of October, November, December, January, February, and March are given in ASTM D 975 in maps for the 48 contiguous states and Alaska. This guidance is of a general nature; some equipment designs, use of flow improver additives, fuel properties, and/or operations may allow higher or require lower cloud point fuels. Appropriate low temperature operability properties should be agreed on between the fuel supplier and purchaser for the intended use and expected ambient temperatures.
- Low-atmospheric temperatures as well as engine operation at high altitudes may require use of fuels with higher cetane ratings.
- EPA requires minimum 40 Cetane Index (ASTM D 976-80) or 35% vol maximum aromatics content (ASTM D 1319).
- When cloud point less than -12 °C (10 °F) is specified, the minimum flash point shall be 38 °C (100 °F), the minimum viscosity shall be 1.7 cSt, and the minimum 90% recovered temperature shall be waived.

- 4. National Survey of Diesel Fuels**—Since the properties of diesel fuels can vary widely, a national diesel fuel survey is conducted annually to provide data on the properties of fuels produced in the United States. Laboratory inspection data on diesel fuels are furnished voluntarily by the refiners. The results are tabulated according to five general regions of the country where the fuels are marketed. The average values reported are arithmetic, and are not weighed according to sales volume. These results have been compiled and published as Bureau of Mines reports from 1950 to 1974, U.S. Energy Research and Development Administration reports for 1975 and 1976, U.S. Department of Energy reports from 1977 to 1982, and National Institute for Petroleum and Energy Research reports since 1983.

Before 1957, the data were tabulated in these reports according to ASTM grade. From 1957 to 1982, they were tabulated according to intended service type as follows:

Type C-B—Diesel fuel oils for city-bus and similar operations

Type T-T—Fuels for diesel engines in trucks, tractors, and similar service

Type R-R—Fuels for railroad diesel engines

Type S-M—Heavy-distillate and residual fuels for large stationary and marine diesel engines

Fuels that met the requirements for ASTM D 975, Grade No. 1-D or 2-D (see Table 1) were so indicated in these reports.

Since 1983, the data have been tabulated according to ASTM Grade No. 1-D or 2-D, and the intended service types (listed previously) have been so indicated.

5. Significance and Methods of Measurement of Diesel Fuel Properties

- 5.1 Hydrocarbon Composition**—The hydrocarbon composition of diesel fuel determines many other properties: the ignition quality, heating value, volatility, gravity, oxidation stability, etc. Thus, it directly affects the power and economy, wear, deposit formation, starting, and smoke performance of diesel engines.

Since diesel fuels are complex mixtures of many individual hydrocarbons, the measurement of their hydrocarbon composition is not simple. A number of procedures are used, and the reader is referred to current ASTM publications for suggested methods.

- 5.2 Ignition Quality**—Engine performance factors which may be influenced by ignition quality of the fuel are: cold starting, warmup, combustion roughness, acceleration, deposits under idle and light load operation, and exhaust smoke density. In each of these cases, other fuel factors as well as engine factors can also affect performance. The ignition quality requirement of an engine depends on design, size, mechanical condition, operating conditions, atmospheric temperature, and altitude. Increase in ignition quality over the level required does not materially improve engine performance.

Ignition quality is measured by ASTM D 613. The ASTM cetane number of a diesel fuel is defined as the percentage by volume of normal cetane in a blend with heptamethylnonane required to match the ignition quality of the test fuel (ASTM Cetane Number = % n-cetane + (0.15) (% heptamethylnonane)). The method requires the use of a standard test engine equipped with accepted instrumentation and operated under prescribed conditions.

When a test engine is not available for determining cetane number, or when the quantity of sample is too small for an engine rating, this property may be approximated by the ASTM calculated cetane index methods provided in ASTM D 976 or ASTM D 4737.

In 1980, ASTM Committee D02.E0.02 concluded a study of the correlation between measured cetane number and calculated cetane index determined from various fuel properties. Data obtained by 17 laboratories on about 1200 diesel fuels, predominantly from the United States and Canada, were used to revise the cetane index formula and improve the correlation with cetane number. A nomograph from ASTM D 976-80, based on this revised formula, is shown in Figure 1. The method for determining the calculated cetane index from the API gravity or density and the mid-boiling point is indicated by the illustrative example on the nomograph.

A more recent test method developed for estimating the cetane quality of distillate fuels is ASTM Method D 4737. This method provides for estimating cetane number of distillate fuels from density and the 10, 50, and 90% distillation temperatures of the fuels. The relationship is given by the following equation:

$$\begin{aligned} \text{CCI} = & 45.2 + (0.0892)(T_{10N}) \\ & + [0.131 + (0.901)(B)][T_{50N}] \\ & + [0.0523 - (0.420)(B)][T_{90N}] \\ & + [0.00049][(T_{10N})^2 - (T_{90N})^2] \\ & + (107)(B) + (60)(B)^2 \end{aligned} \quad (\text{Eq. 1})$$

where:

CCI = Calculated Cetane Index by Four Variable Equation

D = Density at 15 °C, determined by Test Method D 1298

DN = $D - 0.85$

B = $[e^{(-3.5)(DN)}] - 1$

T₁₀ = 10% distillation temperature, °C, determined by Method D 86 and corrected to standard barometric pressure

T_{10N} = T₁₀ - 215

T₅₀ = 50% distillation temperature, °C, determined by Method D 86 and corrected to standard barometric pressure

T_{50N} = T₅₀ - 260

T₉₀ = 90% distillation temperature, °C, determined by Method D 86 and corrected to standard barometric pressure

T_{90N} = T₉₀ - 310

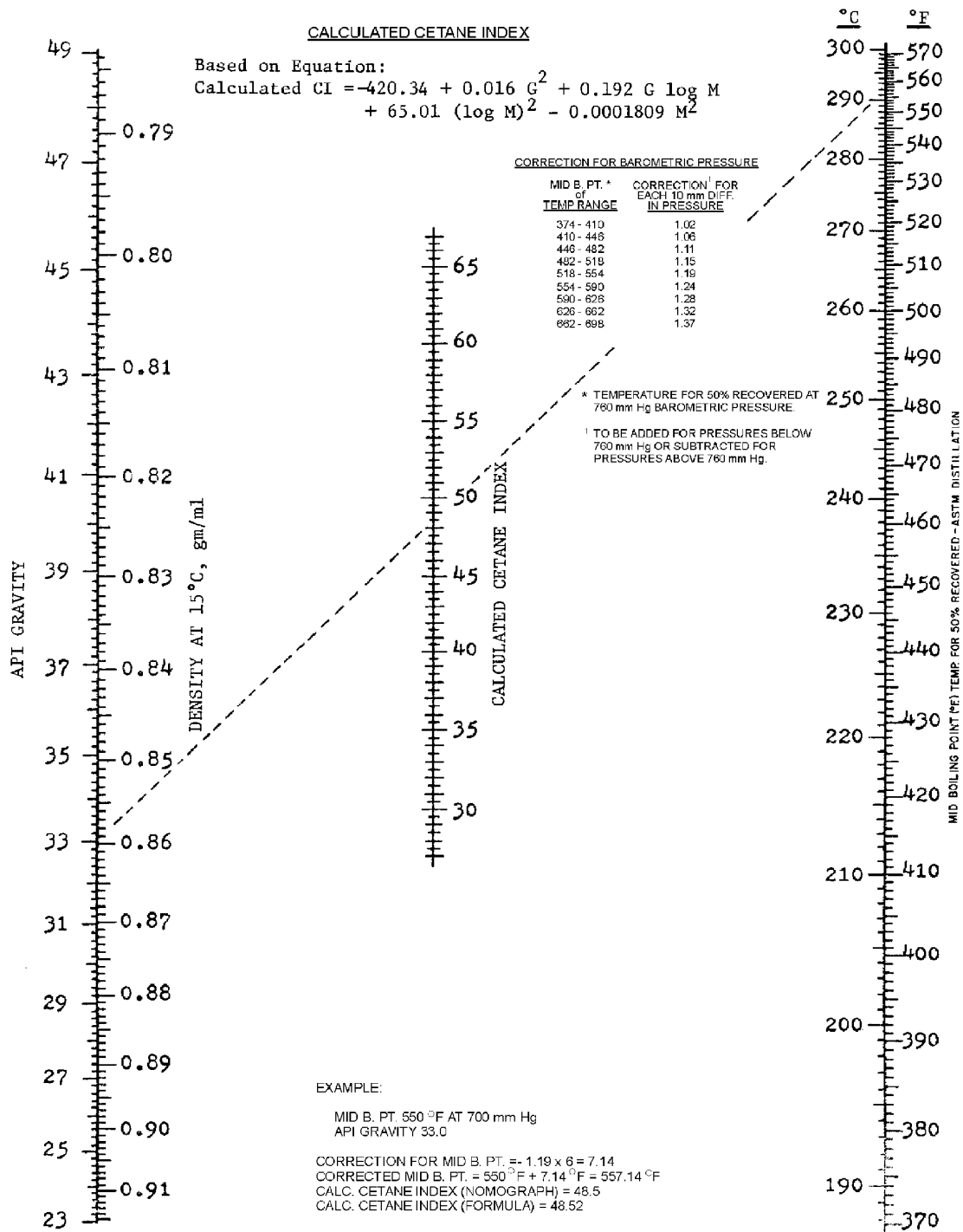
The Calculated Cetane Index by Four Variable Equation is useful for estimating ASTM cetane number when a test engine is not available for determining this property directly. It may be conveniently employed for estimating cetane number when the quantity of sample available is too small for an engine rating. In cases where the ASTM cetane number of a fuel has been previously established, the Calculated Cetane Index by Four Variable Equation is useful as a cetane number check on subsequent samples of that fuel, provided the fuel's source and mode of manufacture remain unchanged.

Procedure: Determine the density of the fuel at 15 °C to the nearest 0.0001 kg/L, as described in Test Method D 1298.

Determine the 10, 50, and 90% distillation temperatures of the fuel to the nearest 1 °C, as described in Method D 86.

Calculation or Interpretation of Results: Compute the Calculated Cetane Index by Four Variable Equation using the equation given in 4.1. The calculation is more easily performed using a computer or programmable hand calculator. Round the value obtained to the nearest one-tenth.

