CHAPTER 47

LIQUID FOSSIL FUELS FROM PETROLEUM

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47.1 INTRODUCTION

The major source of liquid fuels is crude petroleum; other sources are shale and tar sands. Synthetic hydrocarbon fuels—gasoline and methanol—can be made from coal and natural gas. Ethanol, some of which is used as an automotive fuel, is derived from vegetable matter.

Crude petroleum and refined products are a mix of a wide variety of hydrocarbons—aliphatics (straight- or branched-chained paraffins and olefins), aromatics (closed rings, six carbons per ring with alternate double bonds joining the ring carbons, with or without aliphatic side chains), and naphthenic or cycloparaffins (closed single-bonded carbon rings, five to six carbons).

Very little crude petroleum is used in its natural state. Refining is required to yield marketable products that are separated by distillation into fractions including a specific boiling range. Further processing (such as cracking, reforming, and alkylation) alters molecular structure of some of the hydrocarbons and enhances the yield and properties of the refined products.

Crude petroleum is the major source of liquid fuels in the United States now and for the immediate future. Although the oil embargo of 1973–1974 intensified development of facilities for extraction of oil from shale and of hydrocarbon liquids from coal, the economics do not favor early commercialization of these processes. Their development has been slowed by an apparently adequate supply of crude oil. Tar sands are being processed in small amounts in Canada, but no commercial facility exists in the United States. (See Table 47.1.)

Except for commercial propane and butane, fuels for heating and power generation are generally heavier and less volatile than fuels used in transportation. The higher the "flash point," the less hazardous is handling of the fuel. (Flash point is the minimum temperature at which the fuel oil will catch fire if exposed to naked flame. Minimum flash points are stipulated by law for safe storage and handling of various grades of oils.) See Table 44.4, Flammability Data for Liquid Fuels.

Properties of fuels reflect the characteristics of the crude. Paraffinic crudes have a high concentration of straight-chain hydrocarbons, which may leave a wax residue with distillation. Aromatic and naphthenic crudes have concentrations of ring hydrocarbons. Asphaltic crudes have a preponderance of heavier ring hydrocarbons and leave a residue after distillation. (See Table 47.2.)

47.2 FUEL OILS

Liquid fuels in common use are broadly classified as follows:

1. Distillate fuel oils derived directly or indirectly from crude petroleum

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Table 47.1 Principal Uses of Liquid Fuels

Heat and Power	
Fuel oil	Space heating (residential, commercial, industrial) Steam generation for electric power Industrial process heating Refinery and chemical feedstock
Kerosene	Supplemental space heating
Turbine fuel	Stationary power generation
Diesel fuel	Stationary power generation
Liquid propane[a]	Isolated residential space heating Standby industrial process heating
Transportation	
Jet fuel	Aviation turbines
Diesel fuel	Automotive engines Marine engines Truck engines
Gasoline	Automotive Aviation
Liquid propane and butane[a]	Limited automotive use

[a]See Chapter 46 on gaseous fossil fuels.

2. Residual fuel oils that result after crude petroleum is topped; or viscous residuums from refining operations
3. Blended fuel oils, mixtures of the above

The distillate fuels have lower specific gravity and are less viscous than residual fuel oils. Petroleum refiners burn a varying mix of crude residue and distilled oils in their process heaters. The changing gravity and viscosity require maximum oil preheat for atomization good enough to assure complete combustion. Tables 47.5–47.8 describe oils in current use. Some terms used in those tables are defined below.

Aniline point is the lowest Fahrenheit temperature at which an oil is completely miscible with an equal volume of freshly distilled aniline.

API gravity is a scale of specific gravity for hydrocarbon mixtures referred to in "degrees API" (for American Petroleum Institute). The relationships between API gravity, specific gravity, and density are:

Table 47.2 Ultimate Chemical Analyses of Various Crudes[a,6]

Crude Petroleum Source	% wt of C	H	N	O	S	Specific Gravity (at temperature, °F)	Base
Baku, USSR	86.5	12.0		1.5		0.897	
California	86.4	11.7	1.14		0.60	0.951 (at 59°F)	Naphthene
Colombia, South America	85.62	11.91	0.54				
Kansas	85.6	12.4			0.37	0.912	Mixed
Mexico	83.0	11.0	——1.7——		4.30	0.97 (at 59°F)	Naphthene
Oklahoma	85.0	12.9			0.76		Mixed
Pennsylvania	85.5	14.2				0.862 (at 59°F)	Paraffin
Texas	85.7	11.0	——2.61——		0.70	0.91	Naphthene
West Virginia	83.6	12.9		3.6		0.897 (at 32°F)	Paraffin

[a]See, also, Table 47.7.