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NOTE—The Calculated Cetane Index formula represents a useful tool for estimating cetane number. Due to inherent limitations in its application, Index values may not be a valid substitute for ASTM Cetane Numbers as determined in a test engine.

From ASTM D 976-80. Copies of the Nomograph for Calculated Cetane Index are available from ASTM, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959.

FIGURE 1—NOMOGRAPH FOR CALCULATED CETANE INDEX

Calculated Cetane Index by Four Variable Equation can also be easily determined by means of the nomographs appearing in Figures 2 through 4. Figure 2 is used to estimate the cetane number of a fuel based on its density at 15 °C and its 50% distillation temperature. Figure 3 is used to determine a correction for the estimate from Figure 2 to account for deviations in the density and the 90% distillation temperature of the fuel from average values. Figure 4 is used to determine a second correction for the estimate from Figure 2 to account for deviations in the 10% and 90% distillation temperatures of the fuel from average values. The corrections determined from Figures 3 and 4 are summed algebraically with the cetane number estimate from Figure 2 to find the Calculated Cetane Index by Four Variable Equation. The method of using these nomographs is indicated by the illustrative example shown as follows and on Figures 2 through 4.

a. Measured Fuel Properties

ASTM Cetane Number	37.0
Density at 15 °C, kg/L	0.885
D 86 10% Dist. Temp., °C	234
D 86 50% Dist. Temp., °C	274
D 86 90% Dist. Temp., °C	323

b. Calculated Cetane Index

Estimate from Figure 1	34.0
Correction from Figure 2	+0.6
Correction from Figure 3	+2.5
CCI =	37.1

The revised (D 976-80) cetane index method has not been adopted in Europe. Thus, the previous (D 976-66) method is published in Europe as Institute of Petroleum Designation 218/67(75), and is used there for estimating ignition quality.

The ASTM calculated cetane index is particularly applicable to straight-run fuels, catalytically cracked stocks, and blends of the two. Their application is limited as follows:

- The ASTM calculated cetane index test methods are not applicable to fuels containing additives for raising cetane number.
- ASTM D 976 is not applicable to pure hydrocarbons, synthetic fuels, alkylates, or coal-tar products.
- The use of ASTM D 976 may result in substantial inaccuracies in correlation if used for crude oils, residuals, or products having a distillation end point below 260 °C (500 °F).
- ASTM D 4737 is particularly applicable to straight-run and cracked stocks, and blends of the two. It can also be used for fuels containing nonpetroleum derivatives from tar sands and oil shale. The recommended range of application for this test method is as follows in Table 2:

TABLE 2—RECOMMENDED RANGE OF APPLICATION

Property	Recommended Range
ASTM Cetane Number	32.5 – 56.5
Density at 15 °C, kg/L	0.805 – 0.895
D 86 10% Dist. Temp., °C	171 – 259
D 86 50% Dist. Temp., °C	212 – 308
D 86 90% Dist. Temp., °C	251 – 363

The ASTM calculated cetane index test methods are not recommended as a substitute for actual measured cetane number in the preparation of fuel specifications. However, because good correlations can be established between cetane index test methods and cetane number for a given crude oil and processing scheme, cetane index test methods are often used for refinery control of diesel fuel ignition quality.

Part 1 - Estimate Based on Density and D 86 50% Distillation Temperature

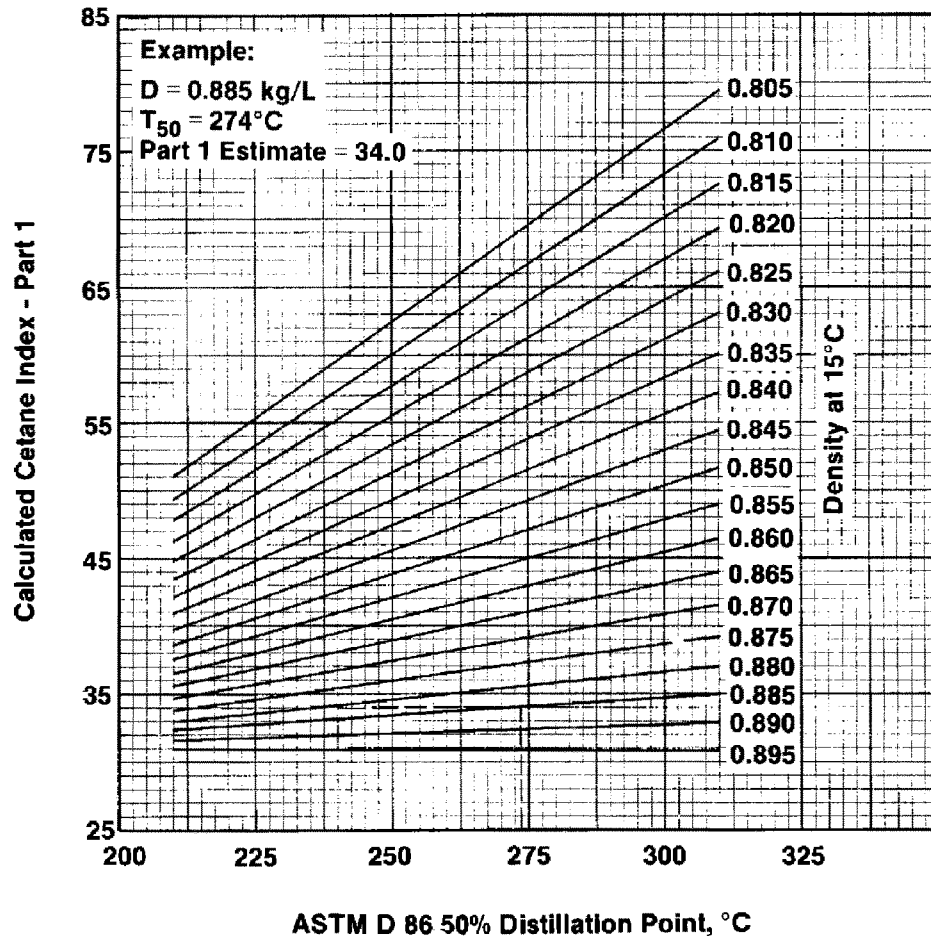


FIGURE 2—CALCULATED CETANE INDEX—ASTM D 4737

Part 2 - Correction for Deviations in Density and D 86 90% Distillation Temperature from Average Values

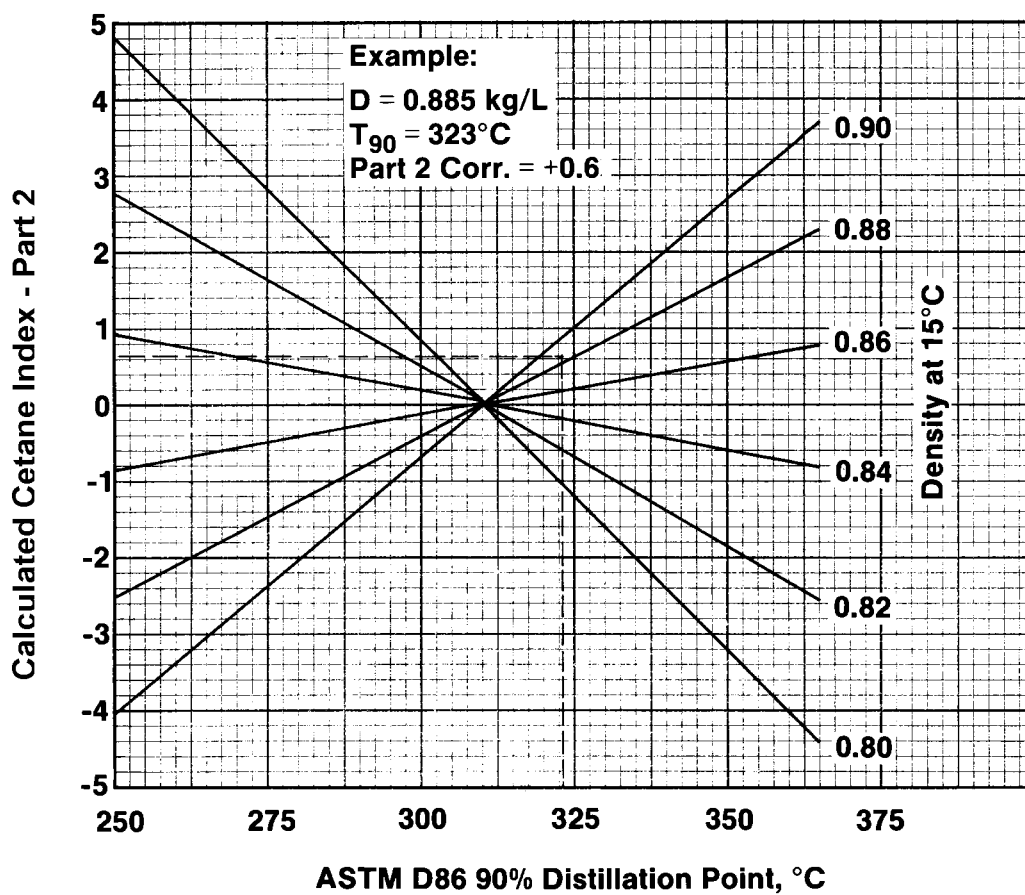


FIGURE 3—CALCULATED CETANE INDEX—ASTM D 4737

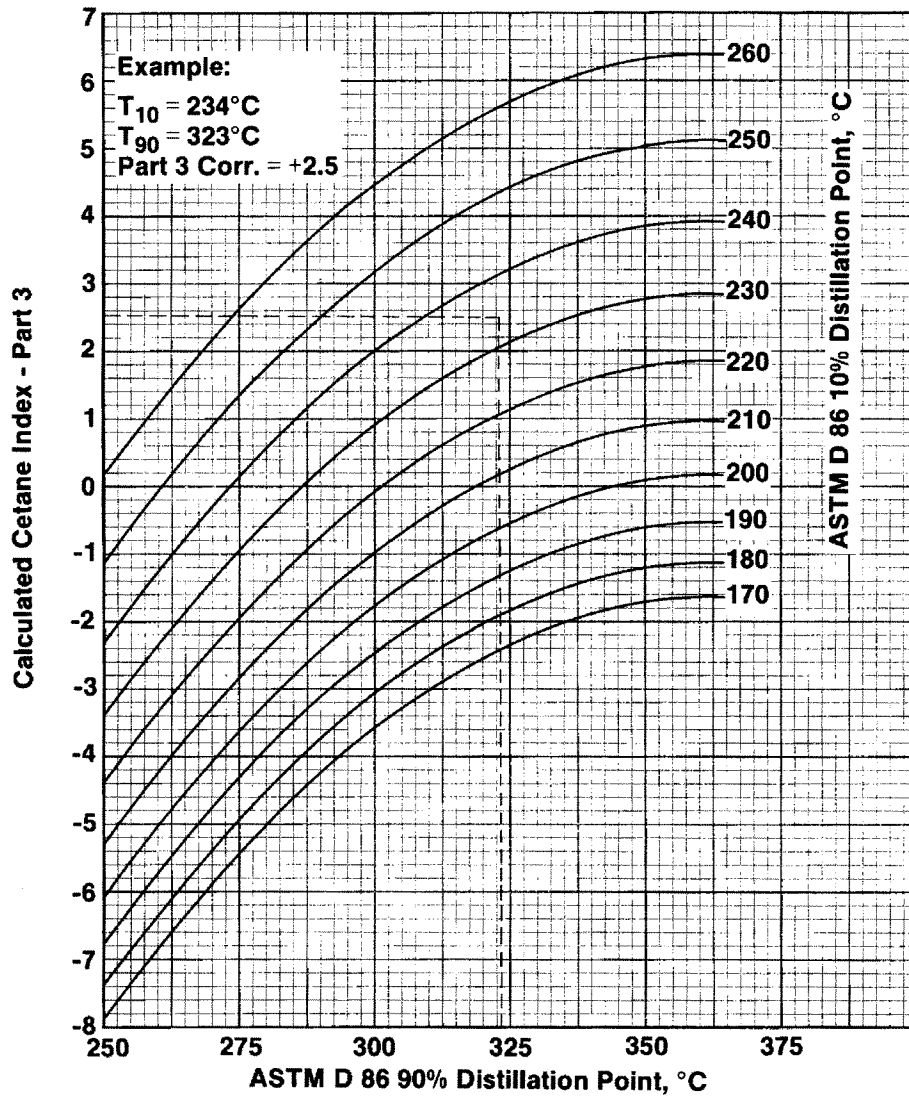
Part 3 - Correction for Deviations in D 86 10% and 90% Distillation Temperatures from Average Values

FIGURE 4—CALCULATED CETANE INDEX—ASTM D 4737

- 5.3 Heating Value**—An important property of a diesel fuel is its heat of combustion, which is a measure of the energy available from the fuel. A knowledge of this value is essential when considering the thermal efficiency of equipment for producing power.

The gross heat of combustion at constant volume is determined by the bomb calorimeter, which measures the amount of heat actually released by burning a known quantity of fuel. ASTM D 240 is applicable to diesel fuels. In the determination of the heating value of fuels by the bomb calorimeter method, the water vapor formed is condensed, which results in the gross or higher heating value for the fuel. The net or lower heating value of fuel is determined by subtracting the latent heat of condensation of water vapor formed in the calorimeter process from the reported gross or higher heating value. It is customary to use the lower heating value for calculating thermal efficiency.

Heating values may be expressed as J/kg, J/L, Btu/lb, Btu/gal, cal/g, or cal/L. Since diesel engine fuel consumption is expressed on a kg/KW·h or lb/bhp·h basis and since diesel fuel is purchased on a liter or gallon basis, both weight and volume bases are of interest to the engine manufacturer and user.

When bomb calorimeter heating values are not available, it is customary to use empirical relationships which yield heating values sufficiently accurate for many purposes. One source of such empirical data is the U.S. Bureau of Standards Miscellaneous Publication No. 97, 1929, "Thermal Properties of Petroleum Products," by C. S. Cragoe. ASTM D 3338 and ASTM D 1405 contain equations for estimating heating value from physical and chemical properties.

Two nomographs for estimating the heating value of fuels from empirical formulas and theoretical considerations are shown in Figures 5 and 6. In Figure 5, the gross or net heat of combustion may be estimated from the API gravity or density, and the aniline point (a measure of the aromatic and naphthenic components), as determined by ASTM D 611. In Figure 6, the gross heating value may be estimated from the API gravity or density, and the mid-boiling point temperature for 50% recovered by ASTM D 86.

Heating values determined from the various empirical relations may not agree precisely, nor will they necessarily indicate the true difference in heating value between two specific fuels. However, as average values, they do offer useful estimates for many purposes. A more extensive discussion of heating values is given in SAE J1498.

- 5.4 Volatility**—Power and economy of diesel engines are insensitive to volatility directly, although less volatile fuels normally have a higher heating value (see Figure 6) and thus indirectly affect these performance factors. On the other hand, starting and warmup are favored by high front end volatility, and deposition, wear, and exhaust smoke in some engines are increased by high 90% and end points.

The volatility of No. 1-D and No. 2-D diesel fuels is normally measured by ASTM D 86.

- 5.5 Gravity/Density**—Knowledge of fuel gravity/density, along with volatility, provides useful information about the composition of the fuel, which in turn relates to heating value (Figures 5 and 6), power and economy, deposition, wear, and exhaust smoke. It should be noted from Figures 5 and 6 that, for fixed aniline point and mid-boiling point, decreased API gravity (increased pound per gallon) increases the heating value per gallon, but decreases the heating value per pound. On the other hand, it should be understood that gravity is not the sole determining factor of heating value.

Gravity and density are normally measured by ASTM D 287 or by ASTM D 1298, or API Gravity of Crude Petroleum and Liquid Petroleum Products by Hydrometer Method.

It should be noted that in the change to the SI metric system of measurement, API gravity and specific gravity are to be eliminated from usage. API gravity is to be replaced by absolute density (kg/m^3) at 15 °C and 101.325 kPa. Specific gravity is to be replaced by relative density at 15 °C and 101.325 kPa where the reference fluids for liquids and gases are water and air respectively.

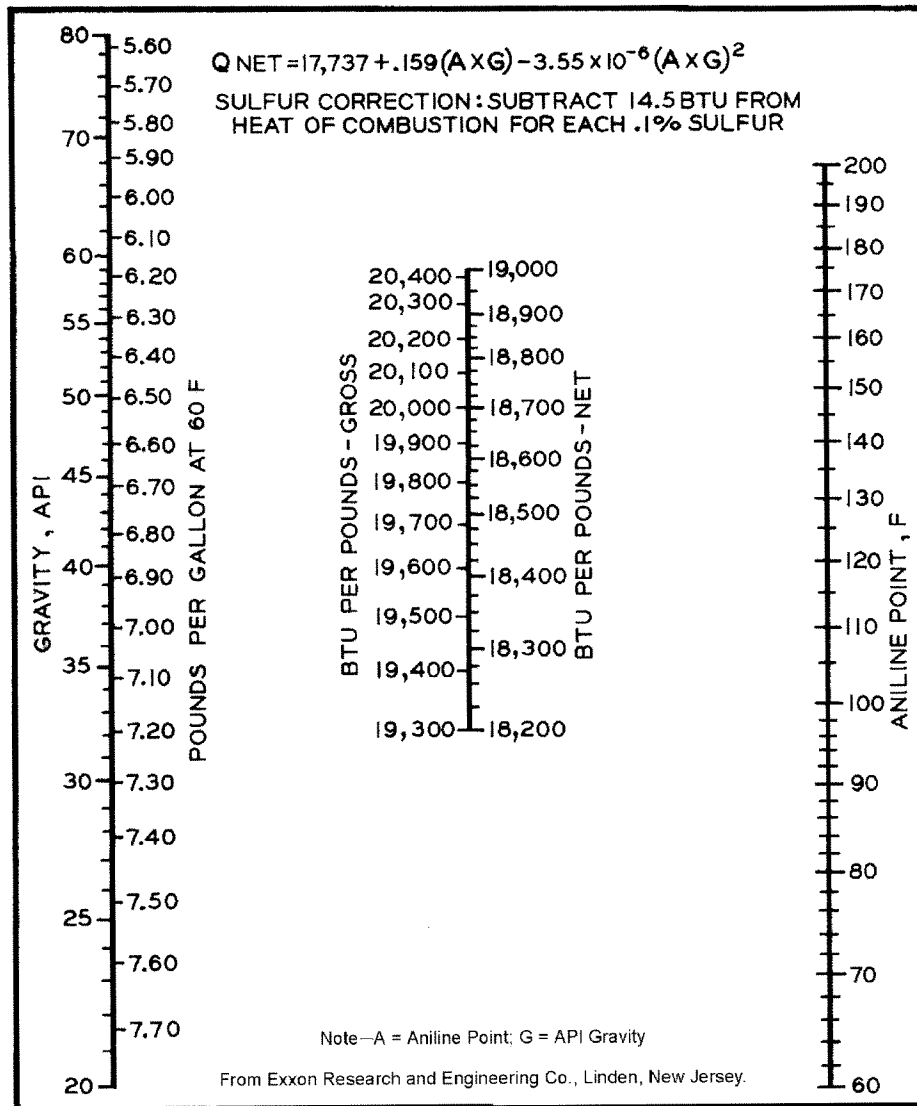
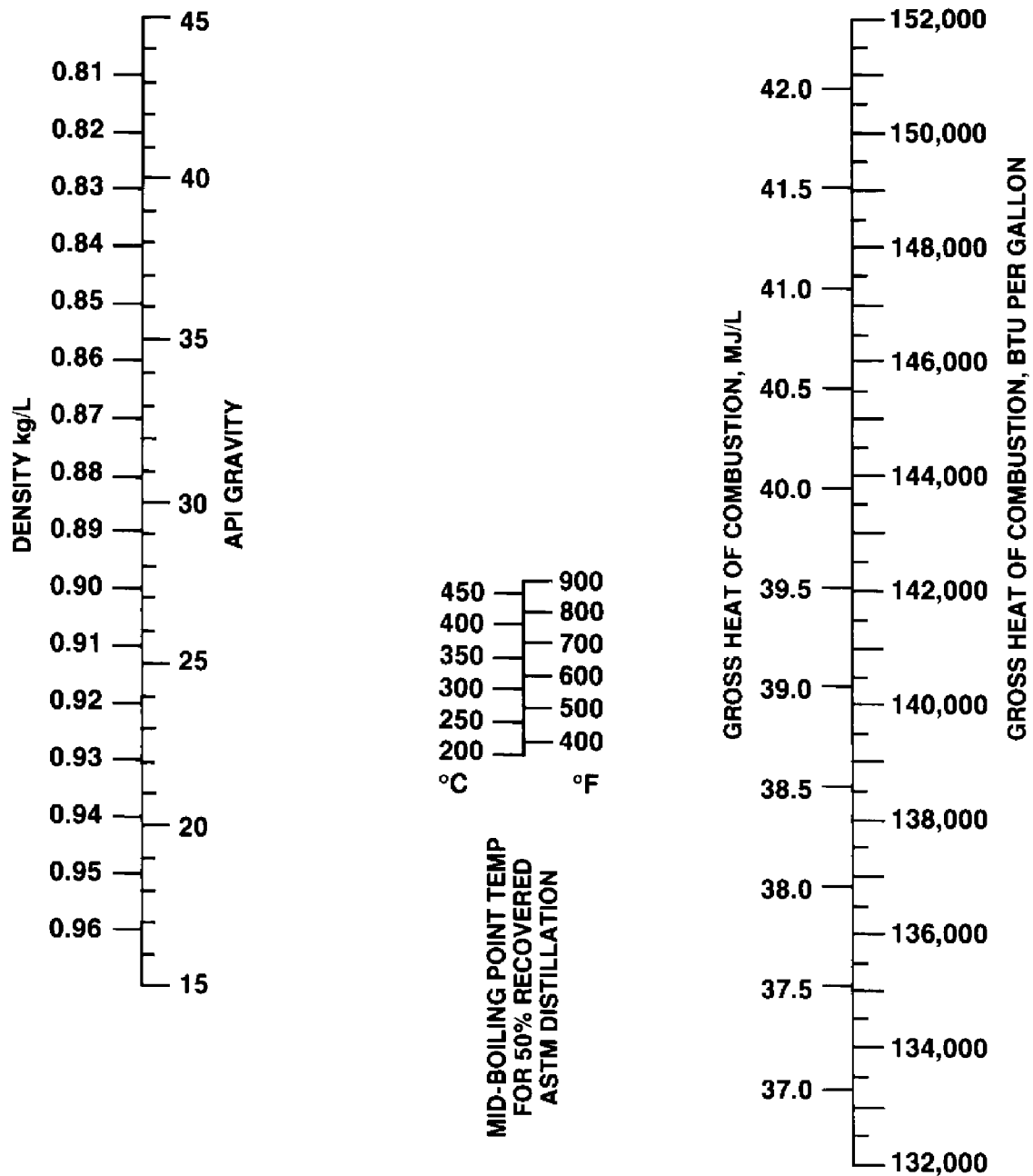