Table 47.3 Some Properties of Liquid Fuels[2]

Property	Gasoline	Kerosene	Diesel Fuel	Light Fuel Oil	Heavy Fuel Oil	Coal Tar Fuel	Bituminous Coal (for Comparison)
Analysis, % wt							
C	85.5	86.3	86.3	86.2	86.2	90.0	80.0
H	14.4	13.6	12.7	12.3	11.8	6.0	5.5
N						1.2	1.5
O						2.5	7
S	0.1	0.1	1.0	1.5	2.0	0.4	1
Boiling range, °F	104–365	284–536	356 up	392 up	482 up	392 up	
Flash point, °F	−40	102	167	176	230	149	
Gravity specific at 59°F	0.73	0.79	0.87	0.89	0.95	1.1	1.25
Heat value, net							
cal/g	10,450	10,400	10,300	10,100	9,900	9,000	7,750
Btu/lb	18,810	18,720	18,540	18,180	17,820	16,200	13,950
Btu/US gal	114,929	131,108	129,800	131,215	141,325		
Residue, % wt at 662°F			15	50	60	60	
Viscosity, kinematic							
Centistokes at 59°F	0.75	1.6	5.0	50	1,200	1,500	
Centistokes at 212°F		0.6	1.2	3.5	20	18	

$$\text{sp gr } 60/60°\text{F} = \frac{141.5}{°\text{API} + 131.5}$$

where °API is measured at 60°F (15.6°C).

$$\text{sp gr } 60/60°\text{F} = \frac{\text{lb/ft}^3}{62.3}$$

where lb/ft^3 is measured at 60°F (15.6°C).

SSU (or SUS) is seconds, Saybolt Universal, a measure of kinematic viscosity determined by measuring the time required for a specified quantity of the sample oil to flow by gravity through a specified orifice at a specified temperature. For heavier, more viscous oils, a larger (Furol) orifice is used, and the results are reported as SSF (seconds, Saybolt Furol).

$$\text{kin visc in centistokes} = 0.226 \times \text{SSU} - 195/\text{SSU, for SSU 32–100}$$
$$\text{kin visc in centistokes} = 0.220 \times \text{SSU} - 135/\text{SSU, for SSU} > 100$$
$$\text{kin visc in centistokes} = 2.24 \times \text{SSF} - 184/\text{SSF, for SSF 25–40}$$
$$\text{kin visc in centistokes} = 2.16 \times \text{SSF} - 60/\text{SSF, for SSF} > 40$$
$$1 \text{ centistoke (cSt)} = 0.000001 \text{ m}^2/\text{sec}$$

Unlike distillates, residual oils contain noticeable amounts of inorganic matter, ash content ranging from 0.01% to 0.1%. Ash often contains vanadium, which causes serious corrosion in boilers and heaters. (A common specification for refinery process heaters requires 50% nickel–50% chromium alloy for tube supports and hangers when the vanadium exceeds 150 ppm.) V_2O_5 also lowers the eutectic of many refractories, causing rapid disintegration. Crudes that often contain high vanadium are

Venezuela, Bachaqoro	350 ppm
Iran	350–440 ppm
Alaska, North Slope	80 ppm

47.2.1 Kerosene

Kerosene is a refined petroleum distillate consisting of a homogeneous mixture of hydrocarbons. It is used mainly in wick-fed illuminating lamps and kerosene burners. Oil for illumination and for

Table 47.4 Gravities and Related Properties of Liquid Petroleum Products

Typical Ranges for: Diesel Fuels	Typical Ranges for: Aviation Turbine Fuels	Typical Ranges for: Fuel Oils	°API	Specific Gravity 60°F/60°F (15.6°C/15.6°C)	lb/gal	kg/m^3	Gross Btu/gal[a]	Gross kcal/liter[a]	% H, wt[a]	Net Btu/gal[a]	Net kcal/liter[a]	Specific Heat @ 40°F	Specific Heat @ 300°F	Temperature Correction °API/°F[a]	ft^3 60°F air/gal	Ultimate % CO_2
			0	1.076	8.969	1075	160,426	10,681	8.359	153,664	10,231	0.391	0.504	0.045	1581	—
			2	1.060	8.834	1059	159,038	10,589	8.601	152,183	10,133	0.394	0.508	—	—	—
		#6	4	1.044	8.704	1043	157,692	10,499	8.836	150.752	10,037	0.397	0.512	—	—	18.0
			6	1.029	8.577	1028	156,384	10,412	9.064	149,368	9,945	0.400	0.516	0.048	1529	17.6
			8	1.014	8.454	1013	155,115	10,328	9.285	148,028	9,856	0.403	0.519	0.050	1513	17.1
			10[b]	1.000[b]	8.335[b]	1000[b]	153,881	10,246	10.00	146,351	9,744	0.406	0.523	0.051	1509	16.7
		#5	12	0.986	8.219	985.0	152,681	10,166	10.21	145,100	9,661	0.409	0.527	0.052	1494	16.4
			14	0.973	8.106	971.5	151,515	10,088	10.41	143,888	9,580	0.412	0.530	0.054	1478	16.1
			16	0.959	7.996	958.3	150,380	10,013	10.61	147,712	9,502	0.415	0.534	0.056	1463	15.8
		#4	18	0.946	7.889	945.5	149,275	9,939	10.80	141,572	9,426	0.417	0.538	0.058	1448	15.5
			20	0.934	7.785	933.0	148,200	9,867	10.99	140,466	9,353	0.420	0.541	0.060	1433	15.2
			22	0.922	7.683	920.9	147,153	9,798	11.37	139,251	9,272	0.423	0.545	0.061	1423	14.9
			24	0.910	7.585	909.0	146,132	9,730	11.55	138,210	9,202	0.426	0.548	0.063	1409	14.7
			26	0.898	7.488	897.5	145,138	9,664	11.72	137,198	9,135	0.428	0.552	0.065	1395	14.5
			28	0.887	7.394	886.2	144,168	9,599	11.89	136,214	9,069	0.431	0.555	0.067	1381	14.3
		#2	30	0.876	7.303	875.2	143,223	9,536	12.06	135,258	9,006	0.434	0.559	0.069	1368	14.0
2D			32	0.865	7.213	864.5	142,300	9.475	12.47	134,163	8,933	0.436	0.562	0.072	1360	13.8
			34	0.855	7.126	854.1	141,400	9,415	12.63	133,259	8,873	0.439	0.566	0.074	1347	13.6
	ID JET A		36	0.845	7.041	843.9	140,521	9,356	12.78	132,380	8,814	0.442	0.569	0.076	1334	13.4
	JP5	↓ #1	38	0.835	6.958	833.9	139,664	9,299	12.93	131,524	8,757	0.444	0.572	0.079	1321	13.3
	(48) (47) (48)	(48)	40	0.825	6.887	824.2	138,826	9,243	13.07	130,689	8,702	0.447	0.576	0.082	1309	13.1
	JP4		42	0.816	6.798	814.7	138,007	9,189	—	—	—	0.450	0.579	0.085	—	13.0
	(56)		44	0.806	6.720	805.4	137,207	9,136	—	—	—	0.452	0.582	0.088	—	12.8