FIGURE 5—RELATION BETWEEN HEAT OF COMBUSTION AND ANILINE POINT AND GRAVITY OF DISTILLATE PETROLEUM FUELS



Adapted from "Diesel Engine Fuel Specifications"
compiled by Ethyl Corporation, August 1967.

FIGURE 6—GROSS HEATING VALUE FOR DIESEL FUELS

- 5.6 Viscosity**—Diesel fuel viscosity can affect the performance of fuel injection systems. Low viscosity can result in excessive wear in some injection pumps and power loss due to pump and injector leakage. High viscosity can result in excessive pump resistance or filter damage. Fuel spray characteristics are also influenced by viscosity.

Diesel fuel viscosity is measured by ASTM D 445.

- 5.7 Cloud Point and Pour Point**—Normal paraffins occur naturally in all diesel fuels. As the fuel is cooled, these components become less soluble, and begin to precipitate as wax crystals. The temperature at which a sufficient number of these wax crystals become large enough to make the fuel appear hazy or cloudy is called the “cloud point.” Cloud point indicates the onset of filter plugging with some fuel system designs, and is expressed in increments of 1 °C (2 °F). As the fuel is further cooled, these wax crystals continue to precipitate and grow. The lowest temperature at which the fuel is observed to flow is called the “pour point.” The pour point may indicate the lowest temperature at which fuel can be pumped, and is expressed in increments of 3 °C (5 °F). For fuels which do not contain a pour point depressant additive, the pour point is usually from 3 °C (5 °F) to 15 °C (25 °F) below the cloud point. Pour point depressant additives have no effect on the cloud point. The applicable measurement methods are ASTM D 2500 and ASTM D 97. ASTM D 3117 gives results which are closely related to cloud point.

A test widely used in Europe to predict low-temperature performance is the Cold Filter Plugging Point of Distillate Fuels (CFPP), IP Test Method No. 309/80. This test measures the lowest temperature at which less than 60 s is required for 20 mL of fuel to flow through a fine wire mesh screen having a nominal aperture of 45 µm. A 1981 CRC study has shown that CFPP does not correlate well with low temperature performance of North American fuels in North American equipment. Other tests have been proposed such as ASTM Method D 4539 (LTFT), which may show better correlation, and they are being evaluated within ASTM.

- 5.8 Flash Point**—The flash point is the lowest fuel temperature at which application of a test flame causes the vapor above the sample to ignite momentarily under prescribed conditions. It is not directly related to engine performance, but is important in connection with legal requirements and safety precautions involved in fuel handling and storage. An abnormally low flash point may denote contamination with lighter products such as gasoline.

The usual method of measurement is ASTM D 93.

- 5.9 Sulfur Content**—The effect of sulfur content on engine wear and deposits varies with engine and operating conditions. Higher sulfur contents than those stipulated in ASTM D 975 should be avoided because of these effects. In some engines, higher sulfur fuels may be used if a crankcase lubricant formulated to combat the effects of high sulfur is used along with an appropriate shortening of the oil drain intervals. Sulfur content of diesel fuels may also be limited by regulations directed at exhaust emission control.

Sulfur content may be measured by one of several methods: ASTM D 129 (prescribed in ASTM D 975), ASTM D 1552, ASTM D 1266, and ASTM D 2622.

- 5.10 Carbon Residue**—Carbon residue may be related to the formation of deposits in diesel engine injection systems and combustion chambers.

Carbon residue is measured by ASTM D 524.

5.11 Ash—Ash forming materials may be present in diesel fuel either as suspended solids or soluble metallic compounds. Suspended solids and certain dissolved organometallic compounds containing sodium, vanadium, etc., may contribute to injector, fuel pump, and ring wear and also to rapid deterioration of engine parts exposed to high temperatures such as turbochargers and valves. Soluble metallic compounds may also contribute to engine deposits.

ASTM D 482 is commonly used to measure ash.

5.12 Copper-Strip Corrosion—Corrosion of copper, brass, or bronze parts of the fuel system can result from certain sulfur compounds in diesel fuel. ASTM D 130 is an indication of possible difficulties of this type.

5.13 Water and Sediment Content—Contamination of diesel fuel by water and sediment sometimes occurs during distribution of diesel fuels from the refinery to the users and during the use in diesel equipment. Control of such contamination is a matter requiring constant vigilance. In engines such contamination can lead to filter plugging and injection system wear, and may promote corrosion. ASTM D 1796 indicates the amount of these contaminants present in a sample.

5.14 Oxidation Stability—The products of oxidation of diesel fuel in storage can result in deposits, filter plugging, and lacquering of fuel pump and injector parts.

ASTM D 2274 is available as a measure of this property.

5.15 Rust Protection—Minimizing rust in fuel distribution and diesel equipment fuel handling systems when engines are idle minimizes filter plugging and wear problems. ASTM D 665 is a possible measure of rust protection of diesel fuels, although it has not been clearly correlated with field experience.

6. Relationships Among Properties—Certain properties of distillate diesel fuels, such as volatility, viscosity, gravity, ignition quality, cloud and pour points, and heating value, exhibit interrelationships. Low volatility, straight run fuels usually have lower API gravity, but higher viscosity, cetane number, cloud and pour points, and heating value than do fuels of higher volatility from similar crude sources. Since diesel fuels are composed of complex mixtures of many hydrocarbon compounds, the influence of hydrocarbon composition is also reflected in the interrelationships of these properties.

It has been established, through extensive experimental investigation, that certain properties of a fuel can be estimated with reasonable accuracy from two or more measured properties, such as volatility and API gravity.

A chart showing the approximate relationship between 50% and 90% recovery temperatures from the ASTM distillation, API gravity, cetane number, viscosity, cloud point, and net heating value is shown in Figure 7. These interrelationships may not be applicable to all distillate fuels produced from current crude oils by current refining processes. Because of these limitations, this chart should only be used to estimate fuel properties in the absence of complete data, and should not be used to establish specifications.

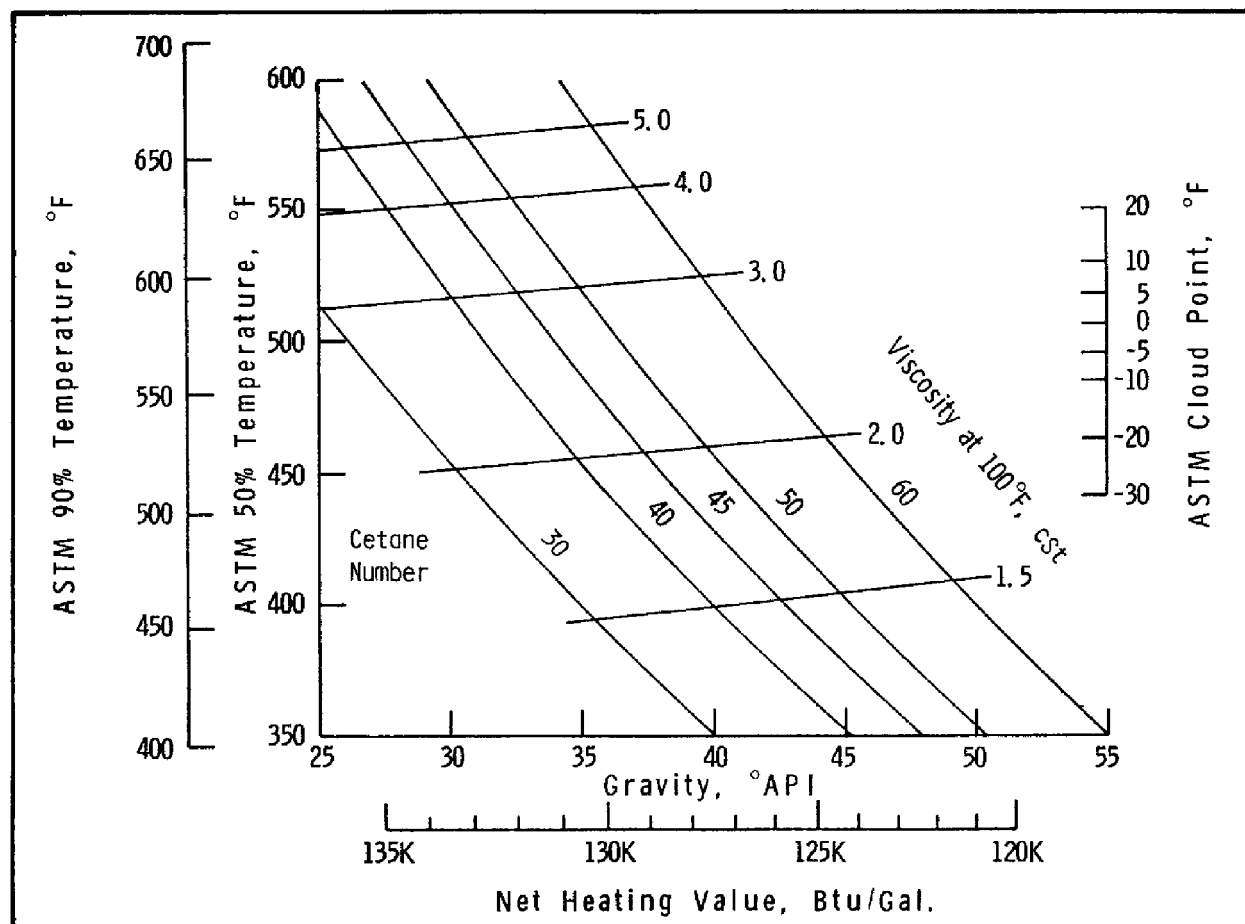


FIGURE 7—RELATED PROPERTIES OF DISTILLATE DIESEL FUELS

Adapted from Reference 8 in 2.3.1

7. **Diesel Fuel Additives**—Commercial diesel fuels may contain a variety of additives to enhance or impart certain desirable properties. Among those which may be found in current fuels are ignition quality improvers, oxidation inhibitors, biocides, rust preventives, metal deactivators, pour point depressants, demulsifiers, smoke suppressants, detergent-dispersants, conductivity improvers, dyes, and de-icers.

Diesel fuel additives are shown by class and function in Table 3. As with any system in which a variety of additives may be used, care should be taken to avoid incompatibilities among additives and unanticipated interactions which may produce undesirable fuel effects.

TABLE 3—COMMERCIAL DIESEL FUEL ADDITIVES—FUNCTION AND TYPE

Class for Function	Common Additive Type
1. Ignition Quality Improvers—Raise Cetane Number thereby promoting faster starts and less white smoke.	Alkyl nitrates.
2. Oxidation Inhibitors—Minimize oxidation and gum and precipitate formation, improve storage life.	Alkyl amines and amine-containing complex materials.
3. Biocides—Inhibit the growth of bacteria and fungi which feed on hydrocarbons, help prevent filter-clogging caused by these organisms.	Boron compounds, ethers of ethylene glycol, quaternary amine compounds.
4. Rust Preventives—Minimize rust formation in fuels systems and storage facilities.	Organic acids and amine salts. A widely used type is based on dimerized linoleic acid.
5. Metal Deactivator—Deactivates copper ions which are powerful oxidation catalysts.	N,N'-disalicylidene-1,2-propane diamine.
6. Pour Point Depressants—Reduce the pour point and improve low-temperature fluidity properties by modifying the wax crystal growth, structure, and/or agglomeration.	Generally consist of polymeric materials such as polyolefins, polyacrylates, polymethacrylates, modified polystyrenes, ethylene-vinyl acetate copolymers, and ethylene-vinyl chloride copolymers.
7. Demulsifiers and Dehazers—Improve the separation of water from distillate fuels and prevent haze.	Surface-active materials which increase the rate of water/oil separation. Usually quite complex mixtures.
8. Smoke Suppressants—Minimize exhaust smoke by catalyzing more complete combustion of carbonaceous materials or by helping to maintain fuel spray patterns.	Catalyst types are generally overbased barium compounds. Maintenance of spray patterns is helped by detergents.
9. Detergent-Dispersants—Promote engine fuel system cleanliness, help prevent nozzle deposit formation and injector sticking, interfere with precipitate agglomeration, thus maintaining optimum filtration characteristics.	These are usually surface-active agents. They are often polymeric materials containing amines and other functional groups.
10. Conductivity Improvers—Improve dissipation of electrostatic charge.	Amine salts, metallic salts, and polymeric compounds.
11. Dyes—Various identification purposes including tax status.	Oil-soluble solid and liquid dyes.
12. De-icers—Reduce the freezing point of small amounts of water to prevent fuel line plugging.	Low molecular weight alcohols (ethanol, isopropanol, and/or methanol), and ethylene glycol monomethyl ether or di-ethylene glycol monomethyl ether.
NOTE—Some materials may also be marketed as multifunctional or multipurpose additives, performing more than one of the functions.	

8. Other Diesel Fuel Specifications

8.1 Commercial Fuels—ASTM D 975 is the specification most commonly used in the U.S. to describe and classify commercial diesel fuels. Other specifications have been established in the U.S. and in other countries. Selected property limits from some of the most widely used specifications for automotive type diesel fuels are shown in Tables 4 to 6. While these specifications are generally similar, they are not identical. The engine manufacturer, fuel supplier, and equipment user must all remain aware of these differences in different parts of the world.

8.2 Test Fuels—Specifications more stringent than those for commercial fuels have been established for special fuels used during exhaust emissions or performance testing. Selected property limits from three widely used test fuel specifications are shown in the right hand columns of 7.

TABLE 4—KEY PROPERTY LIMITS FROM U.S. AUTOMOTIVE DIESEL FUEL SPECIFICATIONS

Property	ASTM D 975 Grade 2-DLS	U.S. Federal VV-F-800 D and Grade DF-2 (U.S.) ⁽¹⁾⁽²⁾	NATO Standardization Agreement (STANAG) 7040, Military F-S4 Diesel Fuel
Cetane Number	40 min	40 min	45 min
Cetane Index, ⁽³⁾ or	40 min	43 min	N.R.
Aromatics Content, vol%	35 max		
Sulfur% wt or	0.05 max ⁽⁴⁾	0.05 max ⁽⁴⁾	0.30 max
Distillation °C			
50% Point	—	Report	Report
90% Point	282-338	338 max	357 max
End Point	—	370 max	370 max
Kinematic Viscosity cSt			
at 20 °C	—	—	1.8-9.5
at 40 °C	1.9-4.1	1.9-4.4	1.4-5.5 ⁽⁵⁾
Density at 15 °C g/mL	—	Report	0.820-0.860
Oxidation Stability			
ASTM D 2274 mg/100 ml	—	1.5 max	1.5 max
Particulate Contamination			
ASTM D 5452 mg/L	—	10 max	10 max

- The US Army cancelled Federal Specification VV-F-800D in January 1996 but it is still used in civilian procurement in the USA.
- The US Army issued Commercial Item Description (CID) A-A-52557 dated January 2/96 entitled, "Fuel Oil, Diesel, for Posts, Camps, and Stations" which covers requirements for two grades of low sulfur diesel fuel oils for military ground compression ignition and gas turbine engines. This specifies the fuel quality to be that of ASTM D 975 No 1 DLS and 2 DLS respectively with the following additions:
 - Fuel Stabilizer Additive —(MIL-S-53021)
(QPL 53021 determines concentration used)
 - Corrosion Inhibitor—(MIL-I-25017)
(QPL 25017 determines concentration used)
 - Fuel System Icing Inhibitor (MIL-I-85470)
(0.15% vol maximum addition)
 - Particulates 10 mg/L max by ASTM D 5452
 - Cloud Point not higher than 10th percentile minimum ambient temperatures as shown for US locations in Appendix A2 in ASTM D 975
- Fuel for off-highway use is not required to meet a 40 Cetane Index by ASTM D 976-80.
- Fuel containing 0.50% wt sulfur is allowed for off-highway use in all states of the USA, except for California vehicular use.
- Estimated—not part of the specification.

**TABLE 5—KEY PROPERTY LIMITS FOR EUROPEAN
AUTOMOTIVE DIESEL FUELS
CEN EN 590-93 (EUROPEAN COMMON MARKET)**

Generally Applicable Requirements					
Property	Limits				
Flash Point °C	55 min	ASTM D 93			
Oxidation Stability mg/100 mL	2.5 max	ASTM D 2274			
Sulfur Content% wt	0.05 max				
Particulate Matter mg/kg	24 max				
Water Content mg/kg	200 max				
Climatically Related Requirements—Temperate Areas					
Cetane Number ASTM D 613	49 min				
Cetane Index (ISO 4264)	46 min				
Density at 15 °C g/mL	0.820-0.860				
Viscosity cSt at 40 °C	2.0-4.50				
Distillation ASTM D 86					
% vol rec. at 350 °C	85 min				
% vol rec. at 370 °C	95 min				
CFPP °C Grade A	+5 max				
Grade B	0 max				
Grade C	−5 max				
Grade D	−10 max				
Grade E	−15 max				
Grade F	−20 max				
Climatically Related Requirements—Arctic Areas					
Fuel Class	0	1	2	3	4
CFPP °C max	−20	−26	−32	−38	−44
Cloud Pt. °C max	−10	−16	−22	−28	−34
Density 15 °C min	0.80	0.80	0.80	0.80	0.80
g/mL max	0.845	0.845	0.840	0.840	0.840
Viscosity min	1.50	1.50	1.50	1.40	1.20
cSt at 10 °C max	4.00	4.00	4.00	4.00	4.00
Cetane No. min	47	47	46	45	45
Cetane Index min	46	46	46	43	43
Distillation					
% vol at 180 °C max	10	10	10	10	10
% vol at 340 °C min	95	95	95	95	95
Note—Cetane Index also requires the 10% and 50% vol recovered temperatures and is equivalent to ASTM D 4737. CFPP is Cold Filter Plugging Point Temperature Test IP 309.					