[a]For gravity measured at 60°F (15.6°C) only.

[b]Same as H_2O.

Table 47.5 Heating Requirements for Products Derived from Petroleum[3]

Commercial Fuels	Specific Gravity at 60°F/60°F (15.6°C)	Distillation Range, °F(°C)	Vapor Pressure,[a] psia(mm Hg)	Latent Btu/gal[b] to Vaporize	Btu/gal[b] to Heat from 32°F (0°C) to: Pumping Temperature	Atomizing Temperature	Vapor
No. 6 oil	0.965	600–1000(300–500)	0.054 (2.8)	764	371	996	3619[c]
No. 5 oil	0.945	600–1000(300–500)	0.004 (0.2)	749	133	635	3559[c]
No. 4 oil	0.902	325–1000(150–500)	0.232 (12)	737	—	313	2725[c]
No. 2 oil	0.849	325– 750(150–400)	0.019 (1)	743	—	—	2704[c]
Kerosene	0.780	256– 481(160–285)	0.039 (2)	750	—	—	1303[c]
Gasoline	0.733	35– 300(37–185)	0.135 (7)	772	—	—	1215[c]
Methanol	0.796	148 (64)	4.62 (239)	3140	—	—	3400[d]
Butane	0.582	31 (0)	31(1604)	808	—	—	976[d]
Propane	0.509	−44 (−42)	124(6415)	785	—	—	963[d]

[a]At the atomizing temperature or 60°F, whichever is lower. Based on a sample with the lowest boiling point from column 3.

[b]To convert Btu/US gallon to kcal/liter, multiply by 0.666. To convert Btu/US gallon to Btu/lb, divide by 8.335 × sp gr, from column 2. To convert Btu/US gallon to kcal/kg, divide by 15.00 × sp gr, from column 2.

[c]Calculated for boiling at midpoint of distillation range, from column 3.

[d]Includes latent heat plus sensible heat of the vapor heated from boiling point to 60°F (15.6°C).

Table 47.6 Analyses and Characteristics of Selected Fuel Oils[3]

	Ultimate Analysis (% Weight)										Flash	HV, Btu/lb		Pour	Viscosity, SSU	
Source	C	H	N	S	Ash	O[a]	ppm if > 50	% wt Asphaltine	% wt C Residue	°API at 60°F	Point, °F	Gross	Net	Point, °F	At 140°F	At 210°F
Alaska	86.99	12.07	0.007	0.31	<0.001	0.62	—	—	—	33.1	—	—	—	—	33.0	29.5
California	86.8	12.52	0.053	0.27	<0.001	0.36	—	—	—	32.6	—	19,330	—	—	30.8	29.5
West Texas	88.09	9.76	0.026	1.88	<0.001	0.24	—	—	—	18.3	—	—	—	—	32.0	28.8
Alaska	86.04	11.18	0.51	1.63	0.034	0.61	50 Ni 67 V	5.6	12.9	15.6	215	18,470	17,580	38	1071	194
California	86.66	10.44	0.86	0.99	0.20	0.85	[b]	8.62	15.2	12.6	180	18,230	17,280	42	720	200
DFM (shale)	86.18	13.00	0.24	0.51	0.003	1.07	—	0.036	4.1	33.1	182	19,430	18,240	40	36.1	30.7
Gulf of Mexico	84.62	10.77	0.36	2.44	0.027	1.78	—	7.02	14.8	13.2	155	18,240	17,260	40	835	181
Indo/Malaysia	86.53	11.93	0.24	0.22	0.036	1.04	101 V	0.74	3.98	21.8	210	19,070	17,980	61	199	65
Middle East[c]	86.78	11.95	0.18	0.67	0.012	0.41	—	3.24	6.0	19.8	350	19,070	17,980	48	490	131.8
Pennsylvania[d]	84.82	11.21	0.34	2.26	0.067	1.3	65 Na 82 V	4.04	12.4	15.4	275	18,520	17,500	66	1049	240
Venezuela	85.24	10.96	0.40	2.22	0.081	1.10	52 Ni 226 V	8.4	6.8	14.1	210	18,400	17,400	58	742	196.7
Venezuela desulfurized	85.92	12.05	0.24	0.93	0.033	0.83	101 V	2.59	5.1	23.3	176	18,400	17,300	48	113.2	50.5

[a]By difference.
[b]91 Ca, 77 Fe, 88 Ni, 66 V.
[c]Exxon.
[d]Amerada Hess.