**TABLE 6—KEY PROPERTY LIMITS FOR CANADIAN, AUSTRALIAN,
AND JAPANESE AUTOMOTIVE DIESEL FUEL SPECIFICATIONS
GENERAL REQUIREMENTS**

Property	Canada CAN 3-517 Grade B-LS	Australia AS 3570-1988	Japan JIS KK 2204-88 Grade 2
Density 15 °C	N.R.	0.82-0.87	N.R.
Distillation °C 90% vol max	360	357	350
Cetane Number min	40	45	45
Cetane Index min	40	45	45
Viscosity cSt 40 °C	1.7-4.1	1.9-5.5	2.0 min ⁽¹⁾
Sulfur% wt max	0.05	0.5	0.20
Oxidation Stability mg/100 mL ASTM D 2274	N.R.	2.5 max	N.R.
Cloud Point °C max	2.5% Low Temp. Map ⁽²⁾	Winter Summer +7 Nth +15 Nth 0 W +6 W -1 E +4 E -4 S -4 S (Spec has map)	N.R.
Pour Point	N.R.	N.R. N.R.	-7.5
CFPP ×C max	N.R. ⁽³⁾	3 °C max below Cloud Point	-5.0
Electrical Conductivity ps/m	25 min	N.R.	N.R.

1. Viscosity at 38 °C—equivalent is about 2.1 cSt at 40 °C.

2. 2.5% Low End Design Temperature maps based on 25 year continuous hourly records.

3. Specification recognizes LTFT ASTM D 4539 as valid for defining low temperature operability.

N.R. means No Requirement in specification.

**TABLE 7—KEY PROPERTY LIMITS FOR VARIOUS
AUTOMOTIVE DIESEL EMISSION REFERENCE FUELS**

Property	1994 EPA Exhaust Emission Testing Type 2-D	1995 California Exhaust Emission Testing Type 2-D	ECE European Reference Fuel Type RF-03-A-80
Density g/mL	0.840-0.865	0.830-0.860	0.835-0.845
Distillation °F			
IBP	340-400	340-420	N.R.
10%	400-460	400-490	N.R.
50%	470-540	470-560	474 min
90%	560-630	560-610	608-644
FBP	610-690	580-660	708 max
Viscosity cSt at 40 °C	2.0-3.2	2.0-4.1	2.5-3.5
Cetane No.	40-48	47-55 ⁽¹⁾	51-57
Cetane Index ⁽²⁾	40-48	N.R.	N.R.
Sulfur% wt	0.03-0.05	0.01-0.05	0.2-0.5
Aromatics% vol	27 min	8-12	N.R.
Polycyclic Aromatics% vol	N.R.	1.4 max	N.R.
Flash Point °F	130 min	130 min	130 min
Nitrogen Content ppmw	N.R.	100-500	N.R.

1. Natural Cetane Number without additives only allowed.

2. ASTM D 976-80 Cetane Index.

Notes (a) Federal Reference fuel is used for certifying all on-highway diesel engines destined for sale in the 49 states outside California. It can also be used to certify engines destined for sale in California if desired.

(b) California Reference fuel may be used to certify engines destined for use in California if desired.

9. Cold Weather Operation

9.1 Fuel Selection—Proper attention to diesel fuel low-temperature properties is essential to minimizing fuel handling and engine operating problems in cold weather. The specific recommendations of equipment manufacturers should be followed explicitly. Most North American manufacturers of automotive diesel engines currently recommend the use of ASTM D 975, Grade No. 2-D fuel at ambient temperatures above -7°C ($+20^{\circ}\text{F}$). At very low temperatures, they recommend the use of No. 1-D fuel (if available), which usually forms fewer wax crystals and thus has much lower cloud and pour points. Otherwise, they recommend the use of “winterized” or “climatized” No. 2-D fuel. Such fuels are made by diluting No. 2-D with No. 1-D or kerosene to lower the cloud and pour points as required. ASTM D 975 suggests that satisfactory operation should be achieved in most cases if the cloud point (or wax appearance point) is specified at 6°C (10°F) above the tenth percentile minimum ambient temperature for the area in which the fuel will be used.

A chart for estimating the cloud point of fuel blends is shown in Figure 8. Such blending is not efficient, as large amounts (20 to 30%) of diluent are required to achieve modest [6°C (10°F)] reductions in cloud point.

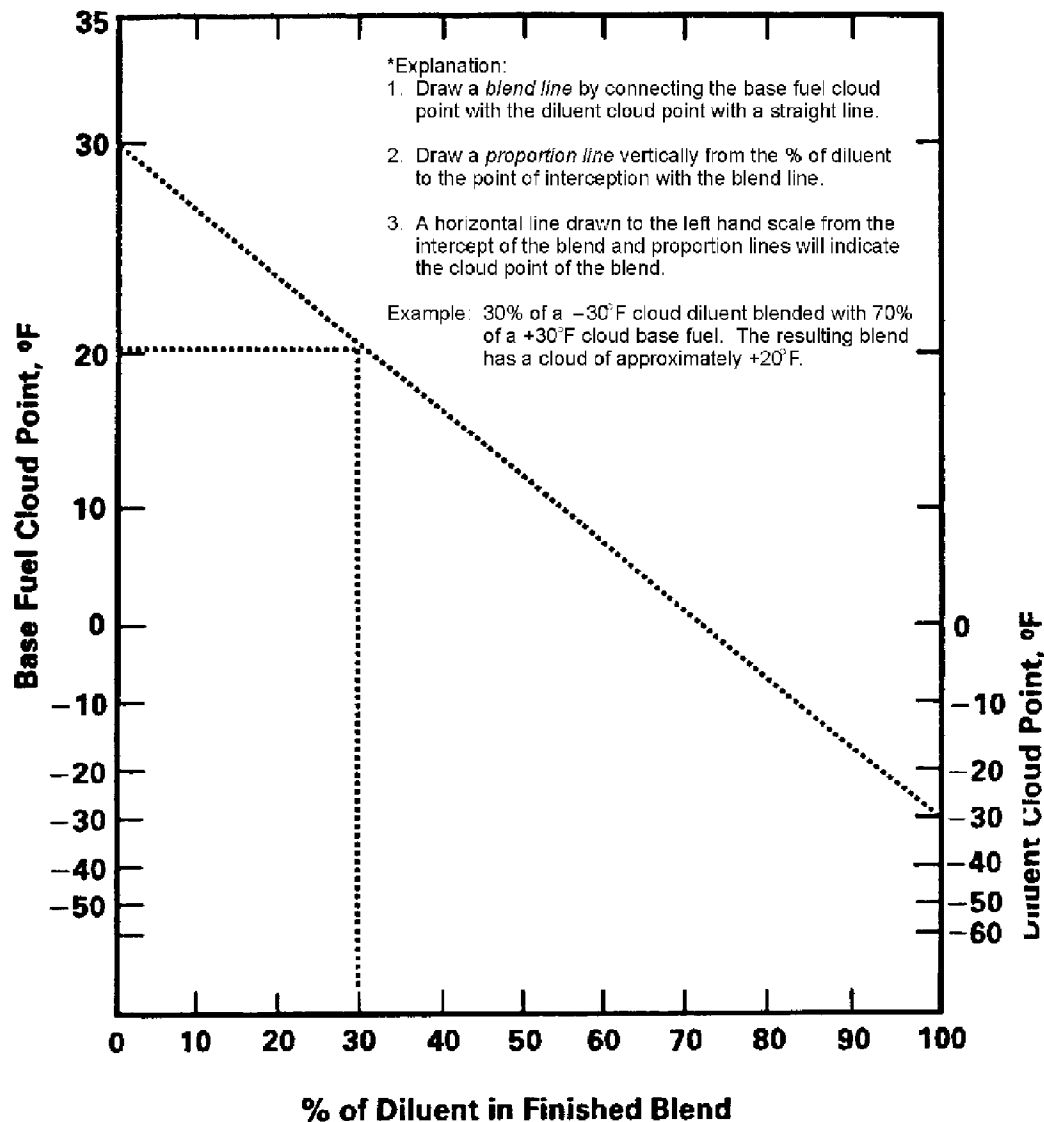


FIGURE 8—CHART FOR ESTIMATING THE CLOUD POINT OF FUEL BLENDS

From "Diesel Fuels and Low Temperatures," Amoco Oil Company,

Product Information Sheet No. 304, December 1977

- 9.2 Additives**—Additives, called pour point depressants, flow improvers, or wax modifiers, can change the size and/or shape of wax crystals as they form, and thus minimize cold weather problems. The additive type and concentration must be optimized for a specific fuel, and the additive must be thoroughly blended into the fuel at temperatures well above the cloud point. Therefore, such additives are most effective when blended by fuel suppliers rather than by equipment users. These additives will not lower the cloud point, but they can lower the temperature at which fuel filter plugging due to wax crystals occurs.

9.3 Minimum Vehicle Operating Temperature—Both vehicle fuel system design and fuel properties are important factors in determining the minimum temperature for acceptable vehicle operation. This temperature can be as high as the cloud point, or as low as the pour point. Thus, cloud point is a fail-safe but conservative predictor of field performance.

Laboratory filter plugging tests have been devised to correlate with vehicle performance, especially using additive-treated fuels. Results from such tests are highly dependent upon the fine wire mesh screen size and the sample cooling rate. A test widely used in Europe is the Cold Flow Plugging Point of Distillate Fuels (CFPP), IP Test Method No. 309/80. This test measures the lowest temperature at which less than 60 s is required for 20 mL of fuel to flow through a screen having a nominal aperture of 45 μm .

The Filterability of Diesel Fuels by Low Temperature Flow Test (LTFT), ASTM D 4539, was developed to correlate with field performance of North American fuels in North American equipment. This test measures the lowest temperature at which less than 60 s is required for 180 mL of fuel to flow through a screen having a normal aperture of 17 μm .

A 1981 CRC study (reference SAE Paper 830594) was conducted using four diesel passenger cars, three heavy-duty trucks, and eight fuels (three base fuels and five additive-treated versions of the base fuels). Of the individual laboratory tests, the LTFT provided the best correlation with overall vehicle performance, followed closely by cloud point and then less closely by CFPP. No single laboratory test was found which adequately predicted the performance of all fuels in all vehicles. Pour point was a poor predictor.