Table 47.7 ASTM Fuel Oil Specifications[8]

Grade of Fuel Oil[a]	Flash Point, °C (°F) Min	Pour Point, °C (°F) Max	Water and Sediment, Vol % Max	Carbon Residue on 10% Bottoms, % Max	Ash, Weight % Max	Distillation Temperatures, °C (°F): 10% Point Max	Distillation Temperatures, °C (°F): 90% Point Min	Distillation Temperatures, °C (°F): 90% Point Max	Saybolt Viscosity, s[d]: Universal at 38°C (100°F) Min	Saybolt Viscosity, s[d]: Universal at 38°C (100°F) Max	Saybolt Viscosity, s[d]: Furol at 50°C (122°F) Min	Saybolt Viscosity, s[d]: Furol at 50°C (122°F) Max	Kinematic Viscosity, cSt[d]: At 38°C (100°F) Min	Kinematic Viscosity, cSt[d]: At 38°C (100°F) Max	Kinematic Viscosity, cSt[d]: At 40°C (104°F) Min	Kinematic Viscosity, cSt[d]: At 40°C (104°F) Max	Kinematic Viscosity, cSt[d]: At 50°C (122°F) Min	Kinematic Viscosity, cSt[d]: At 50°C (122°F) Max	Specific Gravity, 60/60°F (deg API) Max	Copper Strip Corrosion Max	Sulfur, % Max
No. 1 A distillate oil intended for vaporizing pot-type burners and other burners requiring this grade of fuel	38 (100)	−18[c] (0)	0.05	0.15	—	215 (420)	—	288 (550)	—	—	—	—	1.4	2.2	1.3	2.1	—	—	0.8499 (35 min)	No. 3	0.5
No. 2 A distillate oil for general purpose heating for use in burners not requiring No. 1 fuel oil	38 (100)	−6[c] (20)	0.05	0.35	—	—	282[c] (540)	338 (640)	(32.6)	(37.9)	—	—	2.0[c]	3.6	1.9[c]	3.4	—	—	0.8762 (30 min)	No. 3	0.5[b]
No. 4 (Light) Preheating not usually required for handling or burning	38 (100)	−6[c] (20)	0.50	—	0.05	—	—	—	(32.6)	(45)	—	—	2.0	5.8	—	—	—	—	0.876[g] (30 max)	—	—
No. 4 Preheating not usually required for handling or burning	55 (130)	−6[c] (20)	0.50	—	0.10	—	—	—	(45)	(125)	—	—	5.8	26.4[h]	5.5	24.0[f]	—	—	—	—	—

No. 5 (Light) Preheating may be required depending on climate and equipment	55 (130)	—	1.00	—	0.10	—	—	—	(>125)	(300)	—	—	>26.4	65[f]	>24.0	58[f]	—	—	—	—	—
No. 5 (Heavy) Preheating may be required for burning and, in cold climates, may be required for handling	55 (130)	—	1.00	—	0.10	—	—	—	(>300)	(900)	(23)	(40)	>65	194[f]	58	168[f]	(42)	(81)	—	—	—
No. 6 Preheating required for burning and handling	60 (140)	[g]	2.00[e]	—	—	—	—	—	(>900)	(9000)	(>45)	(300)	—	—	—	—	>92	638[f]	—	—	—

[a]It is the intent of these classifications that failure to meet any requirement of a given grade does not automatically place an oil in the next lower grade unless in fact it meets all requirements of the lower grade.

[b]In countries outside the United States other sulfur limits may apply.

[c]Lower or higher pour points may be specified whenever required by conditions of storage or use. When pour point less than −18°C (0°F) is specified, the minimum viscosity for grade No. 2 shall be 1.7 cSt (31.5 SUS) and the minimum 90% point shall be waived.

[d]Viscosity values in parentheses are for information only and not necessarily limiting.

[e]The amount of water by distillation plus the sediment by extraction shall not exceed 2.00%. The amount of sediment by extraction shall not exceed 0.50%. A deduction in quantity shall be made for all water and sediment in excess of 1.0%.

[f]Where low-sulfur fuel oil is required, fuel oil falling in the viscosity range of a lower numbered grade down to and including No. 4 may be supplied by agreement between purchaser and supplier. The viscosity range of the initial shipment shall be identified and advance notice shall be required when changing from one viscosity range to another. This notice shall be in sufficient time to permit the user to make the necessary adjustments.

[g]This limit guarantees a minimum heating value and also prevents misrepresentation and misapplication of this product as Grade No. 2.

[h]Where low-sulfur fuel oil is required, Grade 6 fuel oil will be classified as low pour +15°C (60°F) max or high pour (no max). Low-pour fuel oil should be used unless all tanks and lines are heated.

Table 47.8 Application of ASTM Fuel Oil Grades, as Described by One Burner Manufacturer

Fuel Oil	Description
No. 1	Distillate oil for vaporizing-type burners
No. 2	Distillate oil for general purpose use, and for burners not requiring No. 1 fuel oil
No. 4	Blended oil intended for use without preheating
No. 5	Blended residual oil for use with preheating; usual preheat temperature is 120–220°F
No. 6	Residual oil for use with preheaters permitting a high-viscosity fuel; usual preheat temperature is 180–260°F
Bunker C	Heavy residual oil, originally intended for oceangoing ships

domestic stoves must be high in paraffins to give low smoke. The presence of naphthenic and especially aromatic hydrocarbons increases the smoking tendency. A "smoke point" specification is a measure of flame height at which the tip becomes smoky. The "smoke point" is about 73 mm for paraffins, 34 mm for naphthalenes, and 7.5 mm for aromatics and mixtures.

Low sulfur content is necessary in kerosenes because:

1. Sulfur forms a bloom on glass lamp chimneys and promotes carbon formation on wicks.
2. Sulfur forms oxides in heating stoves. These swell, are corrosive and toxic, creating a health hazard, particularly in nonvented stoves.

Kerosene grades[9] (see Table 47.9) in the United States are:

No. 1 K: A special low-sulfur grade kerosene suitable for critical kerosene burner applications

No. 2 K: A regular-grade kerosene suitable for use in flue-connected burner applications and for use in wick-fed illuminating lamps

47.2.2 Aviation Turbine Fuels

The most important requirements of aircraft jet fuel relate to freezing point, distillation range, and level of aromatics. Fluidity at low temperature is important to ensure atomization. A typical upper viscosity limit is 7–10 cSt at 0°F, with the freezing point as low as −60°F.

Aromatics are objectionable because (1) coking deposits from the flame are most pronounced with aromatics of high C/H ratio and less pronounced with short-chain compounds, and (2) they must be controlled to keep the combustor liner at an acceptable temperature.

Jet fuels for civil aviation are identified as Jet A and A1 (high-flash-point, kerosene-type distillates), and Jet B (a relatively wide boiling range, volatile distillate).

Jet fuels for military aviation are identified as JP4 and JP5. The JP4 has a low flash point and a wide boiling range. The JP5 has a high flash point and a narrow boiling range. (See Table 47.10.)

Table 47.9 ASTM Chemical and Physical Requirements for Kerosene[9]

Property	Limit
Distillation temperature	
10% recovered	401°F (205°C)
Final boiling point	572°F (300°C)
Flash point	100°F (38°C)
Freezing point	−22°F (−30°C)
Sulfur, % weight	
No. 1 K	0.04 maximum
No. 2 K	0.30 maximum
Viscosity, kinematic at 104°F (40°C), centistokes	1.0 min/1.9 max

Table 47.10 ASTM Specifications[10] and Typical Properties[7] of Aviation Turbine Fuels

	Specifications			Typical, 1979		
Property	Jet A	Jet A1	Jet B	26 Samples JP4	7 Samples JP5	60 Samples Jet A
Aromatics, % vol	20	20	20	13.0	16.4	17.9
Boiling point, final, °F	572	572	—	—	—	—
Distillation, max temperature, °F						
For 10% recovered	400	400	—	208	387	375
For 20% recovered	—	—	290	—	—	—
For 50% recovered	—	—	370	293	423	416
For 90% recovered	—	—	470	388	470	473
Flash point, min, °F	100	100	—	—	—	—
Freezing point, max, °F	−40	−53	−58	−110	−71	−56
Gravity, API, max	51	51	57	53.5	41.2	42.7
Gravity, API, min	37	37	45	—	—	—
Gravity, specific 60°F min	0.7753	0.7753	0.7507	0.765	0.819	0.812
Gravity, specific 60°F max	0.8398	0.8398	0.8017	—	—	—
Heating value, gross Btu/lb	—	—	—	18,700	18,530	18,598
Heating value, gross Btu/lb min	18,400	18,400	18,400	—	—	—
Mercaptan, % wt	0.003	0.003	0.003	0.0004	0.0003	0.0008
Sulfur, max % wt	0.3	0.3	0.3	0.030	0.044	0.050
Vapor pressure, Reid, psi	—	—	3	2.5	—	0.2
Viscosity, max SSU						
At −4°F	52	—	—	—	—	—
At −30°F	—	—	—	34–37	60.5	54.8

Gas turbine fuel oils for other than use in aircraft must be free of inorganic acid and low in solid or fibrous materials. (See Tables 47.11 and 47.12.) All such oils must be homogeneous mixtures that do not separate by gravity into light and heavy components.

47.2.3 Diesel Fuels

Diesel engines, developed by Rudolf Diesel, rely on the heat of compression to achieve ignition of the fuel. Fuel is injected into the combustion chamber in an atomized spray at the end of the compression stroke, after air has been compressed to 450–650 psi and has reached a temperature, due to compression, of at least 932°F (500°C). This temperature ignites the fuel and initiates the piston's power stroke. The fuel is injected at about 2000 psi to ensure good mixing.

Diesels are extensively used in truck transport, rail trains, and marine engines. They are being used more in automobiles. In addition, they are employed in industrial and commercial stationary power plants.

Fuels for diesels vary from kerosene to medium residual oils. The choice is dictated by engine characteristics, namely, cylinder diameter, engine speed, and combustion wall temperature. High-

Table 47.11 Nonaviation Gas Turbine Fuel Grades per ASTM[11]

Grade	Description
No. 0-GT	A naphtha or low-flash-point hydrocarbon liquid
No. 1-GT	A distillate for gas turbines requiring cleaner burning than No. 2-GT
No. 2-GT	A distillate fuel of low ash suitable for gas turbines not requiring No. 1-GT
No. 3-GT	A low ash fuel that may contain residual components
No, 4-GT	A fuel containing residual components and having higher vanadium content than No. 3-GT