10. Exhaust Emissions—Historically, exhaust emission control of both light- and heavy-duty diesel engines was centered on visible smoke which was readily perceived by—and generally objectionable to—the public. Recent concern about the health impact of particulate emissions coupled with the nonattainment of ambient air quality standards—especially NO_x and the link between it and ground level ozone—caused the enactment of several U.S. Federal Laws (1)(2)(3)(4) to control both particulate and gaseous emissions from on-highway diesel engines. Similar laws have been enacted, or are under consideration for enactment, in Canada (5) and the European Economic Community (EEC). The stringent emissions levels required for the 1993/94 U.S. standards are considered to be technology forcing both in terms of engine design and fuel quality demands.

10.1 Exhaust Emission Regulations—Key emission standards contained in various regulations for light- and heavy-duty on-highway diesel engines relevant to the USA, Canada, and the EEC are summarized as follows in Tables 8 to Table 12.

- a. Light-Duty Vehicles/Engines USA and Canada
- b. Medium-Duty Vehicles—California Air Resources Board (CARB) approved the proposed Medium-Duty Vehicle (MDV) emission standards for model year 1995 on June 4th 1990. This extends the light-duty chassis emissions test to include vehicles in the 8500 to 14 000 lb GVWR bracket. The final standards for diesel-powered vehicles are:

Alternatively, engines and incomplete vehicles may be tested using the EPA transient dynamometer test and then must comply with the following standards:

1. 120 000 mile Emission Standards g/BHP/h

- a. NMHC + NO_x —3.9
 - b. CO —14.4
 - c. Particulates—0.10
- c. Heavy-Duty Engines—USA

More complete details and discussion of the development of both the light- and heavy-duty diesel emission standards can be found in the referenced literature (6)(7).

TABLE 8—LIGHT-DUTY VEHICLES/ENGINES USA & CANADA

Model Year	Jurisdiction	Emission Standard g/mi H/C	Emission Standard g/mi CO	Emission Standard g/mi NO _x	Emission Standard g/mi Particulates
1988	US Federal	0.8	9.0	2.3	0.45
	California	0.6	9.0	1.5	0.20
	Canada	0.8	9.0	1.7	0.26
1989	US Federal	0.8	9.0	2.3	0.45
	California	0.6	9.0	1.5	0.08
	Canada	0.8	9.0	1.7	0.26
1990	US Federal	0.8	9.0	1.7	0.45
	California	0.6	9.0	1.5	0.08
	Canada	0.8	9.0	1.7	0.26
1991-93	US Federal	0.8	9.0	1.7	0.13
	California	0.8	9.0	1.5	0.08
	Canada	0.8	9.0	1.7	0.13

TABLE 9—MEDIUM-DUTY VEHICLE—120 000 MILE EMISSION STANDARDS

Test Weight lb	Emission Standards g/mi NMHC	Emission Standards g/mi CO	Emission Standards g/mi NO _x	Emission Standards g/mi Particulates
3 751 - 5 750	0.46	6.4	0.98	0.10
5 751 - 8 500	0.56	7.3	1.53	0.12
8 501 - 10 000	0.66	8.1	1.81	0.15
10 000 - 14 000	0.86	10.3	2.77	0.18

TABLE 10—HEAVY-DUTY ENGINES—USA

Model Year	Jurisdiction	Emission Standards H/C	Emission Standards CO	Emission Standards NO _x	Emission Standards Particulates	Smoke Opacity A	Smoke Opacity B	Smoke Opacity C
1988	US Federal	1.3	15.5	10.7	0.60	20	15	50
	California	1.3	15.5	6.0	0.60	20	15	50
1990	US Federal	1.3	15.5	6.0	0.60	20	15	50
1991	US Federal	1.3	15.5	5.0	0.25	20	15	50
	California	Same as Federal except 0.10 particulates max for busses.						
1993	US Federal	Busses must meet 0.10 max particulates.						
1994	US Federal	1.3	15.5	5.0	0.10	20	15	50
		Busses must meet 0.05 max particulates.						
1998	US Federal	1.3	15.5	4.0	0.10	20	15	50
		Busses must meet 0.05 max particulates.						

NOTES—Emissions determined by US EPA transient test where:

$$\text{Transient Emissions} = \frac{1/7 \text{ Cold} + 6/7 \text{ Hot Emissions}}{1/7 \text{ Cold} + 6/7 \text{ Hot Work(BHP - h)}}$$

FTP Smoke Opacity:

A is Accelerating Mode

B is Lugging Mode

C is Peak from A+B Modes

Busses mean urban busses.

TABLE 11—HEAVY-DUTY ENGINES—CANADA

Model Year	Jurisdiction	Emission Standards g/BHP/h H/C	Emission Standards g/BHP/h CO	Emission Standards g/BHP/h NO _x	Emission Standards g/BHP/h Particulates
1988	Canadian Federal	1.3	15.5	6.0	0.60
NOTE—US EPA transient test procedure used.					

TABLE 12—LIGHT-DUTY VEHICLES/ENGINES USA AND CANADA

Model Year	Jurisdiction	Emission Standard g/mi HC	Emission Standard g/mi CO	Emission Standard g/mi NO _x	Emission Standard g/mi Particulates
1988	U.S. Federal	0.8	9.0	2.3	0.45
	California	0.6	9.0	1.5	0.20
	Canada	0.8	9.0	1.7	0.26
1989	U.S. Federal	0.8	9.0	2.3	0.45
	California	0.6	9.0	1.5	0.08
	Canada	0.8	9.0	1.7	0.26
1990	U.S. Federal	0.8	9.0	1.7	0.45
	California	0.6	9.0	1.5	0.08
	Canada	0.8	9.0	1.7	0.26
1991-93	U.S. Federal	0.8	9.0	1.7	0.13
	California	0.6	9.0	1.5	0.08
	Canada	0.8	9.0	1.7	0.13

10.2 Impact of Emission Test Procedures on Fuel Quality Requirements—In conjunction with the use of a dilution tunnel test procedure to evaluate the particulate emissions from diesel engines (3), the exhaust gases are mixed with filtered air and cooled to a temperature which is below the acid dew point for sulfuric acid. Sulfates and their hydrates precipitate from the gas stream and are collected on the filters together with carbonaceous and soluble organic fraction (SOF) particulates. The significance of the sulfur content of the test fuel on exhaust particulates was quickly appreciated (8) and this led ultimately to the historic proposal (9) from:

The American Petroleum Institute (API)
The National Petroleum Refiners Association (NPRA)
The Engine Manufacturers Association (EMA)
The National Council of Farmers Coops (NCFC)

recommending that diesel fuel having a sulfur content of 0.05% weight maximum and a cetane index of 40 minimum by ASTM D 976-80, be available by October 1993 for the 1994 model year engines which would require such fuel to comply with mandated emission standards. The U.S. EPA has translated this agreement into a Final Rule (10) which was published in the Federal Register in August 1990.

In the USA, except for California, low sulfur diesel fuels meeting the requirements of:

- Maximum Sulfur Content—0.05% wt
- Minimum Cetane Index (ASTM D 976-80)—40.0 or
Maximum Aromatic Content (ASTM D 1319)—35.0% vol

have become mandatory for all on-highway operations in the 49 states area which excludes California from October 1, 1993.

In California, all fuel for vehicular use (on- and off-highway) has been required to meet the following criteria since October 1, 1993:

- Maximum Sulfur Content—0.05% wt
- Maximum Aromatics Content (ASTM D 1319)—10.0% vol

Farm equipment, locomotives, etc., can use conventional fuel.

In California, an alternate method of certifying diesel fuel for sale under Section 2282 of the California Code of Regulations Title 13, has been to demonstrate equivalent exhaust emissions in a specified test using a Detroit Diesel Series 60 engine operating on the reference fuel shown in Table 13. This is known as the designated alternative limit and this option has been used by several major refiners resulting in fuel blends being certified with the characteristics in Table 14:

TABLE 13—CALIFORNIA VEHICULAR REFERENCE DIESEL FUEL

Property	
Density g/mL	0.830–0.860
Distillation °F	
IBP	340–420
10% rec	400–490
50%	470–560
90%	550–610
FBP	580–660
Viscosity	
cSt at 40 °C	2.0–4.1
Cetane Number	48 ⁽¹⁾ min
Flash Point °F	130 min
Sulfur% wt	0.05 max
Nitrogen ppmw	10 max
Aromatics% vol	10.0 max
Polycyclic Aromatics% wt	1.4 max

1. Natural Cetane Number without additives only allowed.
 Note—This fuel is used as a reference for emissions when testing designated alternative limit fuels in a specified heavy-duty diesel engine test.

TABLE 14—CERTIFIED CHARACTERISTICS

Refiner Blend	A 1	A 2	A 3	B 1	B 2
Cetane No.	58	59	55	55.2	56.2
Sulfur ppm	54	196	202	33	42
Aromatics% vol	19	19	15	21.7	24.7
Nitrogen ppm	484	466	341	20	40
Polyaromatics	2.22	4.39	3.6	4.6	4.0

Note—All values are maxima except Cetane number which is the minimum. Other compositions are in use commercially to meet Section 2282 but have not been disclosed publicly.

From October 1, 1994 in Canada, all diesel sold through retail and cardlock outlets must meet the following criteria:

- a. Maximum Sulfur Content—0.05% wt
- b. Minimum Cetane Index (ASTM D 976-80)—40.0

In Canada, fuel supplied to a customer's own tankage for on-highway use can continue to contain up to 0.5% wt sulfur except in British Columbia where all fuel must be low sulfur (0.05% wt maximum).

In Canada, high sulfur diesel fuel must contain a green dye. In the USA, the IRS and EPA require addition of a red dye to all untaxed and high sulfur diesel fuels at a rate to provide the spectral equivalent of 3.0 lb/thousand barrels of solid dye Solvent Red 26.

10.3 Impact of Fuel Quality Parameters on Heavy-Duty Diesel Exhaust Emissions—The initial focus, from a fuel quality and compositional perspective, was on the influence of fuel aromatic content, 90 vol% distilled temperature and the sulfur content, and more recently, the fuel cetane number, both natural and when improved with alkyl nitrate ignition improver additives. Some of these properties are quite strongly correlated and this fact must be taken into account when considering the results from programs aimed at identifying the effect of specific fuel parameters.