Table 47.12 ASTM Specifications[11] for Nonaviation Gas Turbine Fuels

Property	Specifications 0-GT	1-GT	2-GT	3-GT	4-GT
Ash, max % wt	0.01	0.01	0.01	0.03	—
Carbon residue, max % wt	0.15	0.15	0.35	—	—
Distillation, 90% point, max °F	—	(550)[a]	(640)	—	—
Distillation, 90% point, min °F	—	—	(540)	—	—
Flash point, min °F	—	(100)	(100)	(130)	(150)
Gravity, API min	—	(35)	(30)	—	—
Gravity, spec 60°F max	—	0.850	0.876	—	—
Pour point, max °F	—	(0)	(20)	—	—
Viscosity, kinematic					
Min SSU at 100°F	—	—	(32.6)	(45)	(45)
Max SSU at 100°F	—	(34.4)	(40.2)	—	—
Max SSF at 122°F	—	—	—	(300)	(300)
Water and sediment, max % vol	0.05	0.05	0.05	1.0	1.0

[a]Values in parentheses are approximate.

speed small engines require lighter fuels and are more sensitive to fuel quality variations. Slow-speed, larger industrial and marine engines use heavier grades of diesel fuel oil.

Ignition qualities and viscosity are important characteristics that determine performance. The ignition qualities of diesel fuels may be assessed in terms of their cetane numbers or diesel indices. Although the diesel index is a useful indication of ignition quality, it is not as reliable as the cetane number, which is based on an engine test:

$$\text{diesel index} = (\text{aniline point, °F}) \times (\text{API gravity}/100)$$

The diesel index is an arbitrary figure having a significance similar to cetane number, but having a value 1–5 numbers higher.

The cetane number is the percentage by volume of cetane in a mixture of cetane with an ethyl-naphthalene that has the same ignition characteristics as the fuel. The comparison is made in a diesel engine equipped either with means for measuring the delay period between injection and ignition or with a surge chamber, separated from the engine intake port by a throttle in which the critical measure below which ignition does not occur can be measured. Secondary reference fuels with specific cetane numbers are available. Cetane number is a measure of ignition quality and influences combustion roughness.

The use of a fuel with too low a cetane number results in accumulation of fuel in the cylinder before combustion, causing "diesel knock." Too high a cetane number will cause rapid ignition and high fuel consumption.

The higher the engine speed, the higher the required fuel cetane number. Suggested rpm values for various fuel cetane numbers are shown in Table 47.13.[5] Engine size and operating conditions are important factors in establishing approximate ignition qualities of a fuel.

Too viscous an oil will cause large spray droplets and incomplete combustion. Too low a viscosity may cause fuel leakage from high-pressure pumps and injection needle valves. Preheating permits use of higher viscosity oils.

Table 47.13 ASTM Fuel Cetane Numbers for Various Engine Speeds[5]

Engine Speed (rpm)	Cetane Number
Above 1500	50–60
500–1500	45–55
400–800	35–50
200–400	30–45
100–200	15–40
Below 200	15–30

To minimize injection system wear, fuels are filtered to remove grit. Fine gage filters are considered adequate for engines up to 8 Hz, but high-speed engines usually have fabric or felt filters. It is possible for wax to crystallize from diesel fuels in cold weather, therefore, preheating before filtering is essential.

To minimize engine corrosion from combustion products, control of fuel sulfur level is required. (See Tables 47.14 and 47.15.)

47.2.4 Summary

Aviation jet fuels, gas turbine fuels, kerosenes, and diesel fuels are very similar. The following note from Table 1 of Ref. 11 highlights this:

No. 0-GT includes naphtha, Jet B fuel, and other volatile hydrocarbon liquids. No. 1-GT corresponds in general to Spec D396 Grade No. 1 fuel and Classification D975 Grade No. 1-D Diesel fuel in physical properties. No. 2-GT corresponds in general to Spec D396 Grade No. 2 fuel and Classification D975 Grade No. 2 Diesel fuel in physical properties. No. 3-GT and No. 4-GT viscosity range brackets Spec D396 and Grade No. 4, No. 5 (light), No. 5 (heavy), No. 6, and Classification D975 Grade No. 4-D Diesel fuel in physical properties.

47.3 SHALE OILS

As this is written, there is no commercial producing shale oil plant in the United States. Predictions are that the output products will be close in characteristics and performance to those made from petroleum crudes.

Table 47.16 lists properties of a residual fuel oil (DMF) from one shale pilot operation and of a shale crude oil.[13] Table 47.17 lists ultimate analyses of oils derived from shales from a number of locations.[14] Properties will vary with the process used for extraction from the shale. The objective of all such processes is only to provide feedstock for refineries. In turn, the refineries' subsequent processing will also affect the properties.

If petroleum shortages occur, they will probably provide the economic impetus for completion of developments already begun for the mining, processing, and refining of oils from shale.

47.4 OILS FROM TAR SANDS

At the time that this is written, the only commercially practical operation for extracting oil from tar sands is at Athabaska, Alberta, Canada, using surface mining techniques. When petroleum supplies become short, economic impetus therefrom will push completion of developments already well under way for mining, processing, and refining of oils from tar sands.

Table 47.18 lists chemical and physical properties of several tar sand bitumens.[15] Further refining will be necessary because of the high density, viscosity, and sulfur content of these oils.