The most definitive and relevant work published on the subject to date are the reports from the Coordinating Research Council (CRC) VE-1 Project (11)(12) which has used three engines of differing design and size and has looked at fuel aromatic content, 90 vol% distilled temperature, sulfur content, natural cetane number, and additive-improved cetane number, in statistically designed experiments with closely tailored fuel sets.

Emission responses from the three engines were sufficiently different and the quantity of data limited so that universal models were not developed for the three engines as a group. Engine design features can be seen from the results to have a much greater effect on emissions of all regulated species than the fuel compositional changes.

From published data (11)(12)(13) and other information from regulatory agency hearings, the following conclusions can be drawn regarding the effects of fuel composition on diesel exhaust emissions in general:

- a. Increases in fuel sulfur content directly increase particulate emissions.
- b. As cetane number increases, CO and hydrocarbon emissions decrease.
- c. As cetane number increases, NO_x emissions decrease with a somewhat higher rate for natural cetane over additive improved fuels.
- d. As aromatic content is decreased NO_x emissions decrease.
- e. Cetane number, both natural and additive-improved, and possibly aromatic content affect particulate emissions. Increasing cetane number particularly natural cetane number reduces particulates while increasing aromatics content increases particulates.
- f. 90 vol% distilled temperature is significant for CO, NO_x, and H/C but the effect is highly engine dependent being most significant for the indirect injection engine tested. The influence on CO emissions was in different directions for different engines.

10.4 Secondary Effects of Emissions Regulation on Diesel Fuel Quality—National Petroleum Refiners Association (NPRA)(14) in the USA and the Canadian Petroleum Producers Institute (CPPI) formerly PACE (15) in Canada have surveyed the availability of diesel fuel meeting the 0.05% weight sulfur maximum and 40 cetane index criteria in North America. A very significant increase in hydroprocessing and hydroconversion capacity will be needed to meet the demands for on-highway diesel fuel with a maximum sulfur content of 0.05% weight and even more if off-highway fuel is similarly regulated in the future as a result of the 1990 Clean Air Act Amendments.

Diesel fuel which is produced by high-pressure, high-temperature hydrotreatment, and hydroconversion process, which are capable of effecting some limited aromatic saturation, can sometimes lack adequate lubricity performance even though they have sufficient viscosity. Field experience with both mechanical and electronic unit injectors and the rotary distributor pumps used on numerous smaller engines, shows that there are already some fuels which can severely reduce service life of critical components through poor lubricity. The need to produce all U.S. on-highway diesel fuel to a maximum of 0.05% weight sulfur content by October 1993 may accentuate this problem.

All of the fuel parameters which relate to low lubricity have not been defined and work is proceeding to provide that better definition but to date a number of field cases have been associated with low sulfur, low cloud point diesel fuels.

Work reported by the U.S. Army Fuels TARDEC and Lubricants Research Facility has identified two distinct wear phenomena known respectively as corrosive wear or oxidative wear and adhesive or scuffing wear. The former occurs more commonly and is of a lower severity than scuffing wear. In a report (16) describing their investigation, it was found that the ASTM D 5001 Ball on Cylinder Evaluator (BOCLE), while not providing a perfect correlation with corrosive wear, does give a very high degree of correlation for both plain fuels and additive treated fuels. For situations where scuffing wear is encountered, the BOCLE test is not severe enough and a more heavily loaded metal-to-metal scuffing interaction is needed.

As a result of engine design changes, particularly the use of retarded timing to lower NO_x emissions, serious increases of white smoke emissions in cold operating conditions have been reported by several manufacturers. This appears to be related to marginal cetane quality and as a result the Engine Manufacturers Association, and this Fuels and Lubricants Committee has requested (17) consideration of raising the minimum cetane number specification to improve performance.

10.5 Emissions Regulations/Fuel Quality/Lubricant Quality Interactions—Mechanical and combustion improvements coupled with cleaner burning reformulated diesel fuels in the 1990s will alter the combustion by-products which the crankcase lubricant has to contend with. A crucial requirement for the crankcase lubricant will be its impact on the soluble organic fraction (SOF) of the particulates and also any effects which the lubricant or performance additives may have on aftertreatment devices, which are expected to be employed on 1994 engines and beyond. These aspects will be addressed in appropriate changes to SAE J183 and SAE J304.

11. Notes

11.1 Marginal Indicia—The change bar (I) located in the left margin is for the convenience of the user in locating areas where technical revisions have been made to the previous issue of the report. An (R) symbol to the left of the document title indicates a complete revision of the report.

PREPARED BY THE SAE FUELS AND LUBRICANTS TECHNICAL COMMITTEE 7—FUELS

SAE J313 Revised MAR1998

Rationale—Changes to the document:

Section 3—1-DLS and 2-DLS were added.

Table 1—1-DLS and 2-DLS were added.

Section 8.1—Table 4 was replaced with Tables 4 to 6. All other tables in the document were renumbered because of this change.

Section 10.2 was added to the document.

Relationship of SAE Standard to ISO Standard—Not applicable.

Application—This SAE Recommended Practice summarizes the significance of the more important physical and chemical characteristics of diesel fuels as well as the pertinent test methods for defining or evaluating these properties. The function and type of diesel fuel additives are also addressed.

Reference Section

SAE J183—Engine Oil Performance and Engine Service Classification (Other Than “Energy-Conserving”)

SAE J304—Engine Oil Tests

SAE J1498—Marine Circuit Breakers

SAE Paper 830594—1981 CRC Diesel Fuel Low-Temperature Operability Field Test, Coordinating Research Council Report 528 (September 1983), Summarized by M. L. McMillan and E. G. Barry, “Fuel and Vehicle Effects on Low-Temperature Operation of Diesel Vehicles—The 1981 CRC Field Test”

ASTM D 86—Method for Distillation of Petroleum Products

ASTM D 93—Test Method for Flash Point by the Pensky-Martens Closed Tester

ASTM D 97—Test Method for Pour Point of Petroleum Oils

ASTM D 129—Test Method for Sulfur in Petroleum Products by the Bomb Method

ASTM D 130—Method for Detection of Copper Corrosion from Petroleum Products by the Copper Strip Tarnish Test

ASTM D 240—Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter

ASTM D 287—Test Method for API Gravity of Crude Petroleum and Petroleum Products (Hydrometer Method)

ASTM D 445—Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (and the Calculation of Dynamic Viscosity)

ASTM D 482—Test Method for Ash from Petroleum Products

ASTM D 524—Test Method for Ramsbottom Carbon Residue of Petroleum Products

ASTM D 611—Test Method for Aniline Point and Mixed Aniline Point of Petroleum Products and Hydrocarbon Solvents

ASTM D 613—Test Method for Ignition Quality of Diesel Fuels by the Cetane Method

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ASTM D 665—Test Method for Rust-Preventing Characteristics of Inhibited Mineral Oil in the Presence of Water

ASTM D 975—Specification for Diesel Fuel Oils

ASTM D 976—Method for Calculated Cetane Index of Distillate Fuels

ASTM D 1266—Test Method for Sulfur in Petroleum Products and Liquefied Petroleum (LP) Gases (Lamp Method)

ASTM D 1298—Test Method for Relative Density (Specific Gravity)

ASTM D 1405—Method for Estimation of Net Heat of Combustion of Aviation Fuels

ASTM D 1552—Test Method for Sulfur in Petroleum Products (High Temperature Method)

ASTM D 1796—Test Method for Water and Sediment in Fuel Oils by Centrifuge Method (Laboratory Procedure)

ASTM D 2274—Test Method for Oxidation Stability of Distillate Fuel Oil (Accelerated Method)

ASTM D 2500—Test Method for Cloud Point of Petroleum Oils

ASTM D 2622—Test Method for Sulfur in Petroleum Products (X-Ray Spectrographic Method)

ASTM D 3117—Test Method for Wax Appearance Point of Distillate Fuels

ASTM D 3338—Method for Estimation of Heat of Combustion of Aviation Fuels

ASTM D 4539—Filterability of Diesel Fuels by Low Temperature Flow Test (LTFT)

ASTM D 4737—Method for Calculated Cetane Index by Four Variable Equation

ASTM D 5001—Test Method for Measurement of Lubricity of Aviation Turbine Fuels by the Ball-on-Cylinder Lubricity Evaluator (BOCLE)

Miscellaneous Publication No. 97, 1929, Thermal Properties of Petroleum Products

1. U.S. Clean Air Act (1970)
2. Federal Register, March 5, 1980
3. Federal Register, March 15, 1985
4. U.S. Clean Air Act Amendments 1990
5. Govt. of Canada Gazette
6. Stockholm Club Emissions—Impact on European Truck Engines. H. D. Freeman—Ricardo Consulting Engineers Autotech 89
7. Worldwide Developments in Motor Vehicle Diesel Particulate Control. Michael P. Walsh, SAE 890168
8. Fuel Effects and Heavy Duty Diesel Particulate Control. J. C. Wall & S. K. Hoekman, SAE 841364



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9. Recommended Federal On Highway Diesel Fuel Specifications to Assist Engine Manufacturers Meet 1991 and 1994 Particulate Standards Joint API/EMA/NPRA/NCFC Report, July 19, 1988
10. Federal Register, August 21, 1990
11. Investigation of the Effects of Fuel Composition and Injection and Combustion System Type on Heavy Duty Diesel Exhaust Emissions. Report from CRC VE-1 Project by Terry Ullman, March 1989
12. Study of Fuel Cetane Number and Aromatic Content Effects on Regulated Emissions from a Heavy Duty Diesel Engine. Report from CRC VE-1 Project by Terry Ullman, Robert Mason and Daniel Montalvo, September 1990
13. Gasoline and Diesel Fuel Qualification—A National Need, K. J. Springer, ASME Paper 90-ICE-19
14. NPRA Diesel Fuel Survey 1988
15. PACE Canadian Diesel Fuel Survey Report 88-3 1988
16. Fuel Lubricity Requirements for Diesel Injection Systems BFLRF Interim Report No. 270 by P. I. Lacey and S. J. Lestz, February 1991
17. Letter from EMA Fuels and Lubricants Committee to SAE Technical Committee 7-Fuels dated February 25, 1991

Also see Related Publications

Developed by the SAE Fuels and Lubricants Technical Committee 7—Fuels

SAE J301—EFFECTIVE DATES OF NEW OR REVISED TECHNICAL REPORTS

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