Extensive deposits of tar sands are to be found around the globe, but most will have to be recovered by some *in situ* technique, fireflooding, or steam flooding. Yields tend to be small and properties vary with the recovery method, as illustrated in Table 47.19.[15]

47.5 OIL-WATER EMULSIONS

Emulsions of oil have offered some promise of low fuel cost and alternate fuel supply for some time. The following excerpts from Ref. 16 provide introductory information on a water emulsion with an

Table 47.14 ASTM Diesel Fuel Descriptions[12]

Grade	Description
No. 1D	A volatile distillate fuel oil for engines in service requiring frequent speed and load changes
No. 2D	Distillate fuel oil of lower volatility for engines in industrial and heavy mobile service
No. 4D	A fuel oil for low and medium speed diesel engines
Type CB	For buses, essentially 1D
Type TT	For trucks, essentially 2D
Type RR	For railroads, essentially 2D
Type SM	For stationary and marine use, essentially 2D or heavier

Table 47.15a ASTM Detailed Requirements for Diesel Fuel Oils[a,h,12]

Grade of Diesel Fuel Oil	Flash Point, °C Min	Cloud Point, °C (°F) Max	Water and Sediment, Vol% Max	Carbon Residue on, 10% Residuum,% Max	Ash, Weight % Max	Distillation Temperatures, °C (°F), 90% Point		Viscosity				Sulfur,[d] Weight % Max	Copper Strip Corrosion Max	Cetane Number[e] Min
								Kinematic, cSt[g] at 40°C		Saybolt, SUS at 100°F				
						Min	Max	Min	Max	Min	Max			
No. 1-D A volatile distillate fuel oil for engines in service requiring frequent speed and load changes	38 (100)	[b]	0.05	0.15	0.01	—	288 (550)	1.3	2.4	—	34.4	0.50	No.3	40[f]
No. 2-D A distillate fuel oil of lower volatility for engines in industrial and heavy mobile service	52 (125)	[b]	0.05	0.35	0.01	282[c] (540)	338 (640)	1.9	4.1	32.6	40.1	0.50	No.3	40[f]
No. 4-D A fuel oil for low and medium speed engines	55 (130)	[b]	0.50	—	0.10	—	—	5.5	24.0	45.0	125.0	2.0	—	30[f]

[a]To meet special operating conditions, modifications of individual limiting requirements may be agreed upon between purchaser, seller, and manufacturer.

[b]It is unrealistic to specify low-temperature properties that will ensure satisfactory operation on a broad basis. Satisfactory operation should be achieved in most cases if the cloud point (or wax appearance point) is specified at 6°C above the tenth percentile minimum ambient temperature for the area in which the fuel will be used. This guidance is of a general nature; some equipment designs, using improved 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.

[c]When cloud point less than −12°C (10°F) is specified, the minimum viscosity shall be 1.7 cSt (or mm^2/sec) and the 90% point shall be waived.

[d]In countries outside the United States, other sulfur limits may apply.

[e]Where cetane number by Method D613 is not available, ASTM Method D976, Calculated Cetane Index of Distillate Fuels may be used as an approximation. Where there is disagreement, Method D613 shall be the referee method.

[f]Low-atmospheric temperatures as well as engine operation at high altitudes may require use of fuels with higher cetane ratings.

[g]cSt = 1 mm^2/sec.

[h]The values stated in SI units are to be regarded as the standard. The values in U.S. customary units are for information only.

Table 47.15b ASTM Typical Properties of Diesel Fuels[7]

	All United States, 1981						Eastern United States, 1981											
	48 Samples			112 Samples			24 Samples			44 Samples			13 Samples			4 Samples		
	No. 1D			No. 2D			Type CB			Type TT			Type RR			Type SM		
Property	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
Ash, % wt	0.000	0.001	0.005	0.000	0.002	0.020	—	0.001	0.005	—	0.002	0.015	—	0.000	0.001	—	0.001	0.001
Carbon residue, % wt	0.000	0.059	0.067	0.000	0.101	0.300	—	—	0.21	0.101	—	0.25	—	0.121	0.23	—	0.148	0.21
Cetane number	36	46.7	53.0	29.0	45.6	52.4	—	49.8	—	—	45.6	—	—	44.8	—	—	—	—
Distillation, 90% point, °F	445	448	560	493	587	640	451	512	640	451	571	640	540	590	640	482	577	640
Flash point, °F	104	138	176	132	166	240	120	140	240	120	162	240	156	164	192	136	162	180
Gravity, API	37.8	42.4	47.9	22.8	34.9	43.1	—	41.5	—	—	36.3	—	—	33.8	—	—	35.3	—
spec, 60/60°F	0.836	0.814	0.789	0.917	0.850	0.810	—	0.818	—	—	0.843	—	—	0.856	—	—	0.848	—
Sulfur, % wt	0.000	0.070	0.25	0.010	0.283	0.950	—	0.086	0.24	—	0.198	0.46	—	0.283	0.580	—	0.155	0.28
Viscosity, SSU at 100°F	32.6	33.3	35.7	33.8	36.0	40.3	32.9	34.3	40.2	32.9	35.7	40.2	34.2	36.0	37.8	36.0	—	37.8

Table 47.16 Properties of Shale Oils[13]

Property	DMF Residual	Crude
Ultimate analysis		
Carbon, % wt	86.18	84.6
Hydrogen, % wt	13.00	11.3
Nitrogen, % wt	0.24	2.08
Sulfur, % wt	0.51	0.63
Ash, % wt	0.003	0.026
Oxygen, % wt by difference	1.07	1.36
Conradson carbon residue, %	4.1	2.9
Asphaltene, %	0.036	1.33
Calcium, ppm	0.13	1.5
Iron, ppm	6.3	47.9
Manganese, ppm	0.06	0.17
Magnesium, ppm	—	5.40
Nickel, ppm	0.43	5.00
Sodium, ppm	0.09	11.71
Vanadium, ppm	0.1	0.3
Flash point, °F	182	250
Pour point, °F	40	80
API gravity at 60°F	33.1	20.3
Viscosity, SSU at 140°F	36.1	97
SSU at 210°F	30.7	44.1
Gross heating value, Btu/lb	19,430	18,290
Net heating value, Btu/lb	18,240	17,260

Table 47.17 Elemental Content of Shale Oils, % wt[14]

	Carbon, C			Hydrogen, H			Nitrogen, N			Sulfur, S			Oxygen, O		
Source	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
Colorado	83.5	84.2	84.9	10.9	11.3	11.7	1.6	1.8	1.9	0.7	1.2	1.7	1.3	1.7	2.1
Utah	84.1	84.7	85.2	10.9	11.5	12.0	1.6	1.8	2.0	0.5	0.7	0.8	1.2	1.6	2.0
Wyoming	81.3	83.1	84.4	11.2	11.7	12.2	1.4	1.8	2.2	0.4	1.0	1.5	1.7	2.0	2.3
Kentucky	83.6	84.4	85.2	9.6	10.2	10.7	1.0	1.3	1.6	1.4	1.9	2.4	1.8	2.3	2.7
Queensland Australia (four locations)	80.0	82.2	85.5	10.0	11.1	12.8	1.0	1.2	1.6	0.3	1.9	6.0	1.1	3.0	6.6
Brazil		85.3			11.2			0.9			1.1			1.5	
Karak, Jordan	77.6	78.3	79.0	9.4	9.7	9.9	0.5	0.7	0.8	9.3	10.0	10.6	0.9	1.4	1.9
Timahdit Morocco	79.5	80.0	80.4	9.7	9.8	9.9	1.2	1.4	1.6	6.7	7.1	7.4	1.8	2.0	2.2
Sweden	86.5	86.5	86.5	9.0	9.4	9.8	0.6	0.7	0.7	1.7	1.9	2.1	1.4	1.6	1.7

oil from the vicinity of the Orinoco River in Venezuela. It is being marketed as "Orimulsion" by Petrtoleos de Veneauels SA and Bitor America Corp of Boca Raton, Florida. It is a natural bitumen, like a liquid coal that has been emulsified with water to make it possible to extract it from the earth and to transport it.

Table 47.20 shows some of its properties and contents. Although its original sulfur content is high, the ash is low. A low C/H ratio promises less CO_2 emission. Because of handleability concerns, it will probably find use mostly in large steam generators.

Table 47.18 Chemical and Physical Properties of Several Tar Sand Bitumens[15]

	Uinta Basin, Utah	South-east Utah	Athabasca, Alberta	Trapper Canyon, WY[a]	South TX	Santa Rosa, NM[a]	Big Clifty, KY	Bellamy, MO
Carbon, % wt	85.3	84.3	82.5	82.4	—	85.6	82.4	86.7
Hydrogen, % wt	11.2	10.2	10.6	10.3	—	10.1	10.8	10.3
Nitrogen, % wt	0.96	0.51	0.44	0.54	0.36	0.22	0.64	0.10
Sulfur, % wt	0.49	4.46	4.86	5.52	~10	2.30	1.55	0.75
H/C ratio	1.56	1.44	1.53	1.49	1.34	1.41	1.56	1.42
Vanadium, ppm	23	151	196	91	85	25	198	—
Nickel, ppm	96	62	82	53	24	23	80	—
Carbon residue, % wt	10.9	19.6	13.7	14.8	24.5	22.1	16.7	—
Pour point, °F	125	95	75	125	180	—	85	—
API gravity	11.6	9.2	9.5	5.4	−2.0	5	8.7	10
Viscosities range from 50,000 to 600,000 SSF (100,000 to 1,300,000 cSt).								

[a]Outcrop samples.

Table 47.19 Elemental Composition of Bitumen and Oils Recovered from Tar Sands by Methods C and S[a,15]

	Bitumen	Light Oil C[b]	Heavy Oil C 1–4 Mo.	Heavy Oil C 5–6 Mo.	Product Oil C	Product Oil S[c]
Carbon, % wt	86.0	86.7	86.1	86.7	86.6	85.9
Hydrogen, % wt	11.2	12.2	11.8	11.3	11.6	11.3
Nitrogen, % wt	0.93	0.16	0.82	0.66	0.82	1.17
Sulfur, % wt	0.45	0.30	0.39	0.33	0.43	0.42
Oxygen, % wt	1.42	0.64	0.89	1.01	0.55	1.21

[a]These percentages are site and project specific.
[b]C = reverse-forward combustion.
[c]S = steamflood.
[d]By difference.

Table 47.20 Orimulsion Fuel Characteristics

Density	63 lb/ft^3	
Apparent Viscosity	41F/20sec-1—700 mPa 86F/20sec-1—450 mPa 158F/100sec-1—105 mPa	
Flash point	266°F	
Pour point	32°F	
Higher heating value	12,683 Btu/lb	
Lower heating value	11,694 Btu/lb	
Weight analysis	Carbon	60%
	Hydrogen	7.5%
	Sulfur	2.7%
	Nitrogen	0.5%
	Oxygen	0.2%
	Ash	0.25%
	Water	30%
	Vanadium	300 ppm
	Sodium	70 ppm
	Magnesium	350 ppm

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